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HYPERSPECTRAL IMAGE CLASSIFICATION USING UNCERTAINTY AND DIVERSITY BASED ACTIVE LEARNING

USHA PATEL, HARDIK DAVE, AND VIBHA PATEL*

Abstract. There has been extensive research in the field of Hyperspectral Image Classification using deep neural networks. The deep learning based approaches requires huge amount of labelled data samples. But in the case of Hyperspectral Image, there are less number of labelled data samples. Therefore, we can adopt Active Learning combined with deep learning based approaches to be able to extract most informative data samples. By using this technique, we can train the classifier to achieve better classification accuracies with less number of labelled data samples. There is considerable amount of research carried out for selecting diverse data samples from the pool of unlabeled data samples. We present a novel diversity-based Active Learning approach utilizing the information of clustered data distribution. We incorporate diversity criteria with Active Learning selection criteria and combine it with Convolutional Neural Network for feature extraction and classification. This approach helps us in obtaining most informative and diverse data samples. We have compared our proposed approach with three other sampling methods in terms of classification accuracies, Cohen Kappa score, which shows that our approach gives better results with comparison to other sampling methods.

Key words: Active Learning (AL), Convolutional Neural Network (CNN), Hyperspectral Image (HSI) Classification, Deep Learning (DL), Diversity, Uncertainty

AMS subject classifications. 68T07

1. Introduction. Hyperspectral Imaging or Imaging Spectroscopy is a field of collection, analysis and processing of information from across wide electromagnetic spectrum [14]. For this, various instruments called imaging spectrometers are used such as AVIRIS (Airborne Visible Infra-Red Imaging Spectrometer), ROSIS (Reflective Optics System Imaging Spectrometer) etc. [27]. These spectrometers collect large amount of information at different wavelength to collectively analyse the region or scene. Usually these information at different wavelengths are called bands or spectral bands or spectral channels. Hyperspectral images (HSIs) contains hundreds of nearly continuous or narrow spectral bands each of which represents the image at different wavelength, thus it provides rich and detailed information of a particular region or scene. With the rapid development in remote sensing field, hyperspectral imaging has proven its usefulness in various domains such as geosciences, agriculture etc. [14], [31], [27].

Significant amount of research has been carried out in the field of classification of hyperspectral images. The large amount of spectral band provided by Hyperspectral images given better accuracy in classification of these images. Essentially, in HSI classification, every single pixel vector of image is categorized into certain class. HSI classification methods have two major categories, spectral-information-based classification methods and the spectral-spatial-information-based classification methods. Spectral-information-based HSI classification utilizes the spectral information contained by Hyperspectral images to classify each pixel vector in the image. Moreover, instead of utilizing all the spectral bands for classification, techniques like principal component analysis and linear discriminant analysis has been used to reducing the spectral bands and retaining most relevant bands [22], [2]. Spectral-based methods do not utilize spatial correlation information which results in low performance of classifier. Spectral-spatial-information-based methods make use of both the spectral and spatial information by using patch instead of single pixel [2].

Unsupervised techniques or clustering algorithms have also been applied for HSI classification [30]. Supervised classification techniques are mostly preferred in HSI classification because of their capabilities in classification with higher performance [13]. Traditional machine learning algorithms such as Support Vector Machines has been employed for HSI classification but did not give significant performance [25]. Various approaches

*Nirma University, Ahmedabad, India (ushapatel@nirmauni.ac.in)

based upon deep learning algorithms have also been applied for HSI classification. Deep belief networks in [20] and [8], Stacked Auto-Encoders (SAE) in [26] and Convolutional Neural Networks (CNN) in [16], [6] and [15] have been used and were successful. CNN are very effective approach for Hyperspectral image classification. CNN is designed in such a way that it can extract features in the images in one go and with less computation. In [6], 1D, 2D and 3D CNNs have been used to classify HSIs utilizing its spectral as well as spatial information. Spectral-spatial-based approach of using 3D CNN gives much better results compared to other methods.

However, these deep learning based approaches require huge amount of labelled data which is very difficult, infeasible and expensive to collect in practice. To address this issue, some methods have been proposed using data augmentation techniques which is used to generate additional data [21]. More efficient method to tackle this issue is Active Learning (AL) which selects most informative samples for labelling by the oracle and thus reducing number of samples required for the classifier to gain significant performance [29]. Active Learning selects highly informative or most useful samples for the current model to learn from using a query function. By including only those samples selected by active learning query function we significantly reduce the amount of labelled data needed for the model to reach certain performance mark.

Active Learning strategies assume that not all the data samples are equal but few samples have characteristics that separates the classes. The idea is to select only those samples for training and still keep or even enhance the performance of the model. AL has been extensively studied for HSI classification in [28], [32], [33].

Diversity in the data samples while active selection has been less studied. Most studies in AL based HSI classification considers only most informative samples for inclusion in training set. This can increase redundancy in data samples to be trained degrading performance of the classifier. Thus, the query function employed for selection of the most useful or informative or uncertain samples should consider two major criteria: 1) informativeness and 2) diversity of data [3], [36]. The diversity criterion selects data samples from a set of most uncertain unlabelled data samples which are as diverse as possible, therefore reducing redundancy among the data samples. Combining the diversity criterion with the query function of the AL technique, the efficiency of the model will be increased potentially.

In this paper, a method to incorporate the AL technique with diversity criterion and deep learning is proposed to utilize effectiveness of all the fields. We propose new clustering-based diversity criterion along with the AL query function which will be incorporated with 3D CNNs to utilize the strong discriminative capabilities of deep learning. By using the diversity criterion with AL query function, the model becomes more robust and generalizes well due to the training of the model on different and diverse data samples. Although, there have been several studies which combines deep learning with AL but our proposed approach has different characteristics which is discussed in related work. Moreover, we employ the data augmentation technique to produce new data samples which helps in addressing the difficulty of insufficient labelled data samples. Furthermore, we retrain the CNN model only on the actively selected data instead of training on whole data, which reduces the computational cost of training the CNN model on whole data again. We have compared four different AL strategies to measure effectiveness of our proposed method. We have performed experiments on three well-known datasets to validate our proposed method.

2. Related Work.

2.1. Deep Learning based HSI classification. Due to the rapid growth in deep learning algorithms research and their applicability, researchers have been attracted to use deep learning algorithms for solving HSI classification problems. Several studies have been carried out in this domain. In [20], [8], Deep Belief Networks were used for feature extraction and classification. In the paper [20], spectral-spatial-based classification was also considered in experimentation. SAE (Stacked Auto-Encoders) which can be formed by multiple sparse autoencoders were used for HSI classification in [26] and features in the data are learned in an unsupervised way. There has been significant work in HSI classification using CNN compared to DBN and SAE. CNNs are more popular because of its ability to learn features in the images naturally [18]. In [16], five layered basic CNN model was proposed for HSI classification, considering only spectral information. Several works has been carried out to consider spectral-spatial features also. In [6], 3D patch-based CNN was used considering spectral-spatial features and in [15] B-CNN (Bayesian CNN) were employed with comparison of 1D, 2D and 3D CNN architectures. In [21], data augmentation techniques were employed for improve the performance of the CNN model.

2.2. Active Learning based HSI classification. Active Learning has been extensively used in HSI classification in recent years. Active Learning strategies can be divided into three major categories 1) Committee-based strategies 2) Large margin-based strategies and 3) Posterior probability based strategies [33]. In [9], the entropy was used as a query function or heuristic combine with Query-by-committee approach. Large margin-based heuristics are mostly used with support vector machines (SVM) due to their direct applicability with margin of separating hyperplane [7] [33]. In [5], [4], naïve and modified version of Margin Sampling (MS) was used as an active learning query function with SVM which is based on selection of samples within the margin of the hyperplane. In [11], the query function MS is extended for multiclass problem with SVM and the heuristic is called multiclass level uncertainty (MCLU). MCLU considers two most probable cases instead of considering only one like MS. Posterior probability based approaches make use of posterior probabilities estimates of individual class membership. Several studies employ the KL-Max heuristic and Breaking ties heuristic in the posterior probability based approaches [17], [33].

Active learning incorporated with deep learning has been actively studied in recent years. In [23], Deep-Transfer learning approach has been employed which is incorporated with AL. Representativeness of the data samples are examined by considering them simultaneously in [23]. In [1], discriminative CNN (D-CNN) were used with AL to consider diversity in the data samples. Similar to [23], study in [12] also considers deep learning and transfer learning together with AL and stacked sparse autoencoders (SSAE) were used. In [6], HSI classification has been carried out using CNNs with AL criteria BvSB. This study also considers Markov Random Fields (MRF) for class label smoothness. The authors of [15] have proposed Bayesian CNN (B-CNN) based framework for HSI classification. Six different active learning strategies were employed and compared in [15].

2.3. Diversity based HSI classification. While selecting the most uncertain or most informative data samples, it is more probable that the selected data samples are redundant among each other. The data samples should be diverse from the current training data also to avoid redundancy. These two approaches namely, 1) diversity among each other and 2) diversity from current training data or current data distribution [33]. In [33], the authors have surveyed the need of diversity criterion and avoiding redundancy. In [29], MS is extended to MS-cSV (closest Support Vectors) to consider the distribution of the data samples in the multidimensional space of features to select only those data samples residing in the different area or region, therefore preserving the diversity. In [3], the selection criteria incorporates diversity among the samples by considering angles between the induced hyperplanes. The authors of [11] have proposed two diversity criteria namely angle based diversity (ABD) which is similar to the work in [3] and clustering based approach based on kernel k-means combined with AL query function. Clustering based method to preserve diversity in has been employed by clustering the uncertain samples and then selecting only one most uncertain or informative sample per cluster [11]. In [34], cluster based approach for diversity in the data samples was employed in different way. The cluster with highest number of uncertain data samples is further divided into two sub-clusters, until certain predefined number of clusters q, the number of samples to be selected for retraining, has been generated. This approach is quite expensive in terms of computation.

In [10], density is also considered along with diversity. Clustering is done on uncertain samples and most representative sample having lowest average distances from all the points in the cluster is selected. In [35], the diversity is found by using a maximum mean discrepancy, a measure for calculating the difference between two different datasets in terms of data distribution. In [19], the authors have proposed the nearest neighbour approach for preserving the diversity.

3. Proposed Approach. In our proposed approach, we have considered a novel clustering based method for preserving the diversity of the data samples from the current training data which boosts the model performance and makes model more robust and generalized.

We also incorporate the diversity among the data samples in the initial training phase for enhancement of the discriminative abilities of the model. In our proposed method DB-MCLU (Diversity-based MCLU), we have combined Diversity based crieria and BvSB (Best versus Second Best). We have employed the BvSB (Best versus Second Best) strategy for actively selecting samples [6]. Also, we have incorporated diversity criteria along with BvSB to preserve diversity among the samples which are actively selected using BvSB. The BvSB strategy for active learning is based on MCLU (Multiclass Level Uncertainty) [33]. The MCLU strategy considers two classes with the highest class membership probabilities and the difference of distances of both to the margin in case of SVM classifier [33]. Similar approach is used in BvSB strategy where posterior probabilities are computed and then difference between two highest class membership probabilities are used as a measure of uncertainty. The data samples with least difference of highest two probabilities are considered as most informative and uncertain data samples. The small value of BvSB measure denotes that the model is not certain with the data sample's class membership and thus the data sample is uncertain. For a data sample x_i, the BvSB measure can be calculated using equation 3.1:

$$B_V SB(x_i) = P_B(x_i) - P_{SB}(x_i) \tag{3.1}$$

The diversity criteria in the proposed approach is implemented by considering clustered data distribution of the current training data and then by selecting only those actively selected data samples which are diverse from the current training data. Clustering of the current training data is done to measure diversity of actively selected samples from current data distribution. A novel clustering based method is used for preserving the diversity in actively selected data samples. First, the current training data is clustered using well known K-Means clustering algorithm in C clusters where C is the number of classes in the dataset [24]. The clusters in the K-Means clustering algorithm can be formed using the equation 3.2 for samples $(x_1, x_2, ..., x_n)$. Where each sample is a d-dimensional vector, then k clusters $C = \{C_1, C_2, ..., C_k\}$ of these samples can be formed.

$$\underset{c}{\operatorname{argmin}}\, \Sigma_{i=1}^{k} \Sigma_{x \in C_i} ||x - \mu_i||^2 \tag{3.2}$$

The Euclidean distance for two points a and $b \in R^d$ can be calculated using following formula:

$$d(a, b) = \sqrt{\Sigma_{i=1}^{d} (b_i - a_i)^2} \tag{3.3}$$

Then, a cluster is assigned to each of the actively selected data samples based on the minimum Euclidean distance from a cluster's centroid i.e. the distances from each cluster centroid to a particular sample x_i are calculated and a cluster's centroid from which the distance to x_i is minimum, is assigned to that particular data sample x_i. Then for those samples who were assigned the same cluster, average of distances from those samples to the assigned cluster's centroid is calculated and the data samples whose distance to the assigned cluster's centroid is greater than the average distance calculated before, are chosen as diverse samples. This step in the proposed method preserves the diversity in the actively selected samples from current training data distribution.

We have employed data augmentation methods for images such as Flip Up-Down, Flip Left-Right and Rotate the image to increase the amount of labelled data samples. The hyperspectral image contains hundreds of spectral bands which may lead to over-fitting problem. So, to extract most representative dimensions from the whole dataset, we make use of dimensionality reduction method such as Principal Component Analysis (PCA). Instead of retraining the CNN model on whole training data in every iteration, we retrain the CNN model only on the data samples selected by uncertainty and diversity criteria. The data samples at each iteration are selected for retraining the CNN model based on combination of uncertainty and diversity criteria. The complete structure of the proposed approach is shown in Fig. 3.1. In the Fig. 3.1, the word fine-tuning refers only to retraining of CNN model with only the actively selected data and not the whole dataset. This fine-tuning has nothing to do with structural/architectural changes in CNN model.

The distribution of whole dataset is shown in Table 3.1.

In Algorithm 1, the initial training of the CNN model is carried out on D_{train}. The remaining dataset is D_{remain}. The 60% of (D_{remain}) is called D_{pool} from which we actively select samples for retraining of CNN. The 40% of the D_{remain} is called D_{test} which will be utilized for evaluation of the trained CNN model. D_{active} is the data which is selected from D_{pool} for retraining on the basis of active learning and diversity criteria.

We have designed the Algorithm 2 to be executed until desired criteria is met. The desired criteria can be Time limit, Model Accuracy criteria or it can be Number of actively selected samples for training. We have selected accuracy criteria for implementation which means we execute the algorithm until we reach desired model accuracy. The data samples are selected for retraining from the D_{pool} based on DB-MCLU approach. The DB-MCLU approach combines diversity criteria along with MCLU (i.e. based on BvSB). According to

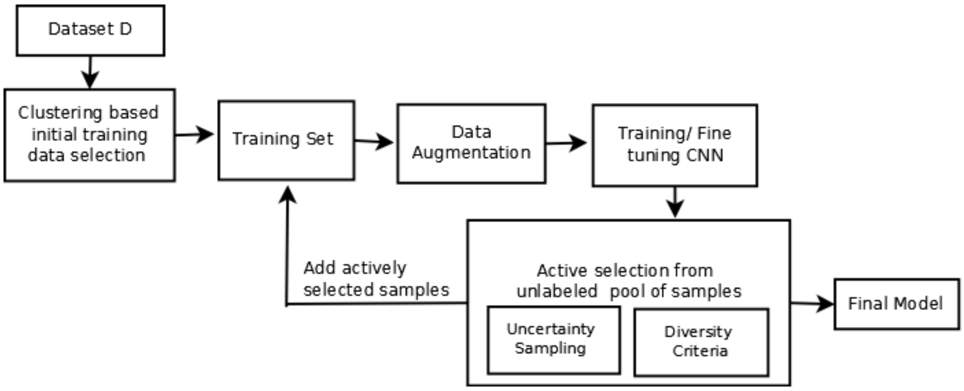

Fig. 3.1. *Proposed diversity based HSI classification framework*

Table 3.1
Samples for Each Dataset

Dataset	Train	Pool	Test	Total
Indian pines	400	5909	3940	10249
Salinas	400	32237	21492	54129
Pavia University	225	25530	17021	42776

Algorithm 2, "h" most uncertain data samples are selected from D_{pool} based on BvSB Active Learning criteria. Further, from these data samples, some data samples D_{active} are selected based on diversity criteria. Thus we ensure to combine both uncertainty and diversity in selection of data samples for retraining. This approach preserves diversity among the uncertain samples.

4. Implementation Details and Results. The proposed approach is implemented on three publicly available Hyperspectral datasets (Table 3.1) and discussed implementation perspective in this section.

4.1. Dataset Description. The first HSI dataset used is well known Indian Pines dataset which was collected by AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) sensor in 1992. This dataset has 145 x 145 pixels with 220 spectral bands with range of the wavelength between 0.4 and 2.5 μm. Each pixel in this image dataset is assigned one of the 16 ground-truth classes. The second dataset used is Pavia University which was collected by ROSIS (Reflective Optics System Imaging Spectrometer) sensor. The dataset consists 610 x 340 pixels with nine land-cover classes and 103 spectral bands with the wavelength range between 0.43 and 0.86 μm. The third dataset used in experiments was Salinas Valley scene which was collected by AVIRIS sensor. The dataset consists of 512 x 217 pixels and has 204 bands after removing 20 water absorption bands. The dataset has 16 ground-truth classes.

4.2. Hyperparameter Settings and Description. In the experiments, we have two major hyperparameters which are empirically tuned. The first hyperparameter "s" is number of samples to be selected from each cluster for initial training data. This hyperparameter is carefully tuned to be 25 during experiments. The number of initial training samples greatly affect on the final classification results because subsequent iterations of active selection of uncertain and informative data samples depend greatly on the initially trained CNN model. The second hyperparameter "h" is the number of most uncertain and informative data samples selected by active learning strategy. This hyperparameter is tuned empirically to 200. The diversity based criteria is employed on these actively selected data samples and less than half of the data samples from these 200 data samples are selected, which was observed during experiments. The other hyperparameters for CNN training are set empirically such as batch size in [16, 32] and number of epochs in the range of [10, 20]. We used dimensionality reduction technique PCA to obtain most useful and representative dimensions of dataset and to decrease the complexity. We consider 30 principal components for Indian Pines dataset and 15 principal components for rest of the two datasets. The value of principal components is chosen based on the variance

Algorithm 1: Initialize D_{train}, D_{pool}, D_{remain}, D_{test}

Input: Initial Dataset D
Output: Intial D_{train}, D_{pool}, D_{remain}, D_{test}
Where N number of classes, t split ratio, s number of samples selected

- Run K-Means clustering algorithm on initial Dataset and get clusters $\{C_i\}_{i=1}^{N}$ and cluster centroids $\{\Delta_i\}_{i=1}^{N}$ from equation (2)
- Select s samples from each cluster based on minimum Euclidean distance given in equation (3)
- $D_{train} = \{x_i, y_i\}_{i=1}^{l}$ where $l = s * N$
- D_{remain} = D / D_{train} , split D_{remain} into D_{pool} and D_{test} with ratio t

Algorithm 2: Training using Active Learning (DB-MCLU)

Input: Initial D_{train}, D_{pool}, D_{remain}, D_{test}
Output: Trained Model with D_{train} Samples
Train/Retrain CNN model on current training dataset D_{train}

repeat

$D_{uncertain} = \{x_i\}_{i=1}^{h}$ Where, h is most uncertain samples from D_{pool} using BvSB AL strategy

Update $\{C_i\}_{i=1}^{N}$ and $\{\Delta_i\}_{i=1}^{N}$ based on current D_{train}

Assign a cluster C_j to sample x_i based on minimum distance from Δ_j to the sample x_i For each, $x_i \in D_{uncertain}$

for $x_i \in C_j$ **do**

Find average distances a_j

$$a_j = \frac{\Sigma_{i=1}^{r} d(\Delta_j, x_i)}{r}$$

where, r is number of samples in each cluster

Add sample x_i to D_{active} where, $d(\Delta_j, x_i) > a_j$

$D_{pool} = D_{pool}$ / D_{active}
$D_{train} = D_{train} \cup D_{active}$

Retrain the CNN model with D_{active} and Get prediction on D_{test}

until *desired criterion*;

of the dataset. We preserved 99.6% variance in the datasets after applying PCA. To preserve the variance of 99.6% in the dataset practically, the values 30 and 15 principal components were chosen for Indian Pines and Rest of the two datasets respectively. The learning rate is set to 0.001.

For all the experiments carried out, we used Google Colab platform for all the computation work.

4.3. Comparison with other Active Learning Methods:. In this section, the comparison of our proposed method and three other Active Learning methods based on uncertainty sampling strategy is presented. These three other Active Learning methods are namely, 1) Random Sampling or Baseline, 2) BvSB and 3) Maximum Entropy.

1. Random Sampling or Baseline: The Random Sampling or Baseline method for choosing data sampels employs the uniform random distribution for selection of the data samples. This method chooses the data samples following uniform random distribution from pool of data samples by generating random number over the interval [0,1].
2. BvSB (Best versus Second Best): Best versus Second Best method for selection of the uncertain data samples is based on the MCLU strategy [6], [33]. It considers difference between highest and second highest class membership probabilities for selection criteria according to equation – (1). Less the

difference of highest and second highest class membership probabilities, more uncertain and informative the data sample is.

3. Maximum Entropy: This method selects data samples having highest uncertainty in classification [6], [29]. In other words, this method selects the data samples that maximizes the entropy. The maximum entropy for a data sample x_i can be calculated by using the following equation:

$$E[y_i|x_i, D_{train}] = -\Sigma p(y_i = c|x_i, D_{train}) \log p(y_i = c|x_i, D_{train}) \tag{4.1}$$

4. DB-MCLU: Our proposed method is different from these three methods described above. These three methods have only single criteria for selection of the data samples for consequent training. In contrast, our method combines two criteria for selection of data samples, one based on uncertainty and the second based on diversity. For uncertainty, we use BvSB approach as it is most suitable for our model and gives efficient results than Random Sampling and Maximum Entropy measure. We incorporate diversity criteria also with the uncertainty criteria to build the model more robust and generalized. The diversity criteria in our method is based on clustering of current training data, associating the actively selected samples with one of the clusters based on the Euclidean distances and then selecting distant data samples from current training data distribution. By integrating diversity criteria in selection of data samples for subsequent retraining iteration for CNN model, we preserve dissimilarity and variety in data samples.

4.4. Results and Discussion. Series of experiments are conducted on three datasets using four different AL strategies. As we consider diversity in the selection of initial training set also, we use K-means clustering algorithm with number of clusters taken as number of classes for particular dataset. Then we select 25 samples nearest to the centroid of each cluster. Thus we get 400 diverse samples in case of Indian Pines and Salinas dataset and 225 samples in case of Pavia University dataset as our initial training dataset. We split remaining data into D_{pool} and D_{test} using split ratio 0.4 i.e. from the remaining data 60% data samples were used as pool and 40% data samples were used as testing set. As per this split ratio, the partitioned data samples for training, testing and pool are shown in Table 3.1.

For each iteration of selecting the data samples actively, we choose data samples in the range of [50, 200] from D_{pool} based on the uncertainty criteria. This range has been observed empirically. The second criteria for diversity reduces these selected samples by considering only diverse samples from current data distribution. We repeat the active learning iterations until we reach desired accuracy on testing dataset. The average experimental results are shown in Table 4.1, 4.2 and 4.3. For achieving the accuracy given in Table 4.1 for Indian Pines dataset, only 15% of the total data samples have been used. Similarly, for Pavia University and Salinas dataset only 5% of total data samples are used for achieving given accuracies in Table 4.2 and 4.3. From these observations, we can say this method significantly reduces the number of labelled samples required for achieving higher accuracy. The experimental results of all the methods are shown in the Table 4.1, 4.2 and 4.3 for three datasets respectively. The results of using other active learning methods are compared with the proposed method in the Table 4.1, 4.2 and 4.3 in terms of OA (Overall Accuracy), AA (Average Accuracy), CA (Class Accuracy) and K (Cohen Kappa Score). For all the methods, the experiments are repeated five times and the average of all the results are shown. In the experiments conducted on Indian Pines dataset shown in Table 4.2, the methods Entropy and Random Sampling did not able to correctly classify or distinguish the samples for class “Oats”. The number of data samples belong to the class ”Oats” are only 20 in the whole dataset. Even then the methods BvSB and DB-MCLU gave better classification accuracy than other methods with very less data samples of a particular class.

From Table 4.1, 4.2 and 4.3, it can be observed that the proposed method DB-MCLU achieves best classification results with measures of OA (Overall Accuracy) and AA (Average Accuracy) and also, for most of the classes, the proposed method gives best class accuracies compared to other methods. Classification result obtained by our proposed approach along with ground truth image for all three dataset is shown in Figure 4.1.

The method DB-MCLU achieves best accuracies as compared to other shown methods while using very less number of labelled data samples, 15% of total data samples for Indian Pines and only 5% of total data samples for Pavia University and Salinas Dataset. Thus our proposed method helps in reducing the cost for labelling the data samples while still preserving the diversity of data samples and higher performance of the model.

Table 4.1
Classification Accuracies on Indian Pines Dataset

Class/Method	Random	EP	BvSB	DB-MCLU
Alfalfa	54.44	61.11	93.33	88.89
Corn-notill	90.41	89.05	93.53	93.15
Corn-mintill	91.35	95.77	88.04	93.74
Corn	95.27	89.03	96.99	95.48
Grass-pasture	93.72	87.23	96.38	96.17
Grass-trees	97.80	95.53	97.16	96.17
Grass-pasture-mowed	0	83.63	76.36	87.27
Hay-windrowed	100	90.05	99.45	99.78
Oats	0	0	45	65
Soybean-notill	88.31	94.85	87.69	94.79
Soybean-mintill	96.73	96.94	94.01	94.82
Soybean-clean	84.73	84.64	84.91	92.41
Wheat	98.63	92.27	89.86	96.99
Woods	98.26	97.02	99.29	97.39
Buildings-Grass-Trees-Drives	96.16	89.35	87.55	97.35
Stone-Steel-Towers	100	83.17	83.70	91.11
AA	80.36	82.12	88.33	**92.53**
OA	93.52	92.79	93.09	**95.08**
K	92.60	91.78	92.11	**94.39**

Table 4.2
Classification Accuracies on Salinas Dataset

Class/Method	Random	EP	BvSB	DB-MCLU
Brocoli_green_weeds_1	99.80	99.95	99.92	100
Brocoli_green_weeds_2	99.93	99.33	99.04	95.54
Fallow	93.37	97.52	98.43	99.85
Fallow_rough_plow	83.73	97.99	93.01	100
Fallow_smooth	73.39	96.66	80.83	95.66
Stubble	99.34	99.67	97.91	98.95
Celery	97.48	97.89	96.85	99.79
Grapes-untrained	97.89	94.16	92.64	97.75
Soil_vinyard_develop	99.97	99.93	97.15	99.91
Corn_senesced_green_weeds	98.70	97.43	96.13	99.25
Lettuce_romaine_4wk	96.30	91.88	95.22	99.49
Lettuce_romaine_5wk	96.43	97.27	85.94	99.87
Lettuce_romaine_6wk	86.79	94.26	77.39	91.67
Lettuce_romaine_7wk	85.03	92.98	67.31	89.01
Vinyard_untrained	93.25	93.32	93.79	93.65
Vinyard_vertical_trellis	99.78	96.18	99.91	99.97
AA	93.82	96.66	91.97	**97.52**
OA	95.64	96.58	93.83	**97.63**
K	95.14	96.19	93.13	**97.36**

5. Conclusion. In this paper, we have presented a novel diversity-based Active Learning approach for classification of Hyperspectral Images using Convolutional Neural Network. We have incorporated the diversity criteria with Active Learning sampling strategy. Thus we can consider the diversity in the data samples in each subsequent round of active selection of most informative data samples from the pool of unlabelled data samples to be labelled by oracle. We also make use of data augmentation technique to leverage the training process as it provides more information by augmenting the data samples. The retraining of the Convolutional Neural Network model only on the actively selected data samples instead of training on whole dataset signif-

Table 4.3
Classification Accuracies on Pavia University Dataset

Class/Method	Random	EP	BvSB	DB-MCLU
Shadows	68.83	59.58	83.27	69.95
Self-Blocking Bricks	90.91	94.18	86.95	95.94
Bitumen	94.83	96.46	91.62	89.33
Bare Soil	98.37	99.70	94.95	98.25
Painted metal sheets	98.90	100	59.85	93.86
Trees	92.69	91.30	89.37	95.27
Gravel	82.30	88.12	61.82	94.02
Meadows	99.29	98.82	99.06	99.61
Asphalt	95.25	96.56	96.39	98.14
AA	91.27	91.64	84.81	**92.55**
OA	95.70	96.20	92.81	**97.13**
K	94.40	94.97	90.41	**96.19**

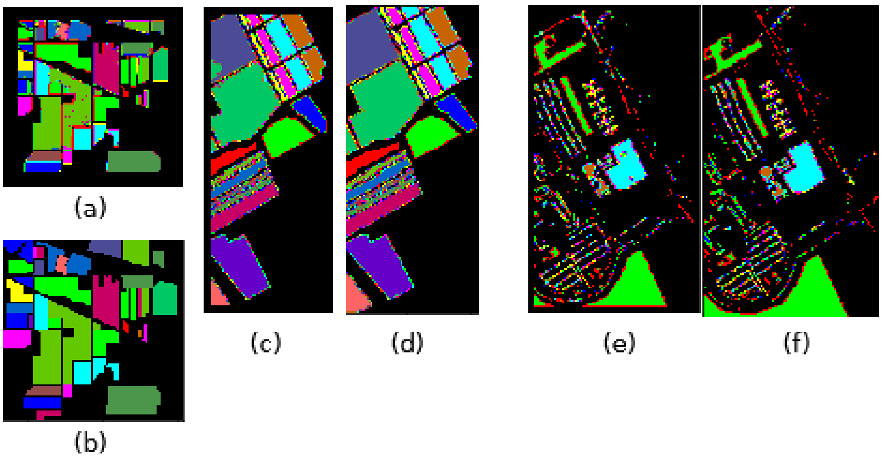

Fig. 4.1. *(a), (c), (e) Classification result of Indian Pine, Salinas and Pavia University. (b), (d), (f) Ground truth image of Indian Pine, Salinas and Pavia University.*

icantly reduces the training cost. The proposed diversity-based Active Learning approach incorporating with Convolutional Neural Network for feature extraction and classification tasks effectively utilizes the strengths of all the techniques together and gives better classification performance compared to other sampling methods used for Hyperspectral Image Classification.

The future work includes incorporating different novel diversity based approaches apart from clustering and exploring more Active Learning selection strategies or design a novel one. This work can be extended to semi-supervised and unsupervised approach utilizing the abilities of both the domain.

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FOG TASK SCHEDULING USING CLUSTERING BASED RANDOMIZED ROUND ROBIN

SHAHID SULTAN HAJAM* AND SHABIR AHMAD SOFI†

Abstract. Fog computing serves the delay-sensitive applications of the Internet of Things (IoT) in more efficient means than the cloud. The heterogeneity of the tasks and the limited fog resources make task scheduling a complicated job. This paper proposes a clustering based task scheduling algorithm. Specifically, the K-Means++ clustering algorithm is used for clustering the fog nodes. Randomized round robin, a task scheduling algorithm is applied to each cluster. The results show that the proposed algorithm reduces the system's average waiting time.

Key words: Task scheduling, K-Means++, clustering, round robin, random, Fog computing

AMS subject classifications. 68M14, 68T07

1. Introduction. Internet of things (IoT) are found everywhere around the globe, thus generating the data in bulk. Cloud provides its reliable services to IoT devices' enormous data, including storage, infrastructure, platform, and software as a service [10, 4]. Computing the data at the cloud needs massive network bandwidth and adds the burden of transmission delay. Therefore the delay-sensitive benefits of IoT cannot be responded to and processed quickly.

Fog computing, a computing paradigm brings cloud services closer to the edge of the network [6]. The fog benefits are available nearer the edge of the network, in between the IoT devices and the cloud servers. Fog reduces the cloud's burden by performing the filtering, pre-processing, and data analysis before sending the data to the cloud.

Although the cloud possesses enormous storage and processing capabilities, its large distance from the end devices incur delays that affect the delay-sensitive applications' quality of service. Hence the fog is a good solution for IoT. The fog layer comprises the numerous fog nodes or devices which are geographically distributed and dynamic. To efficiently utilize the resource and provide the quality of the service, resource and task scheduling is an urgent need. Heterogeneity, uncertainty, and dispersion of fog resources pose a challenge for resource and task scheduling.

K-means clustering algorithm, one of the most popular clustering algorithm, is an effective classification algorithm. It is an unsupervised learning algorithm used to find the groups in the unlabelled data [7]. Although K-means is popular for its speed, usability, effortlessness, it lags in accuracy mainly due to randomly choosing the centroids [3, 8]. K-means requires good initialization of the centroids; otherwise, it may end in a local minimum. K-means++ solves this problem of choosing the initial centroids. K-means++ chooses those datapoints as the initial centroid, which are farther from each other, hence avoiding the K-means clustering algorithm's poor clustering. In this paper, we choose the K-means++ clustering algorithm to cluster the fog nodes.

We begin by clustering the fog resources into clusters and then use the randomized round robin scheduling algorithm for task scheduling inside the clusters. At last, the proposed policy is compared with the random, round robin scheduling algorithms.

The remainder of the paper is organized as follows: Section 2 discusses the related work, the algorithms used in this work is discussed in section 3, the system model is described in section 4, Randomized Round Robin Scheduling Algorithm is discussed in section 5, section 6 comprises of experimental results, and finally there will be the conclusion in section 7.

*Department of Information Technology N.I.T Srinagar, Kashmir, India (shahid.nit002@gmail.com)
†Department of Information Technology N.I.T Srinagar, Kashmir, India

2. Related Work. The resource scheduling is NP-hard problem; various scheduling algorithms are proposed to solve this problem. A dynamic resource allocation policy is proposed for Industrial Internet of Things (IIoT), particularly for tactile applications in Fog computing [1]. Based on the average delay, jitter, latency, packet loss, blocking probability Fog nodes are ranked for resource allocation. Selection is performed based on required resources and ranking of Fog. The results show the resource is utilized efficiently and QoE is improved. Fog based IoT is also used in super markets in order to manage the resources smartly and in real time [16]. K-Means clustering algorithm along with the Principal Component Analysis are used to cluster the products as per their demand and the product distribution decisions are made based on the reinforcement learning model. Fog can also be helpful in medical data wherein it will reduce IoT data by filtering the data before sending to the cloud. In [11], the EEG data is reduced before sending to the cloud. Agglomerative hierarchical clustering is used to cluster the EEG data and Huffman encoding is applied to each cluster for data compression. K-means clustering along with Support Vector Regression is used to predict the drought [13]. The authors have also taken power consumption and accuracy of the system in consideration.

In [2] an architecture for resource allocation between cloud and Fog servers is proposed. In the Fog layer, a Fog server manager reviews the available resource and may agree to execute all or some of the tasks and postpone others. In terms of response time, loading time, and total cost compared with other algorithms, including optimize response time policy, re-configuring dynamically with load balancing, the proposed algorithm performs better.

The authors in [12] have compared the K-means, K-means++ and Fuzzy C-means clustering algorithms. The algorithms are fed with sorted and unsorted data and are analysed on the factors of elapsed time and number of iterations. Fuzzy clustering along with the particle swarm optimization is used for resource allocation in fog computing environment [14]. The fog nodes are clustered into three clusters which are made available to the tasks that require computing, bandwidth and storage resources respectively. In another work [17], the authors have used Agglomerative Hierarchical Clustering for the resource pooling and to diminish the delay. K-means clustering algorithm is used for analysis of speech data of patients suffering from Parkinson's diseases in fog architecture [7]. The authors in [5] have used K-means on River Ganga basin and diabetes data. The results shows fog computing performs well for medical and geospatial data. Unlike these studies, our paper uses K-means++ with randomized round-robin for task scheduling.

3. Algorithms. In this section we will discuss the algorithms used in this work.

3.1. K-means++ Clustering algorithm. k-means++ is an unsupervised clustering algorithm used to cluster the unlabelled data. Rather than randomly choosing the initial centroid points like the K-means clustering algorithm, the centroids are chosen iteratively based on the distance [3]. Initially, the first centroid is selected uniformly at random from the set of datapoints. The distance is calculated for each datapoints from the previously chosen centroid. The next cluster centroid is chosen with the probability proportional to the square of the distance ($d(x)^2$). After obtaining, the required number of cluster centroids datapoints are assigned to the clusters based on the minimum distance from the cluster centroids. The cluster centroids are updated by taking the mean of the datapoints of the cluster. The process is repeated until no datapoints are reassigned.

3.2. Round Robin Scheduling. Round Robin is the scheduling algorithm, which is mainly used and designed especially for time sharing systems. The processes which are ready to execute are kept in a ready queue (circular queue) in FIFO (first in first out) order. The scheduler assigns the CPU to the processes in a circular fashion for a period of time quantum. The process is given the CPU for time quantum; if the process is still executing, it is preempted and added to the end of the queue. The process will release the CPU if it completes before the time quantum expires. In both cases, the CPU is assigned to the next process in the ready queue. The value of time quantum will directly affect the performance of the algorithm. Shorter burst time will result in more context switches and hence adds extra burden to the processing time. If the burst time is very large, it will make the algorithm behave like FCFS. Various dynamic time quantum policies have been proposed [9, 15], where the time quantum changes for every iteration.

3.3. Random Scheduling. Random scheduling is a technique where the tasks are chosen randomly with equal probability. From the pool of the tasks, a task is chosen randomly and assigned to the processor and the

Algorithm 1 K-means++ algorithm

Input: Processing power of 'n' fog nodes, $C_F = \{c_{f1}, c_{f2}.......c_{fn}\}$ and number of clusters
Output: K clusters.

```
1: procedure K–MEANS++
2:     Select a cluster centroid c_fi uniformly at random from C_F
3:     for each c_fi
4:         compute distance from the nearest centroid chosen previously. do
5:     end for
6:     Select new centroid from c_fi with probability proportional to
```

$$\frac{D(c_{fi})^2}{\Sigma_{c_{fi} \epsilon C_F} D(c_{fi})^2}$$

```
7:     Repeat steps from 3 to 6 untill k centroids are obtained.
8:     for each c_fi's do
9:         Assign c_fi to that cluster centroid whose distance from the cluster centroid is minimum.
10:    end for
11:    Recalculate the new cluster centroid by taking the mean of data points of cluster.
12:    Repeat steps from 8 to 11 until no data point (c_fi) is reassigned.
13: end procedure
```

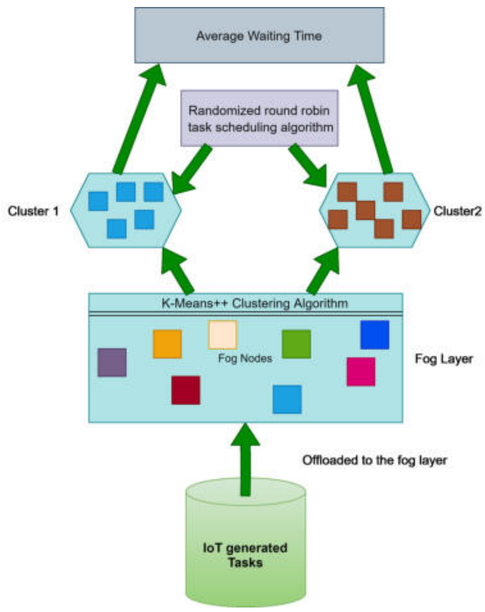


Fig. 4.1: System Model

process is repeated till the pool becomes empty.

4. System Model. The proposed system architecture is shown in figure 4.1. The IoT devices do no computation of their own; instead, tasks are offloaded to the fog layer for processing. The fog layer comprises multiple fog nodes; they are grouped into two clusters using the K-Means++ clustering algorithm. The IoT generated tasks are randomly distributed between the clusters, and also inside the clusters, the tasks are randomly assigned to the fog nodes. Randomized round robin scheduling algorithm is used to schedule the

Algorithm 2 Proposed Algorithm: Clustering based Randomized Round Robin Scheduling Algorithm

Input: Burst time, $S_T = \{s_{t1}, s_{t2}.......s_{tn}\}$ and time quantum (T_q)
Output: waiting time.

1: **procedure** RANDOMIZED ROUND ROBIN
2: Cluster fog nodes into two clusters using K-means++ clustering algorithm.
3: **for** each cluster **do**
4: Place the processes (here $s_{ti's}$) in ready queue of each fog node randomly in FCFS order.
5: **while** Burst time of the processes $S_T = \{s_{t1}, s_{t2}.......s_{tn}\} \neq 0$ **do**
6: choose the process s_{ti} from $s_{ti's}$ randomly.
7: **if** $s_{ti} < T_q$ **then**
8: s_{ti} executed completely.
9: goto step 5
10: **else**
11: s_{ti} is executed till T_q unit of time, interrupted and added to the queue.
12: **end if**
13: goto step 5
14: **end while**
15: **for** each process $s_{ti's}$ **do**
16: Calculate Waiting Time
17: Waiting Time = Completion time - arrival time - burst time
18: **end for**
19: **end for**
20: **end procedure**

tasks present in the fog nodes' queue.

5. Proposed Algorithm. In this section we will discuss the clustering based randomized round robin scheduling algorithm in detail (Algorithm 2).

Clustering based Randomized Round Robin Scheduling Algorithm. Randomized round robin scheduling algorithm is an extension of the round robin algorithm. The algorithm begins by clustering the fog nodes by means of K-Means++ clustering algorithm. Based on the processing power, the fog nodes are clustered into two clusters. The IoT generated tasks are randomly distributed among the clusters. For each cluster, like the round robin algorithm, each task is executed for the time quantum, preempted, and added back to the queue. It differs in the selection of the tasks from the queue. From each fog node's ready queue, jobs are chosen randomly after another without repetition and executed for a quantum time. If the job's burst time is greater than the time quantum, the job is preempted and updated in the ready queue. The control of the processor is given to the next job chosen randomly from the ready queue. If the burst time is lower than the time quantum, then the job is completely executed, and the next process is randomly chosen from the queue without repetition. The process is repeated for the next iterations until the value of the processes' burst time becomes zero. By introducing the randomness in the round robin, the waiting time is reduced considerably compared to round robin. It is due to the selection of the tasks from the ready queue. The task does not have to wait for all other tasks to gain control of the processor back; instead, tasks can be chosen randomly, which reduces the waiting time.

6. Experimental Results. With the K-Means++ clustering algorithm, the fog nodes are classified into two clusters. The processing power of fog nodes is chosen as a criterion for clustering. The fog nodes having higher processing power form one cluster, and the rest will form another. The IoT tasks are randomly distributed among the cluster nodes. Each fog node has a scheduling queue in which the jobs are queued. Jobs are distributed randomly and scheduled independently on different processors. The tasks in the queue of the nodes are scheduled using a randomized round robin scheduling algorithm.

This section studies the performance of the proposed algorithm. The number of fog nodes and the tasks are

Table 6.1: Performance at different traffic

Type of algorithm	Number of tasks					
	1000	2000	3000	4000	5000	6000
	Average waiting time					
Random	6.200	12.728	19.541	26.143	32.414	39.079
Randomized Round Robin (RRR)	7.531	14.483	21.062	26.321	31.657	35.983
Round Robin	7.931	15.997	24.759	32.694	40.951	49.608
RRR without clustering	7.871	14.976	21.929	27.636	33.368	37.449

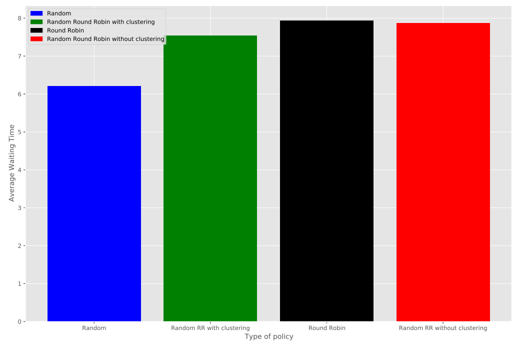
randomly set. The processing power of fog nodes is randomly set between 250-600 Millions of instructions per second(MIPS). Similarly, the tasks' size is randomly set between the range of 10-300 MI (million instructions). Fog nodes are clustered using the K-means++ algorithm based on the processing power. The randomized round robin algorithm is applied to each cluster and is analyzed for the waiting time. The time quantum is dynamically calculated for each fog node which is equal to the average of the size of the tasks present in the ready queue. The proposed algorithm is compared with the round robin, random and randomized round robin without clustering algorithms.

The random performs better than round robin in terms of waiting time because in round robin each process is given a time quantum after which the process is preempted and added back to the ready queue. This preemption adds an extra burden to the waiting time. The randomized round robin algorithm introduced the factor of randomness in the round robin, in which the jobs are chosen randomly from the ready queue. Choosing jobs randomly lower the waiting time of the processes as compared to the round robin.

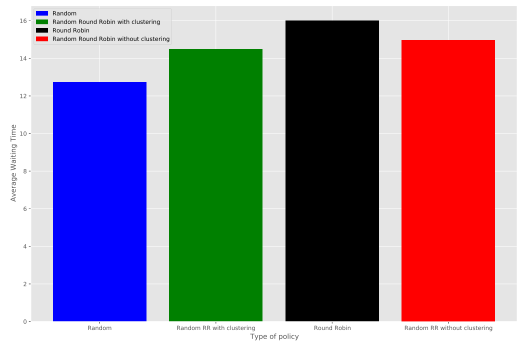
The proposed algorithm's performance is evaluated at different traffic as shown in table 6.1. The figures 6.7,6.14 shows the comparison of randomized round robin, round robin, random task scheduling, and randomized round robin without clustering algorithms.

Figure 6.7 shows the algorithms' performance with respect to the average waiting time at different numbers of tasks. To evaluate the algorithms at different traffic, the number of tasks is set to six different values that is 1000, 2000, 3000, 4000, 5000, 6000. The results in figures 6.1, 6.2, 6.3, 6.4 depicts that at lower traffic random algorithm performs better than all others. It is due to the preemption of task after every time quantum in round robin, which adds to the process's waiting time. In the randomized round robin, no doubt we choose the tasks randomly, but at the same time, we assign the processor to the processes or tasks circularly after every time quantum, which in turn will increase the waiting time. The randomized round robin algorithm performs better at high traffic load as shown in figures 6.5,6.6. The round robin performs worst at higher load because a task has to wait time quantum times the number of tasks in the ready queue minus one unit of time before attaining the processor. The random as such does not rely on time quantum so its waiting time is comparatively lower than round robin. A process has to wait for the entire burst time of the previous process before attaining the processor, which incurs the increase in that process's waiting time. In the randomized round robin, processes are given time quantum and are randomly chosen, which sometimes helps in choosing processes that can be completed in a few time quantum's which otherwise was blocked by the huge processes(huge burst time) as in random scheduling. The increased traffic increases the waiting time of the processes, but with the randomized round robin scheduling, the processes' waiting time decreases considerably.

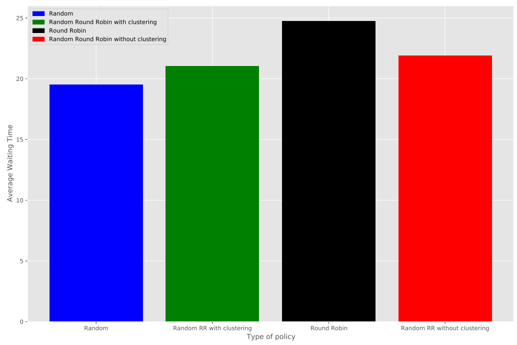
Figure 6.14 shows the average waiting of each fog node at different number of tasks. The figures 6.8, 6.9, 6.10, 6.11, 6.12, 6.13 shows the out performance of the randomized round robin algorithm with increase in the traffic. The results also show randomized round robin with clustering performs better than randomized round robin without clustering in terms of waiting time.



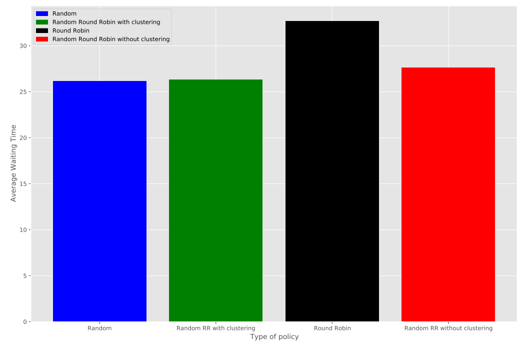
(a) Tasks = 1000



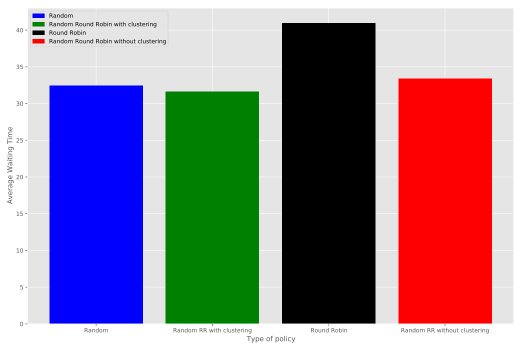
(b) Tasks = 2000



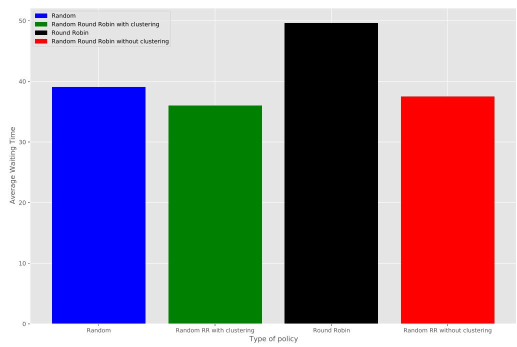
(c) Tasks = 3000



(d) Tasks = 4000

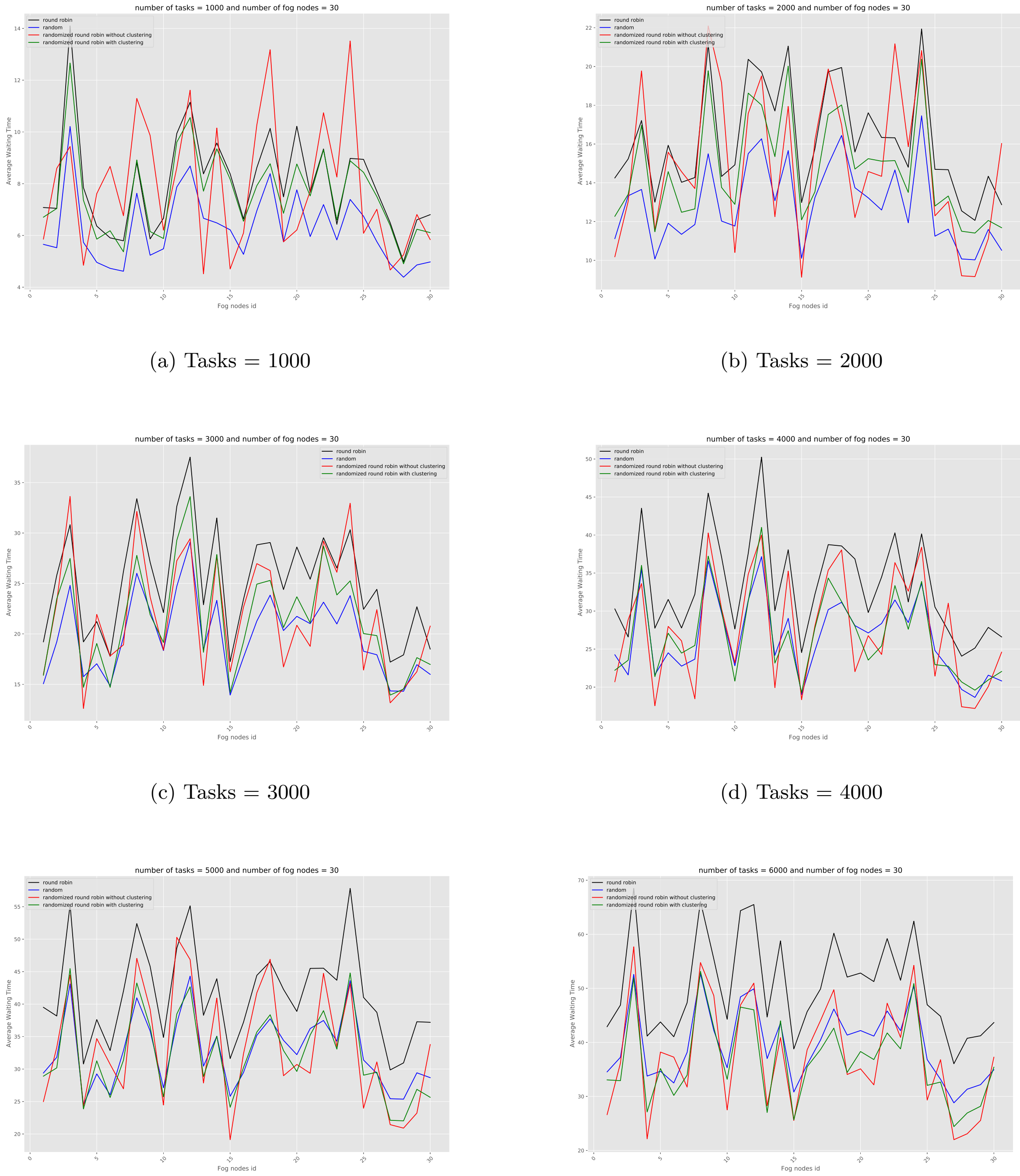


(e) Tasks = 5000



(f) Tasks = 6000

Fig. 6.1: Evaluation at different number of tasks



(a) Tasks = 1000

(b) Tasks = 2000

(c) Tasks = 3000

(d) Tasks = 4000

(e) Tasks = 5000

(f) Tasks = 6000

Fig. 6.2: Evaluation at different number of tasks

7. Conclusion. This paper discusses the task scheduling at the fog layer. K-Means++ clustering algorithm is applied to categorize the fog nodes into different clusters based on their processing power. The tasks generated by the IoT devices are distributed randomly among the clusters. The tasks are scheduled using a randomized round robin scheduling algorithm. The comparative analysis of different algorithms was done to see the effect on waiting time. The results shows that the proposed algorithm achieves the minimum waiting time with the increase in the number of tasks. When compared with the random, round robin, and randomized round robin without clustering scheduling algorithms, the proposed algorithm outperforms all.

The proposed algorithm shall be suitable for delay sensitive IoT applications where it will minimize the delay by minimizing the waiting time. The proposed policy can be used for smart transportation systems, smart parking, smart homes, and all those applications where delay of even microseconds matters.

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BIG DATA ANALYTICS FOR ADVANCED VITICULTURE

JITALI PATEL,* RUHI PATEL,† SAUMYA SHAH,‡ AND JIGNA PATEL§

Abstract. Big data analytics involve a systematic approach to find hidden patterns to help the organization grow from large volume and variety of data. In recent years big data analytics is widely used in the agricultural domain to improve yield. Viticulture (the cultivation of grapes) is one of the most lucrative farming in India. It is a subdivision of horticulture and is the study of wine growing. The demand for Indian Wine is increasing at about 27% each year since the 21st century and thus more and more ways are being developed to improve the quality and quantity of the wine products. In this paper, we focus on a specific agricultural practice as viticulture. Weather forecasting and disease detection are the two main research areas in precision viticulture. Leaf disease detection as a part of plant pathology is the key research area in this paper. It can be applied on vineyards of India where farmers are bereft of the latest technologies. Proposed system architecture comprises four modules: Data collection, data preprocessing, classification and visualization. Database module involves grape leaf dataset, consists of healthy images combined with disease leaves such as Black measles, Black rot, and Leaf blight. Models have been implemented on Apache Hadoop using map reduce programming framework. It applies feature extraction to extract various features of the live images and classification algorithm with reduced computational complexity. Gray Level Co-occurrence Matrix (GLCM) followed by K-Nearest Neighborhood (KNN) algorithm. The system also recommends the necessary steps and remedies that the viticulturists can take to assure that the grapes can be salvaged at the right time and in the right manner based on classification results. The overall system will help Indian viticulturists to improve the harvesting process. Accuracy of the model is 82%, and it can be increased as a future work by including deep learning with time-series grape leaf images.

Key words: Big Data, Viticlture, Disease Detection

AMS subject classifications. 68T09

1. Introduction. India has a population of about 1.38 billion people. Out of those, around 60% of the population is employed in agriculture and it accounts for approximately 20% of the country's GDP. Most of these people belong to the rural areas and do not have access to any kinds of technologies or smart devices. As the demand for agriculture is growing with the increasing population, many farmers are slowly adopting the means of smart agriculture. In smart agriculture, farmers can monitor a wider range of crops, implement a dynamic irrigation system, find and stop diseases before most of the crops are lost. Big data analytics help in all these tasks, especially in the case of disease detection in the crops.

1.1. Motivation. Big data is of immense importance these days. Because of the industrial revolution shift to the 4.0 stage, there has been the incorporation of technologies like the Internet of Things(IoT) and several other technologies. All these technologies work harmoniously to create a big data pool, and it is up to us to process this data and make it useful for the people. Big data can be understood as a variety of data collection that can be of structured, semi-structured, and unstructured nature [1].

In the big data context, the 3 types of data can be classified as:-

1. Structured data: It is the type of data that is available as a well-formatted repository database like spreadsheets, relational databases etcetera.
2. Semi-structured: This type of data is not in a properly formatted fashion, but it has some level of organized structure like XML(eXtensible Markup Language) data.
3. Unstructured: This type of data generally includes not organized data like multimedia data such as audio, video images fall under this category.

*Assistant Professor, CSE Department Nirma University(jitali.patel@nirmauni.ac.in).
†Student, CSE Department ,Nirma University(17bit097@nirmauni.ac.in).
‡Student, CSE Department, Nirma University (17bit101@nirmauni.ac.in).
§Assistant Professor, CSE Department Nirma University(jignas.patel@nirmauni.ac.in).

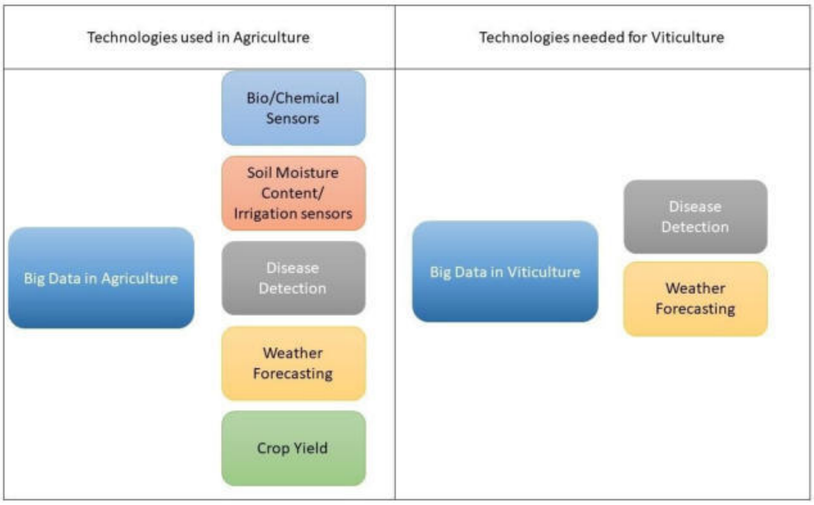

Fig. 1.1: Key research areas of agriculture and viticulture

Agriculture is the backbone of the Indian economy and contributes to up to 23% to Indian Gross Domestic Product (GDP) [2]. The inception of big data to the field of agriculture is relatively a novel concept and has not been explored extensively. Hence, this paper delves into the sphere of using big data for agriculture and in particular, viticulture. Some of the reasons for adopting big data in agriculture are that it helps farmers with planned harvesting and provides them with tools for better prediction, providing them with proper guidance and suggestions of possible remedies and fertilizers [3] [4] [5]. For these reasons, the application of big data in agriculture is of increasing importance.

In this paper, we proposed a method for viticulture. Key research areas of agriculture and viticulture have been shown through Figure 1.1. The Indian subcontinent's climate ranges from tropical to temperate and it does not lie in the cold weather belt, which is favorable for wine production and consequently for viticulture. Despite not having the optimum weather conditions, Indian states like Maharashtra, Karnataka, Telangana, and Punjab have been highly successful with the production of grapes. Maharashtra alone accounts for more than 80% production of grapes in India [6]. With the arrival of Industry 4.0, the farming sector has increasingly incorporated precision farming techniques that help them maximize their throughput with automation, the Internet of Things, and other information technology. Precision viticulture (PV) helps in developing optimum viticulture techniques. It allows for many features like selective harvesting which could provide benefits that justify the input cost by the cultivators. PV creates a surge in the amount of data available to the farmer and big data technologies are required to convert this raw data to valuable information that the farmer can easily interpret [7]. Apart from the farmers, a good viticulture practice can benefit various stakeholders of its supply chain like having a high quality of the wine is beneficial for the winemakers; healthy grapes are also good for consumption by the end-user as well the phenolic compounds in grapes are used by the cosmetic industry [8].

To ensure that the information from big data is retrieved in the most efficient way possible there is a need to use effective machine learning algorithms to detect patterns within the data. Also, there is a need to make the output of such algorithms transparent and easily understood by the operator. Moreover, it is also beneficial that such algorithms are computationally feasible so that the applications can be successfully constructed [1] [9]. In this paper, we are using KNN to detect grape leaf diseases, the motivation behind choosing the K-Nearest Neighborhood (KNN) algorithm is that it allows for a reduced recognition time as well as reduced computational complexity (Figure 1.2). Reduced computational complexity is of key importance as the primary users of this system would be farmers who may not have access to advanced devices that can carry out high complexity algorithms [10].

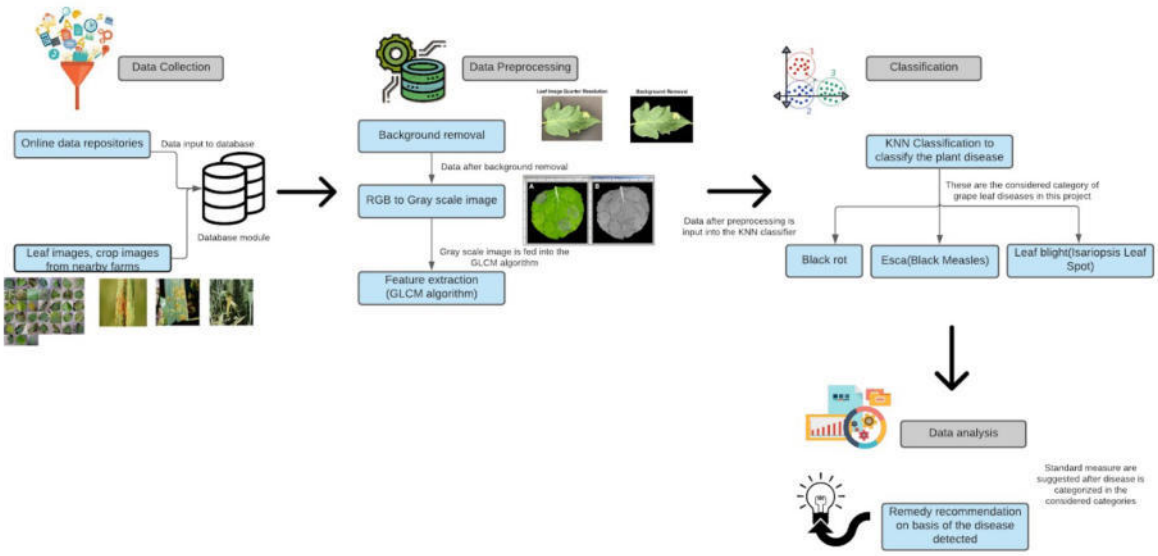

Fig. 1.2: Methodology

1.2. Contribution. For our approach, we have taken the vineyards in Maharashtra, India, as they are the country's biggest vineyards. Vineyards have become an important part of our current economy. Along with the production of grapes for wine, vineyards have become the first step of the supply chain of many cosmetic products, food and wine producers and packagers, bottlers and distributors. Supply chains are now overseeded and improved with the help of big data analytics. This is because each and every step will generate lots of data. However, big data is not being applied on a large scale in vineyards, which is the very first step. Big data is important to implement smart farming so that the different agricultural challenges of production can be tackled

Big data is being applied for the creation of smart vineyards in some parts of the world. Most of these companies that provide smart vineyard solutions are located in Europe. All of them focus on these three solutions that gather big data and after analyzing, work towards decreasing the yield loss and decrease the working hours of the viticulturists as per [11].

1. Precision Sensors: These sensors are deployed between the grapevines, and they gather the acute weather details of the grape plant such as leaf moisture and humidity.
2. Microclimate Monitoring: Precision monitoring of climatic conditions per plant measuring its humidity so that monitoring the intensity of fungal diseases becomes possible.
3. Grape Disease Prediction: Monitoring the leaf images of the grape plant can help to identify the early onset of diseases which can be treated or the bad plant may be removed to protect the rest.

Big data is slowly being applied to the agricultural sector in India. While farming may have other factors like irrigation and soil moisture, for vineyards, weather forecasting, and disease detection are the main areas that require the help of analytics as per [4]. In this paper, we have worked towards implementing a machine learning algorithm on a big data platform that can distinguish between healthy plants and disease ridden grape plants.

A feature extraction algorithm along with a machine learning classification algorithm is used alongside big data technologies to classify the leaf on whether it is disease ridden or not which will provide an accuracy between 60-70%. The reason for using a machine learning algorithm instead of a deep learning algorithm which would provide 100% accuracy is to create a system that would be able to give instant results with maximum possible accuracy and can be implemented without any extensive hardware requirements. This is done so that the system can easily be made use by the farmers who do not have that much technology to run the high-end

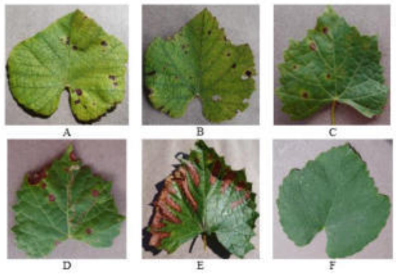

Fig. 3.1: Leafs

software.

The importance of big data technologies along with machine learning in the application of smart viticulture is given in this section of the introduction. The dataset used and literature reviewed is discussed in section 2. Section 3 talks about our proposed methodology and architecture in detail. Section 4 explains the implementation of our selected algorithm. Finally, section 5 shows the results of our implementation and the conclusion of the paper is given along with future scope and aspects.

2. Literature Review. Literature from reputed journals and conference proceedings have been referred to identify the suitable methodology and research gaps. Key objectives of the literature are as follows

1. Identification of data analytics algorithms to predict crop yield, crop production, crop price and crop protection from agriculture fields.
2. Review all grape disease detection algorithms

In Table 2.1, authors have figured out all the data analytics techniques implemented in the agriculture domain in the past 6 years. Table 2.2 depicts a comparison of the different algorithms implemented to detect disease in the grape plant and provide an analytical comparison with their advantages and disadvantages.

Table 2.1 given above provides a glimpse of what big data techniques have achieved in the field of agriculture in the last 6 years. Big data can help us predict crop yield [15] [17], crop production [14], crop price [18] and finally crop protection [16]. In this paper, we would be focusing on the concept of crop protection under big data in agriculture. We would specifically focus on big data in viticulture and grapefruit protection from diseases. To do this, we would be employing a machine learning model to predict the leaf disease in real-time collected from sensors in the vineyards.

Table 2.2 shows good accuracy offered by Convolutional Neural Networks [31] [32], but the major problem faced is the integration of these techniques with real-time data.

3. Proposed Architecture. In this paper, we have used the grape leaf dataset, which consists of images of healthy as well as grape leaves with diseases such as Black measles, Black rot, and Leaf blight. Moreover, we will also collect the data related to the diseases so that it can be used in the final recommendation of remedies for the detected disease(s).

Proposed model comprises four modules as per figure 4.1. Data collection module, data preprocessing module, Classification module and data analysis module. Data collection module deals with the gathered data(online and physically acquired) and will be stored in the database. The gathered data is then preprocessed and maintained by a preprocessing module. In the preprocessing the first step is to remove the background from the leaf images which will give us only the selected leaf portion, after this step the RGB image is converted to Grayscale image so that it can be processed with GLCM algorithm. The GLCM algorithm stands for Gray Level Co-occurrence matrix. This will help to convert the image data to numerical data, various features extracted from the image can be (contrast, correlation, energy, homogeneity, and entropy)[33]. As per Classification module achieved numerical data can be fed into the KNN classifier to classify images on the basis of the extracted features the dataset can be split into training, testing and validation as 80% train, 10% validation, 10% test. Visualization module proposes to recommend the necessary steps and remedies that the viticulturists

Table 2.1: Big data techniques in agriculture comparison

Data Source	Contribution	Pros	Cons
AkkerWeb Data for Satellite data and DairyCampus, Netherlands data [12]	Ontology is made of use for a combination of sensor data and applying big data techniques to the dairy farming	A system was created by the researchers that are based on the principle that ontology can be made use of to handle the big-data questions and create SPARQL federated queries on the data sources used by making use of ontology matching. As a result, farmers can pose questions in terms of the common ontology concepts instead of the detailed and specific concepts of the DairyCampus and Akkerweb data sources.	More advanced algorithm with hybrid approach could be applied
Web of Science and Scopus Database with search queries related to big data and farming [13]	Applied Ontology models as well as Machine learning models such as ANN, SVM and provided a deep comparison.	Made a list of all the insights got from the detailed study that can give rise to future scope and creation of applications	Not provided any suggestive list of all the challenges faced while implementing.
A dataset in agricultural sector Crop vise agricultural data Agricultural data of different districts Agriculture based on weather, temperature, and relative humidity [14]	wrote a paper that has its main focus on analyzing the agricultural data to find out the optimal parameters to maximize the production of crop by using data mining techniques such as Multiple Linear Regression, CLARA, PAM and DBSCAN.	A range of 5 different crops were selected with their yield data of over 6 years to provide as key measure. Comparison models were done between the different crops as well as the methods.	The research was limited to external quality metrics and not the internal ones too. The crops were selected only based on its economic importance, and not other factors like topography were included.
Cloud Database in Agriculture that gets data from sensors. [15]	Proposed a model to analyze the crop yield by combining the methodologies of IoT, cloud and big data concepts to deliver the prediction attributes to the farmers through the mobile computing technology. This is done using multiple nodes in MapReduce in Hadoop to predict the outcomes accurately at low costs.	The model will predict and notify the farmers regarding how much fertilizer to use for the crop and when to use it. This prediction will also try to decrease the total cost as much as possible.	They did not provide any insights on irrigation or how to deal with crop diseases. The focus of sensors was just on the amount of fertilizers to use.
A data source is from Charles Stuart University, Australia - herbicide resistance testing service from the years 2001-2005. Along with it, agricultural survey data is taken from the Australian Bureau of Statistics for each shire. [16]	TThe paper focuses on crop protection using big data with a focus on weed control and management using different machine learning techniques	A comparison between various machine learning approaches including discriminative/generative and supervised/unsupervised was done.	Samples were specific to just ryegrass. Out of the 173 shires available, only 121 were utilized to create the final dataset to avoid bias which could also have been removed using scalability.
Data collected from Onsite and remote farming [17]	The paper presents a hybrid model that first implements Grey Wolf Optimization on SVM classification to improve its results.	The proposed model has better precision, recall, accuracy and F1 values than a regular SVM classification.	No other optimization techniques were used as a comparison.
Created the dataset by finding the price of corn grain products in recent 10 years and the corn balance sheet for each year. [18]	Applied multiple linear regression to predict the price fluctuation in corn price under big data more accurately	Chinese special circumstances and the domestic and international market price of corn are also considered by the multiple linear regression model implemented in this paper to estimate the parameters by linear regression of corn prices.	No other regression techniques were used as a comparison

Table 2.2: Comparison of grape disease detection algorithms

Major Techniques	Data Source	Pros	Cons
First image processing is applied on the images and then classification of diseases is done using BPNN [19]	PlantVillage Dataset	Various techniques to segment the disease part of plant image were discussed	Other methods of classification were not compared.
Image segmentation is done using K-means clustering and classification is done using SVM [20]	Manually collected from different regions of Maharashtra, India	Provides a automatic, fast, accurate and less expensive method to detect and classify the grape leaf diseases	Other segmentation algorithms or classification methods were compared
Opposite Colour Local Binary Pattern Feature and Multiclass SVM [21]	Manually taken from farms	Provides a comparison with other methods for classification and their accuracy.	The algorthim was not implemented in a real time system by the researchers.
Detection using K means clustering [22]	-	A survey on different classification techniques	Segmentation of the disease area is difficult with these algorithms
Disease detection and classification using multiclass SVM [23]	PlantVillage Dataset	Clustering and Classification is done in Matlab with LAB and HSI color models	The number of images used in the dataset is just 160 which is less for real time data analysis.
Improving Classification accuracy by spatial-spectral analysis of hyperspectral images [24]	Manually capturing images of grape from a non-commercial vineyard.	Tested different dimenstionality reduction methods to study performance of spatial-spectral segmentation using Random Forest classifiers	The algorithm needs to be validated in other controlled conditions
Individual leafs are identified using leaf skeletons and then leaf disease classification is done using KNN classification. [25]	Created using agrnomical crop images	As the individual leafs are identified before classifiying, this approach is more efficient than other real time systems.	Apart from the luminance and linear characteristics of leaves, other features aren't taken.
A Transfer learning approach is applied in which Features from Rectified Linear unit layer of AlexNet (CNN) applied to MSVM [26]	PlantVillage Dataset	A high accuracy of about 99.23% is achieved.	The hardware requirements are stringent with GPU and high RAM requirements.
First, a local contrast haze reduction (LCHR) enhancement technique is applied. Next, LAB color transformation is done. Color, texture, and geometric features are extracted and fused by canonical correlation analysis (CCA) approach. Noise is removed by Neighborhood omponent Analysis (NCA). The classification is done by M-class SVM. [27]	PlantVillage Dataset	Provides a comparison between different algorithms for feature extraction and between different algorithms for classification	There is degraded accuracy in case of complex images.
Different machine learning algorithms are applied for classification [28]	PlantVillage Dataset	Provides a detailed comparison on the accuracy of the different models.	Apart from accuracy, other items like computational need, ease of apply etc are not compared.
Image analysis and back propogation Neural Network [29]	Manually taken from a farm in Zhengzhou City, Henan Province.	5 different grape diseases could be identified with high classification accuracy	The dataset just consisted of 60 images which are relatively less to give accurate results when applied elsewhere.
Artificial Bee Colony algorithm was applied to pre processed images. [30]	Plant village dataset	Comparison is done with two other algorithms namely Particle Swarm Optimization and Genetic Algorithm. Relatively better accuracy is observed	The accuracy is dependent on a SVM based classification to which the ABC is applied. Other classification algorithms are not applied for comparison.
Lightweight convolutional neural network along with channelwise attention with ShuffleNet V1 and V2 as backbones [31]	PlantVillage Dataset	A comparison is given between all the different models of CNN along with their accuracy and parameters.	Although the improved shufflenet provides maximum accuracy, its still not able to integrate with IoT for real time big data monitoring. The computing is cost effective but only compared to other CNNs.
A UnitedModel convolutional neural network based on multiple CNNs [32]	PlantVillage Dataset	Created a united model architecture based on InceptionV3 and ResNet50. It outperforms VGG16, InceptionV3, DenseNet121 and ResNet50.	The integration of the two CNNs is still not proper. Trained model cannot be applied in real time diagnosis needed in crop protection

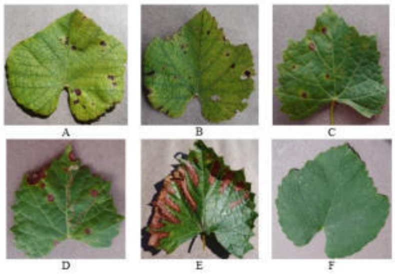

Fig. 4.1: Leafs

can take to make sure that the grapes can be salvaged at the right time and in the right manner and overall help them in the harvesting process.

4. Dataset Description. An important aspect of viticulture is to take care of the health of the grapevine. This paper focuses on three main diseases that afflict the grape plant, namely black rot, esca (black measles) and leaf blight (Isariopsis leaf spot). Black rot is a fungal disease that affects all the parts of the plants, i.e. leaves, berries, shoots and stems. The fungal disease spreads via spores and has to be contained during the first two weeks or all the plants grown for that season are lost. Fungicides need to be sprayed, and the rot needs to be detected as early as possible. Such rot especially spreads in warm and humid conditions as per [34] like the weather condition in Maharashtra, and thus it is important for our proposed algorithm to detect this disease early on to curb its growth. Esca or black measles affect the grapefruit and leaves and has plagued the viticulturists for a long time. With no apparent management strategy for measles, field crews are needed to check for them every day and remove the infected plant before the nearby plants can be infected. This problem can be solved with the help of big data analytics where each leaf is monitored, and our proposed algorithm can detect the measles along with the location, so that field crews just need to remove them. Isariopsis leaf spots is another fungal disease that if not controlled, will lead to a reduction in the population of the plant as per [35].

To deal with these three major diseases, the dataset was taken from Kaggle [36] in which there are 1180 images of black rot, 1383 images of esca, 1076 images of isariopsis leaf spots and 423 images of healthy grape leaves. Total of 6000 images were 4062 images taken from Kaggle and 1938 images taken from Ambapur village farms situated in Kalwan district, Maharashtra as shown in Figure 4.1.

5. Implementation. Execution of the proposed model is carried out on three nodes set up with commodity computers of 64 bit operating system with 8GB RAM, windows 10,core i5 CPU, 120GB hard disk(built in),Extra 1TB hard disk on specific node. One of the nodes in the cluster worked as Hadoop Master and the rest of the two nodes worked as Hadoop Slave. Selection of competitors is on MapReduce and parallel processing ground. The implementation details are as follows:

Step 1: At first the images of all the healthy and the diseased leaf images are combines and are split into 80:20 ratio of training to testing.

Step 2: After that the images are preprocessed, the background is removed and conversion of the RGB to Grayscale image takes place, the function cvtColor() is used to change the color space of the image.

Step 3: Then, the HSV(Hue, Saturation, Value) and their mean values are calculated, these values are then concatenated with the GLCM features in the final CSV sheet.

Step 4: The GLCM features used for this project are Contrast, Dissimilarity, Homogeneity, ASM(angular second moment), and Energy , these terms are calculated as given in equations 5.1, 5.2, 5.3, 5.4, and 5.5.

Contrast:

$$\sum_{i,j=0}^{N-1} P_{i,j}(i-j)^2 \tag{5.1}$$

Dissimilarity:

(5.2)
$$\sum_{i,j=0}^{N-1} P_{i,j}|i-j|$$

Homogeneity:

(5.3)
$$\sum_{i,j=0}^{N-1} \frac{P_{i,j}}{1+(i-j)^2}$$

ASM:

(5.4)
$$\sum_{i,j=0}^{N-1} P_{i,j}^2$$

Energy:

(5.5)
$$\sqrt{ASM}$$

where $P_{i,j}$ is the element i, j of the normalized symmetrical GLCM and N is the number of gray levels in the image as specified by Number of levels in under Quantization.

Step 5: The GLCM calculation and feature extraction process:

GLCM: GLCM is used to calculate how frequently a pixel with gray with a certain gray-level grayscale intensity or level (grayscale intensity or Tone), namely value i occurs either horizontally, vertically, or diagonally to adjacent pixels with the value j. In the process of calculating the co-occurrence matrix we firstly quantize the image data. Each sample on the echogram is treated as a single image pixel and the value of the sample is the intensity of that pixel. Quantization is used to quantize the levels of intensity of the pictures by specifying the discrete gray levels.

5.1 Create the GLCM matrix, which is an $N \times N$ square matrix where N signifies the Number of levels specified under Quantization. The matrix is built as follows:

5.1.1 S are the samples taken for the calculation.

5.1.2 W are the samples around sample S that fall in a window centered around sample S with the size specified by the window size.

5.1.3 Considering only the samples in the set W, define each element i, j of the GLCM as the number of times two samples of intensities i and j occur in specified Spatial relationship (where i and j are intensities between 0 and Number of levels-1). The sum of all the elements i, j of the GLCM will be the total number of times the specified spatial relationship occurs in W.

5.1.4 To make a symmetric GLCM matrix, we create a transposed copy of the GLCM matrix.

5.2 Adding this copy to GLCM itself produces a symmetric matrix in which the relationship i to j is indistinguishable for the relationship j to i (for any two intensities i and j). As a consequence the sum of all the elements i, j of the GLCM will now be twice the total number of times the specified spatial relationship occurs in W (once where the sample with intensity i is the reference sample and once where the sample with intensity j is the reference sample), and for any given i, the sum of all the elements i, j with the given i will be the total number of times a sample of intensity i appears in the specified spatial relationship with another sample.

5.2.1 We normalize the GLCM by dividing each element by the sum of all elements. The final matrix contains elements that represent the probability of finding the relation between i and j in W.

5.3 Calculate the selected Feature. This calculation uses only the values in the GLCM. The features are given as follows:

Table 6.1: Calculation metrics

Test	**Positive**	**Negative**	**Total**
Disease Present	P(TP)	R (FN)	P+R(TP+FN)
Disease Absent	Q(FP)	S (TN)	Q+S(FP+TN)
Total	P+Q	R+S	P+Q+R+S

Table 6.2: Example table

Sr. No	**Measures**	**Values**
1	Accuracy	0.824
2	F1_score	0.84
3	Precision	0.846
4	Recall	0.77

1. Energy 2. Entropy 3. Contrast 4. Homogeneity
5. Correlation 6. Shade 7. Prominence

5.4 The sample s in the resulting virtual variable is replaced by the value of this calculated feature.

Step 6: At the end of pre-processing and feature extraction we are left with a CSV data sheet containing the selected GLCM and HSV values along with the label of the type of leaf.

Step 7: In the KNN code, the label from the CSV data are represented on the Y axis, whereas the features (GLCM and HSV) are represented on theX axis.

Step 8: The KNN algorithm used to find the nearest neighbor is the Brute force algorithm which calculates the distances between all pairs of points in the dataset. Efficient brute-force neighbors searches can be very competitive for small data samples.

Step 9: We also randomized the value of K and found the most accuracy when the value of K is set to 15 we get an accuracy of 72%.

6. Result and Discussion. As per table 6.1, TP represent true positive, TN represent true negative, FP represents false positive, and FN represents the false negative. The fraction of the population expresses accuracy of the model are rightly classified as disease affected leaves, and it is calculated using the formula $(P + Q)/P + Q + R + S$. With the application of the KNN model on grapes leaves, 82% accuracy have been achieved. The precision of the model is expressed by the fraction of true positive samples among all positive sample by the formula $P/P+Q$. Table 6.2 shows achieved results for the metrics accuracy, F1_score, precision and recall.

Disease type would be identified by a classification module. Based on the class of the grape leaf visualization and recommendation module would suggest primary level solutions.

1. Black measles: There is no operational solution to control black measles till date. Agriculture experts' solution is to remove the infected grapes, leaves and. Shield them by pruning wounds which spread minimum fungal infection using spiral sealant (5% boric acid in acrylic paint). Use of neem oil or suitable fungicides.
2. Leaf blight: Only sprinkle of fungicides would help in reducing this disease.
3. Black rot: Removal of all wrinkled grapes from vines during latent pruning. Also, cultivation of new soil during outgrowth break to bury mummies. One can apply suitable fungicides to control the disease.

7. Conclusion and Future Scope. In this paper, we have proposed an approach to implement big data analytics in vineyards which extracts the features from the leaf images using GLCM and then classifies them using KNN and with a primary level of recommendations. In our experiment dataset, the leaves were classified into three diseases, namely black rot, esca, leaf blight and healthy leaves. The final accuracy of our experiment comes to about 82% but this algorithm can be directly applied to a big data environment to create a smart vineyard where technological limitations are prevalent. This system can be easily implemented to a mobile application so that farmers in India can easily find out if their crops have any diseases or not. As GLCM and KNN do not require any high end graphic cards or high technical configuration to run, a smart vineyard system to monitor the grapes can be implemented easily at low costs. In the area of agriculture, the absence of demonstrative devices in underdeveloped nations impacts improvement. In this way, it is essential to determine at the beginning phase to have open and economical solutions. As a future scope, other grouping strategies in machine learning like decision trees, Naïve Bayes classifier, reinforcement learning might be utilized for infection discovery in plants and help the farmers to make an automated harvesting decision-maker, with the help of the statistics collected form economical classification algorithms which can be accessed by mobile devices and collaborate it with other precision farming techniques which will ultimately contribute towards making a sound harvesting decision or suggested most beneficial remedies for the infected plants covering more diseases for various crops.

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SERVICE DEPLOYMENT CHALLENGES IN CLOUD-TO-EDGE CONTINUUM

DANA PETCU*

Abstract. This position paper aims to identify the current and future challenges in application, workload or service deployment mechanisms in Cloud-to-Edge environments. We argue that the adoption of the microservices and unikernels on large scale is adding new entries on the list of requirements of a deployment mechanism, but offers an opportunity to decentralize the associated processes and improve the scalability of the applications. Moreover, the deployment in Cloud-to-Edge environment needs the support of federated machine learning.

Key words: Cloud computing, Edge computing, Resource management

AMS subject classifications. 68M14

1. Introduction. The requirements of a deployment process in current distributed environments (listed in [1], for example) are currently far from being satisfied by the available support tools. The main concerns are related to contextualization, data transfer, negotiation, deployment optimization, service manifest construction, discovery of IPs, or even filtering available IPs. Moreover, the Cloud is bringing new items on the requirement lists, like the elasticity: the deployment service should add or remove Cloud resources in a dynamical way [2]). Furthermore, recent studies on automated or semi-automated deployment processes of distributed software systems have revealed the low efficiency of the deployment of distributed software systems. In particular, this is the case when scalability, dynamics, openness, distribution or heterogeneity are primary concerns [3]. Such concerns are often encountered in Cloud computing.

The emergence and widespread adoption of Cloud computing, mobile technologies, social media and big data analytics is transforming how society operates and interacts and is heralding the so-called Industry 4.0. In Cloud computing, processing takes place within the clear boundaries on its underlying infrastructure. Cloud computing was not designed to deal with the scale of geographically dispersed, heterogeneous end points and low latency required for many Industry 4.0 use cases. Therefore, conventional paradigms of computing need to be rethought to deal with the scale of data processing needed to support the requirements of the devices from the edge of the network to work in a distributed and coordinated way at minimum latency. Fog and Edge computing are two paradigms of computing that have been proposed to address these challenges. Fog computing is seen as a horizontal, physical or virtual resource paradigm that resides between smart end-devices and traditional Cloud or data centers. Edge computing, in contrast, is local computing at the network layer encompassing the smart end-devices and their users. Fog and Edge computing provides significant advantages for processing data closer to the source and thus mitigate latency issues, lower costs of data transmission, and reduce network congestion [29]. Despite the flexibility and advantages offered by this distributed architecture, it poses substantial challenges related to resource management, infrastructure or application orchestration. These challenges are exacerbated when considering deployments spanning Cloud-to-Edge continuum (denoted by C2E).

In this position paper we try to identify the main challenges for the near future research and development activities dedicated to the application or service deployments in C2E. The paper has three parts. The first deals with the current limitations of the available deployment mechanisms. The second discusses the expected effects of adopting lightweight virtualisation techniques on the deployment mechanisms. The third part deals with the particular issues of C2E.

*West University of Timioara, Romania (dana.pecu@e-uvt.ro)

2. Solutions for Application Deployments in Clouds and their Limitations. In the first section we are studying the deployment mechanisms classified as application-oriented (according [4]), i.e. following an application-specific deployment plan that is portable as enabling infrastructure abstracting and not bounded to a specific e-infrastructure.

Automation with deployment management tools. Current extensively used configuration management tools, like Chef or Puppet, support the automation of complex deployments, even on heterogeneous systems. However, they employ proprietary domain specific languages allowing to abstractly describe the workload creation process. The problem is getting exponentially more complicated when Cloud services of different providers are expected to be simultaneously accessed (Multi-Cloud case). Multi-Cloud deployment services exposed by commercial providers, as Rightscale, support the application deployment processes across multiple Clouds through a simple web-based user interfaces as well as a RESTful API, both aiming to hide the complexity of their automation tasks. Moreover, the proof-of-the-concept prototype, autoJuJu [5], designed as an autonomic Cloud deployment manager for Ubuntu virtual machines, has shown how autonomous decisions about when to scale-in or out or to deploy various architectural components can be taken in order to improve performance. However, above enumerated solutions are complex and not designed to enable the flexibility required to choose a certain provider, despite their goal to make deployments faster and easier as well to be compatible with the Cloud service interfaces of a certain number of selected providers.

Automated deployment versus flexibility. Introducing autonomy in deployment is expected to enable the automatic elasticity in terms of number and type of the deployed application or service components, in order to meet performance requirements or energy consumption constraints. Flexible deployment service that support the specification and execution of deployment plans are now technically possible, but not yet implemented on a large scale. The application can be described through a pattern reflecting a logical view of the application together with its components mapping into the Cloud resources. Following this idea, the service described in [2], based on Chef, and accessible through a RESTful interface, is able to instantiate the pattern and update at runtime the deployment. A similar RESTful accessible service is described in [6] and unattended deployment is tested for security platform deployments.

Assisted deployment. Low-level scripts that are hands-one designed to use specific service APIs and tools are the opposite solution to the automation scripts. However, their development is a complex task requiring the deep knowledge of the services that are used, is error prone and should be repeated when the interfaces are changed. Guided writing can help the script development process to a certain extent. For example, the deployment documents proposed by Contrail [7] allows to specify how many and which kind of resources are needed to be deployed (but the resources should use the OVF format). Most of the proof-of-concept toolsets aiming to assist in the application deployment are dependent on the Cloud services of certain providers. Disnix [8], for example, is a toolset for automatic deployment in a network of machines of a distributed system; it uses declarative specifications for properties such as rollbacks, dependencies, or upgrades, but is not portable to all operating systems as being dependent on certain Unix packages. The deployment framework described in [9] and designed for analytics is based on customization workspaces and Chef. Another approach using deployment specification for component-based applications is proved to be able to automate the deployment of scientific applications in Azure Cloud[10]. High level domain specific language are in this context useful for the definition in a provider-independent manner of the deployment process of an application with its resource requirements, as well the definition for the process that transforms the definitions into deployment scripts for a large variety of services of different providers. A such domain specific language is proposed in [11]; a drawback is its incompatibility with Chef or Puppet. A Ruby-based domain specific language was also proposed [12] to automate the deployment of software frameworks, but only for AppScale platforms.

Deployment plan synthesis. Automatic synthesis of deployment plans are the done in a step before the actual deployment. A deployment plan synthesis process was proposed, for example, in[14]. Multi-objective optimization, as proposed in [13], are used often to establish a deployment plan. Another paper [15] proposed an approach for deployment mechanism based on requirements decomposition and clustering techniques. A clustering-based method for the optimal selection of Cloud nodes on which the application should be deployed can be used, as reported in [16], in the particular case of a communication-intensive application. The communication traffic between services and its performance are taken into account in the deployments reported in [17].

Multi-Cloud deployment requirements. The modern deployment system should work together a service broker enhanced with different scheduling strategies for near-optimal deployments based on individual or multiple criteria like placement constraints, cost, energy consumption, performance, instance types, service loads [18]. The Chef cookbooks are not bound to a specific platform, but they are implemented with a specific domain specific language.

Application deployment versus their dependencies. Deploying an application is often requiring the deployment of several software components associated with that application. Chef and Puppet are requiring the creation of application-specific deployment plans that are usually not reusable when the application dependencies are changed. To mitigate this problem a middleware-oriented deployment approach can be used, according [19], to offer software components as building blocks for configurable and composable deployment plans.

Continuous deployment. The introduction of DevOps concepts in the Cloud context is justified by the need of application continuous deployment both in design and production phases. Proof-of-concept tools, such as the ones described in [20] or [21], are allowing to close the loop between the application design, deployment and execution through the intelligent interpretation of the monitoring process results. A large scale of this idea take-up has not been reached yet.

Standards and blueprints. TOSCA is the OASIS standard that is designed to describe composite Cloud applications and their management in a portable way. The structure of a composite application is described as a topology that includes components and relationships. However, the deployment procedures are not defined in this topology. Instead, deployment artifacts are specified for the actual implementation (for example, the OS type may have as artifact an image). A protocol for deploying application blueprints on the Cloud is CAMP, which uses YAML language to describe the application deployment plans. Apache Brooklyn is an example of an open-source engine able to deploy blueprints specified in TOSCA and CAMP. The use on a large scale of TOSCA, CAMP, Brooklyn is not yet registered.

Decoupling the software deployment from virtual machine deployment. Such decoupling as proposed in [22] is improving the deployment flexibility. The virtual machine size on storage is smaller as the software is not pre-stored in it. The software is streamed on demand from an application repository as soon as the user request it to run in a virtual machine. The performance tests are in favor of such approach in the case that multiple similar virtual machines are activated in a cluster of a particular Cloud. Moreover, a thrird decoupled layer, as we proposed in [6] (mOS Enabling Platform), can provide further benefits without a significant overhead: the third layer is the middleware that allows the on-demand software to be deployed is view as independent from the operating system and allowing a supplementary independence from the Cloud services.

Self-organisation. CloudLightning [23] proposes a delivery architecture based on the principles of self-organisation and management that addresses the challenges of complexity introduced by heterogeneous resources (a market like approach rather than client-server approach). This approach can be beneficial by shifting the deployment effort from the consumer to the software stack running on the e-infrastructure while reducing power consumption and improving service delivery. The overall goal is to address inefficient use of resources through over-provisioning and to deliver savings to the Cloud provider and consumer in terms of reduced power consumption and improved service delivery, with hyperscale systems particularly in mind. A proof-of-concept implementation has been recently finalized, including a simulator for large and heterrogeneous e-infrastructure services [24].

Serveless computing. In this novel approach (named also Function-as-a-Service or event-based programming), parts (modules, functions) of the application are executed when necessary without requiring the application to be running all the time. Examples of platforms suppiring the concept are AWS Lambda, OpenLambda, Google Cloud Functions or Lambda@Edge. The current challenge is to develop programming models that allow high-level abstractions to facilitate serveless computing [25]. The infrastructure is expected to be abstracted away from the user who can focus the attention to control, cost and flexibility rather than application deployment or over-or under- provisioning of resources for the application. The trade-offs in using Cloud services along with serverless computing services need further investigation.

Deployments in Micro Clouds. Small sized and low power computing processors like Raspeberry PIs co-located with switches or routers are now used to develop Micro Clouds. However, networking Micro Cloud installations over multiple sites, integration with existing computing ecosystem, or just-in-time deployment of workloads in Micro Clouds are not yet possible.

Bare-metal services require guided deployments. The HPC-as-a-service (HPCaaS) concept makes a compromise between the common understanding of distributed Cloud services and the HPC requirements. It refers to a bare-metal compute model similar to an in-house cluster (cluster-on-demand). Several services are available from large companies like Amazon and SGI. Open source applications that are often used by the HPC community are ready to be deployed in the acquired environments. However, theirand application deployment process is not automated. The scale-up and scale-out options are rarely encountered (a counterexample is the offer of Cyclone). Self-configuration is not yet implemented and the vision of an autonomic HPC Cloud is far from being achieved [26].

3. Services Deployment Challenges following the Lightweight Virtualisation Approaches. Beyond the hypervisor approach to virtualization in which context the above described solutions were intensively tested, a new virtualization approach has gained a large community interest in the last years, the one based on containers. Furthermore, the newest approach, that of unikernels is now raising the community interest. New virtualization techniques for HPC applications like Singularity are also emerging. Additionally, smaller virtualisation overhead provided by containers and unikernels enables to run significantly more workloads than in case of using heavier virtual machines and thus results in greater energy efficiency.

All these new virtualization approaches are changing the order of magnitude of the deployed artifacts, the hardware devices that can host the services, as well as the deployment time and therefore they are generating to new challenges for the deployment mechanisms.

Automated deployment of microservices. The total time to provision a virtual machine is a burden for the current Cloud applications resulting in pre- or over-provisioning of resources. A solution to reduce the deployment time is the use of microservices. While a microservice virtual machines contains the core OS kernel, runtime, frameworks, libraries, code, configuration, and any other application's dependencies, the container eliminates the need of packaging the OS Kernel. Consequently, the microservices are quick to start, launching and being able to respond to a request in milliseconds. The usage of containers that controls the execution of microservices make them easily portable and re-deployable in different context (containers are tehrefore seen as an alternate virtualisation technology). Docker and LXC are helping the implementation of this vision. In particular, Docker offers facilities to package a service in a container, creating a lower footprint on the overall execution environment and increasing the service portability. A proof-of-concept engine that is able to deploy automatically a container-based distributed system acting as a monitoring platform was build and reported for example in [27]. Container-as-a-Service, like Google Kubernetes or Docker Swarm, offers the deployment and management of containers, allowing workload execution in ad hoc Clouds and Micro Clouds enabling Fog computing. Container monitoring, live migration and portability remains opens issues [25].

Dynamically tailored deployment engines. The approach to generate dynamically deployment engines tailored for specific application stacks was presented first in [28]. The generated engines should be portable i.e. able to run them on various e-infrastructures. APIs are expected to be generated for particular scripts and plans that perform specific jobs in an automated deployment process. Then the deployment tasks are triggered through the generated API endpoints (offering an abstraction layer detached from details of various deployment automation tools). The proposal is fitting well with the novel microservice architectures, as a tailored engine can be dynamically generated for each component of the application.

Edge computing new requirements for deployment mechanisms. Being able to build and manage on demand a hosted computing environment as close as possible to the Edge is advantageous in services that benefit from locality of data production, processing and consumption. When deploying the service several specific requirements, like an software-defined network based fabric, federation of the devices, remote installation of Edge small artifacts, are emerging. A complex task should be depicted by a configuration engine in order to select a deployment blueprint suitable for the on-line devices as well as the scripts stating what is needed to be deployed in each individual Edge node. This is a complex task and a moving target as the amount of computing power at the edge of the Internet is increasingly very rapidly, thanks to the constant deployment and churn of multitudes of heterogeneous devices (personal, embedded, or environment-situated, with ever-increasing computing and communication capacity and capabilities). Furthermore, responds to issues related to the adaptation to an dynamic and open computing environment, like the policy for re-deployments, are still not available.

Unikernels usage. Unikernels are fixed-purpose images that run directly on a hypervisor without a guest operating systems. Unikernels run a single application, relying on the underlying hypervisor to isolate each unikernel system it is hosting. They are constructed using library operating systems having a minimal set of services that are required for an application to run. An unikernel is a virtual machine specialised and optimised for the particular application. Unikernels meet the requirement of the fast deployment as do traditional containers. However, they do not have most of the multi-process and user handling, unneeded device drivers and unnecessary system services and are able to start on bar metal. Therefore they start much faster, have a smaller storage footprint and allow an just-in-time spawning of new services. The reduced size of unikernel allow Cloud providers to increase their hardware utilisation rates, increasing margins and opening scope for reduced service development costs. However, unikernels deployment tools are still in infancy phase.

Distributed Clouds supplementary requirements. The usage of lightweight virtualisation solutions that can be deployed anywhere in the network raises another problem for the deployment mechanism. While the unikernel images or microservices can boot in microseconds the supporting software frameworks are not designed for such rapid and large-scale deployments, with the major bottleneck being the centralized framework. Moreover, assuming that Edge, Fog and Cloud resources are integrated, the deployment mechanism need to be aware of the resource configurations available at each location and on each special device. Furthermore, the small, rapid-response workloads images should be small enough to be moved quickly through the network.

Service dependency versus deployment complexity. Many current deployment frameworks rely on having declared the dependency chain for each of the services to be deployed (e.g. service X cannot be deployed until service Y is deployed). Assuming that the services can start in microseconds, the dependency can be solved instantaneous (if the service Y is not started, X requests service Y deployment and start). This offers the opportunity to have a light deployment mechanism that is built within the service that is deployed.

Compute-on-Demand. The concept refers to the creation and start of a virtual machine only when is needed. Jitsu is a prototype DNS server which is able to boot virtual machines on demand when a query is received. Today only single atomic services can be delivered in this fashion using Jitsu. However, using techniques to parallelise the creation of unikernels with the supporting network through orchestration, the same functionality for composed services is also possible, but not yet implemented.

Deployment versus configuration. Leveraging light virtualisation resources such as unikernels or containers, the boundary between service deployment and its configuration vanishes. While initial deployment is only one concern, once the service has been deployed it needs to be (re-)configured, managed and updated. Deployments of updates should be facilitated via gateway APIs allowing new code to be uploaded to a single virtual or physical node. This node can then ensures that the update is propagated to others ensuring that the easy upgrade deployments are possible.

4. Challenges in Cloud-to-Edge continuum. The discovery and provisioning of cross-layer resources in a fragmented landscape, in terms of heterogeneity of hardware, in an automated and unified manner cannot be performed seamlessly. More specifically several different frameworks need to be invoked manually, each one with a different scope, goals and algorithms, to obtain a coalition of resources that could host an end-to-end deployment. These different frameworks have diverse goals when allocating resources that in many cases result in suboptimal allocation of resources with respect to resource efficiency and energy consumption since over-provisioning is utilized to avoid Service Level Agreement violation, since application-level requirements are not considered. This procedure introduces significant obstacles from both the side of infrastructure providers as well as the side of potential users. Even mature orchestration tools such as OpenStack Heat, Kubernetes, Docker Swarm, are designed with a conventional Cloud architecture in mind and are not ready or sufficient for the scale and complexity of the C2E paradigm. Open projects trying to address handling and scheduling of microservices in a fragmented heterogeneous environment such as EdgeX Foundry Project and OpenFog Consortium have been also presented, however they are targeted primarily to IoT devices.

The C2E has been foreseen in early 2016, even in a paper of [30], at that moment under the name "CloudIoT paradigm", but identifying part of the problems encountered today. C2E challenges have been formulated in [31]. Under investigation C2E solutions referring to C2E resources are focusing today on costs [32], workflows

[33], adaptive placement [34], network [35, 36] or provisioning [37].

The majority of related work of resource management (like compute nodes, devices etc.) in Edge computing assumes that these entities are already discovered and integrated into the system. The hierarchical architecture is the most adopted solution using services and devices divided into layers. Due to this aspect the approaches that make use of this architectural model are focusing less on how the resources are discovered and integrated into the model. Some research directions are already investigating the possibility to switch computations from Cloud to Edge [41] and partially tackles the resource discovery problem in Edge environments [38, 39, 40], but without emphasizing the case were devices or resources are dynamically added to the ecosystem and how are integrated and related to proper Edge computational nodes.

Transprecise computing breaks away from the traditional notion that computing must be exact and can be applied with success in C2E environments. It proposes to perform computations at a reduced precision while reducing accuracy of the computation in a controlled way. Here, precision indicates the level of detail in the computation (e.g., the bit width of a number) while accuracy indicates the fidelity of the computed values to the exact values. Many computations inherently allow a reduction in accuracy [42, 43] or even allow approximation [44, 45].

Machine learning (ML) algorithms that apply best-effort algorithms to inherently noisy data are prime candidates for transprecise operation [51]. Operating at reduced precision can significantly improve speed of training and prediction. Moreover, hyper-parameter selection can compensate for lack of precision in machine arithmetic [46, 47, 52].

Monitoring of distributed systems is a challenging prospect, more so on a system based on the C2E, specifically in Fog computing which lies between IoT and Cloud, where any device that has computation, networking and storage capabilities can act as a processing node [48]. These types of devices have an inherent high rate of failure which can be caused by any number of factors [49, 50] like wireless connectivity issues, power failure, lack of computational availability. It is easy to see how this has a major impact on scheduling but there are also opportunities when considering failure as a special case of runtime behavior in a transprecision framework. Furthermore, monitoring appropriate metrics that are able to create the proper context entails complementing traditional system metric monitoring with specialized metrics related to identifying and reporting anomalous behavior especially for Infrastructure-as-a-Code (IaC) scenarios [48]. IaC anomalies and anti-patterns can include but are not limited to: golden image - bespoke infrastructure server image overuse; postponing secret isolation - information that should be secret but is included in the code; massive file copying - all configuration files for a particular package copied onto target by provisioning tool; data as code - data included in IaC. In some circumstances it is not desirable to send the collected monitoring data to a central location where predictive ML models can be trained. In these scenarios an adaptive federated training model [53] is preferred. These more localized models can be used to update a global predictive model via some form of global parameter aggregation. This approach minimizes both network traffic and also helps in predictive model specialization.

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MOVING BEYOND THE CRYPTO-CURRENCY SUCCESS OF BLOCKCHAIN: A SYSTEMATIC SURVEY

MIR SHAHNAWAZ AHMAD* AND SHAHID MEHRAJ SHAH†

Abstract. Blockchain (BC) is a technology whose value today is estimated by the success of Bitcoin. However, the spectrum of Blockchain applications goes beyond the financial sector. It has displayed enormous potential for revamping the customary industry with its key merits like decentralization, persistency, anonymity, and auditability. In this paper we conduct a comprehensive survey on the blockchain technology, explaining its structure and functioning. This work has analyzed the potential of BC in seven crucial sectors vis. voting systems, supply chain management, the security of Internet of Things (IoT), healthcare, intelligent transportation systems, government services, and tourism. Moreover, this paper has critically evaluated the traditional technologies used in various sectors, the problems in them, and the benefits that will be provided by the employment of BC. With its future directions, this paper will help researchers to create and realize new value for various sectors that is beyond anything we can imagine with existing technologies.

Key words: Blockchain, Bitcoin, Decentralization, voting systems, intelligent transportation systems, security of Internet of Things (IoT) and government services.

AMS subject classifications. 68M25

1. Introduction. A mixture of technologies like Artificial Intelligence, Internet of Things (IoT), robotics, cloud Computing, and Blockchain is marking the dawn of a new era in the world of information technology. Among these, BC is particularly noteworthy for its contribution in the creation of a strong backbone for decentralized data processing technology [1]. Although, originally conceived as the cardinal framework of the first cryptocurrency, i.e., Bitcoin, BC has cruised its way through the financial sector into a broad spectrum of applications, most of which are identified in this paper. Today, Bitcoin is identified as one of the most paradigmatic utilizations of Blockchain. Recognized as a famous substitute to fiat money, it is appreciated for its anonymity [2]. The users of Bitcoin are identified through cryptographic pseudonyms [3] and as long as the attacker's power of computation does not exceed that of the honest nodes in the network, the Bitcoin ledger has reliable liveness and consistency features [4]. Blockchain technology created this reputation of Bitcoin by being an immutable ledger that is secured by a network of peer-peer participants [5]. US Treasury identifies Bitcoin as a decentralized peer-peer virtual digital currency [6]. After the creation of Bitcoin in the year 2009, about 200 more crypto-currencies referred to as alt-coins were developed. Although these currencies were built by branching out from the original Bitcoin protocol, they do have their unique characteristics which make them different. Figure 1.1 lists various crypto-currencies as per their market capitalization values [7].

As per [7], the total market cap in digital currencies was approximated at 242 billion USD on 18th January 2020. With the present market value of 3,964 USD per unit of Bitcoin (bitcoin) and a total market cap of 68 billion USD, Bitcoin takes a 52% share of the whole market cap and ranks number one among all the crypto-currencies available today [8]. Figure 1.1 also demonstrates that the second and third largest digital currencies according to their market values are the Ethereum, and Ripple/XRP accounting for 12% and 10% capitalization values. Other currencies form the remaining 22% of the market capitalization value.

The decentralized nature of BC attract the attention of IoT, Supply Chain Management (SCM), Voting and multitude of other environments fitted out with decentralized topologies [9, 10]. Moreover, the distributed

*Communication Control & Learning Lab, Department of Electronics & Communication Engineering, National Institute of Technology, Srinagar, J&K, India. (mirshahnawaz888@gmail.com).

†Communication Control & Learning Lab, Department of Electronics & Communication Engineering, National Institute of Technology, Srinagar, J&K, India.

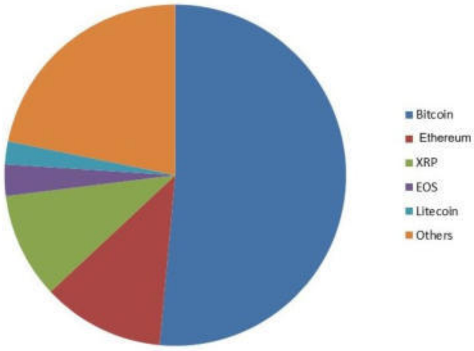

Fig. 1.1: Crypto-currencies by their market capitalization values.

consensus mechanism offered by the BC networks makes it crucial in the organization of global state machine for general purpose byte-code execution [11]. The consensus mechanisms used in BC offer concession that requires very less messaging overhead and absolutely no identification authentication on the global BC-data state. In addition to these reasons, since, BC can offer transaction driven asset management in communication networks, it is considered as one technology that can become the strength of developing trusted open-access virtual computers [12].

Although, a lot of potential areas concerning BC and research gaps in them have been identified in this paper, the key obstacle, however, in the path of true realization of BC in real business environments is that of the scalability [13]. Firstly, compared to the 2000 transactions per second carried by the VISA system, the Bitcoin system can only handle 7 transactions per second [3] and hence gives less throughput. Also, the block interval time is nearly 10 minutes and the number of transactions is limited by the size of the block which is 1 megabyte (MB). In real world, however, the number of transactions emerging is huge, and hence efficient schemes need to be built for BC to enhance its scalability and throughput. Secondly, the entire process of blockchaining consumes a lot of network resources because each transaction needs to be transmitted to all the nodes twice, first, when it is generated and second when it is mined. This not only wastes the network resources, but also increases block propagation delay. Thirdly, in BC, it is required that any node that processes the transaction stores it back to the genesis block. This makes it difficult to directly implement BC in environments where the nodes have limited computational and memory resources [14].

The main contribution of this paper is highlighted as follows:

- There is an adequate amount of literature on BC from diverse outlets, such as forums, wikis, forum articles, documents, conference proceedings, and journal papers. However, most of these scientific studies (discussed in the paper) revolve around decentralized digital currencies, including Bitcoin. Our paper, instead, focuses on the wholesome aspect of the BC technology, viewing it from both technological and application outlooks.
- Our work has organized the literature according to its categorization. It has compared the advantages of using BC technology over the ones that are currently being used.
- Our survey protocol is that first we have identified the fields where BC could be used apart from crypto-currencies, then we have reviewed the work done in that field, critically reviewing it and providing BC based solutions. As such, this paper can act as a guiding torch to the researchers for identifying the gaps and limitations in the existing work in various domains and direct them in how BC could be helpful.
- The IoT attack surfaces have also been explored in this paper. It also speaks how and where BC can help to mitigate this buzzing problem.
- Future research directions are collated for effective integration of Blockchain into various networks.

The rest of the paper is organized as follows: section 2 describes all the basic features of BC and its functioning. This section lays down the foundation for understanding the BC. Section 3 analyzes the areas

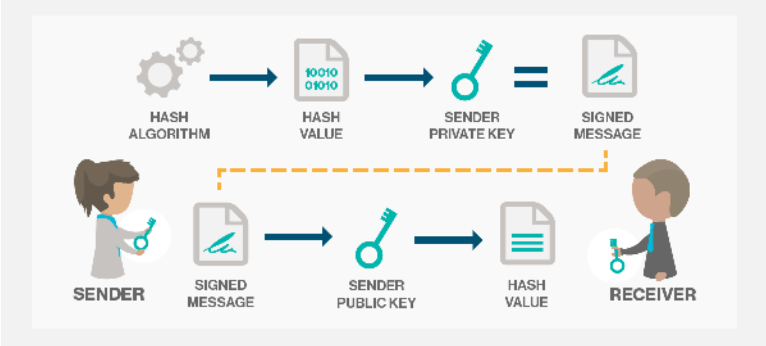

Fig. 2.1: Digital Signature in a Peer-Peer Network.

of voting systems, supply chain management, the security of Internet of Things (IoT), healthcare, intelligent transportation systems, government services and tourism from the viewpoint of BC, and sketches out the research directions in each of these fields. This section forms the major contribution of this article, describing the benefits of using BC in different fields where till date; otherwise, only the traditional technologies were used. Section 4 discusses various challenges that are posed in the way of implementing Blockchain technology in various fields. Finally, section 5 concludes the paper and identifies the research opportunities arising from the challenges in BC.

2. Basic features and functioning of Blockchain. A BC is a distributed, decentralized, shared and an immutable database that holds an encrypted ledger to keep the people involved in it completely anonymous. The fundamental building blocks of BC and their functioning is explained in the following sub-sections:

2.1. Block. It is a collection of all the recent verified transactions. All the transaction details are grouped, and their hash codes are created. These transaction groups along with hash codes are stored in a block. This hash code acts as a specific identification mark for the block. For every verified transaction, a block is permanently added to the BC.

2.2. Miner. Miners are elected as per the consensus algorithms discussed in subsection 2.6, and their job is to verify if a person like James has enough money to transfer. Valid transactions are time-stamped, ordered and packed into blocks [15]. Miners own what are called the supercomputer and solve complex puzzles. For performing their duties, they invest their energy and resources. For their effort every time they solve a puzzle, they get rewarded by the system.

2.3. Peer-Peer (P2P) network. The first thing that is needed to use a BC is a P2P network that ensures complete consistency concerning the BC. In a P2P network, every node gets two keys: the public key and a private key. Nodes sign a transaction using their private keys which ensure authentication, integrity, and non-repudiation; this is explained in figure 2.1. Verification of the received signed transactions are carried out by the peers before they broadcast it further into the network. Public keys, on the other hand, are used to encrypt data which can be decrypted only by the node that has got a unique private key. Hence, there is no scope of fraud in a distributed P2P network.

2.4. Blockchain Types. The type of BC is decided based on its accessibility and permissions available to the user. As a result, currently, BCs are divided amongst public, private and consortium types. Each of the kinds could be open (permission-less) or restricted (permissioned) and are described as:

- *Permission-less Public BC:* Ledgers are visible to everyone on the internet; anyone can join the BC, verify and add a block of transactions to it without requiring an approval from any third party/ validator/ miner. Public BCs are most often open and include examples like Ethereum, Bitcoin, and Litecoin [16].

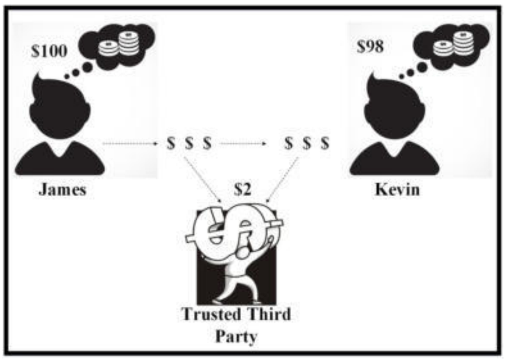

Fig. 2.2: High Transaction fees.

- *Permissioned Private BC:* Only specific individuals from an organization are allowed to verify and add transaction blocks. However, everyone on the internet is generally allowed to view it. Ripple [17] and Hyper-ledger [18] form the typical examples of permissioned private BCs.
- *Consortium BC:* A mix of public and private BCs which allows a group of organizations to verify and add transactions to blocks. The ledger here is either open or restricted to the select groups.

Christine et al. [19] provides a detailed analysis of various barriers and drivers of diffusion related to permissioned and permission-less blockchains using a case study of the Italian wine industry. They also highlight various application domains based on the unique characteristics/ properties of each type of blockchain and how the applications of blockchain can be further enhanced by diffusing permissioned and permissionless blockchains.

2.5. Hash Function used. Secure Hash Algorithm SHA-256D employed by crypto-currencies like Bitcoin and Namecoin, SHA-256 used by Ethereum, and Scrypt utilized by Litecoin, and Dogecoin represent the most famous of all the hash functions employed in BC applications.

2.6. Algorithms used. A lot of algorithms are needed for the proper functioning of a BC. Various cryptographic algorithms, time-stamping algorithms, consensus, validation and mining algorithms are used by the BC to suit the requirements of different applications.

- *Cryptographic algorithms:* The commonly used cryptographic algorithms in BC include RSA and Elliptic-Curve Diffie-Hellman Key Exchange. They guarantee strong encryption of the ledger for maintaining the anonymity of the users [20].
- *Time-stamping algorithms:* Transactions need to be time-stamped to track changes on the BC. For this purpose, time-stamping mechanisms have to be used. Bitcoin, for example, uses the procedure offered in [21], where the transaction order is maintained by having every timestamp to include the last time-stamps hash code. The procedure makes it hard to add fraudulent transactions to the chain. Other mechanisms used in other crypto-currencies include the ones essayed by the authors of [22, 23].
- *Consensus mechanisms:* Consensus ensures the apt working of BC by making it possible to establish the ultimate truth about the transaction histories. Consensus mechanism refers to the procedure that decides what conditions need to be met so as to presume that an understanding has been reached in respect to the validation/approval of the blocks to be added to the BC [24]. In other words, they help the transactions to be confirmed without depending on a bank or any other third party.

Some of the consensus mechanisms used in BC are listed in table 2.1.

2.7. Basic Financial issues tackled by Bitcoin. Banking systems suffer from major issues like varying interest rates, high transaction fees (figure 2.2) and double spending. Peer-peer doubling spending was such a huge problem that it became the motivation for the development of Bitcoin technology [33]. Current banking systems are prone to double spending where a person can spend an amount two times. Figure 2.3 explains the problem.

Table 2.1: Consensus Mechanisms used in BC.

Consensus Mechanism	**Description**	**Highlights**	**Drawbacks**
Proof of Work based BC (POW-BC)	Assumes that if some node is performing a lot of work for the network, there is less probability that it will attack the network, e.g., miners [15].	Sybil attacks cannot be carried out in POW-BC because the attacker will have to perform extensive computations for forging the identity. These computations are not only complex but also expensive to be carried out by a single individual [25]. Used by Ethereum.	Miners need to prove they are doing work. POW-BCs have fewer through- puts, are expensive, have less scalability, and consume high energy. Are prone to be attacked by miners because they gain dominance [25].
Proof of Stake based BC (POS-BC)[26]	It considers the nodes with greater stake/currency in the network to be the least prying about attacking it [15].	Needs less computation power than POW and utilizes less energy.Requires less hardware. Highest stakeholders validate and create the blocks.	The richest rule the BC, hence unfair. Rich with a motive to destruct the system can do so.
Delegated Proof of Stake based BC (DPOS-BC)	Instead of stakeholders, delegates are chosen to perform generation and validation of blocks [27].	Quicker transactions because lesser nodes perform validation tasks. Any misbehavior by delegates leads to their substitution. Election of delegates brings democracy into the system.	Ownership still rules. Organization of attack is easier because only a few delegates who control the network need to be compromised.
Transactions as proof of stake based BC (TaPOS-BC)	Nodes responsible for the generation of a transaction contribute to network for security [28].	Enhanced network security. All the nodes and not only the bigger stakeholders take part in the consensus.	Requires more hardware and more complexity. More computational energy required.
Proof of Activity based BC (POA-BC)	The validator in all of the POS variations has all the power to commit the crime of double spending. POA is a hybrid consensus algorithm comprising of features from both POW and POS [29].	Unlike POS-BCs that increase the status of nodes which are not even connected to the network, it limits the status if the node does not connect. It rewards only those stakeholders that take part in the network activities. Prevents chances of attack.	Extra power consumption from POW. Ownership problems from POS.
Practical Byzantine Fault Tolerance based BC (PBFT-BC)	It tries to solve the popular Byzantine general problem, explained as the problem of knowing that all the entities allowed to take action are in full agreement before they do so [30]. PBFT considers that not more than 1/3rd of nodes in BC can be nefarious [30].	Selects leaders for each transaction, a selection which is agreed upon by a minimum 2/3rd of all the nodes. Democracy in selection. The block becomes final when nodes in the PBFT system agree upon it. Less energy consumption as compared to POW.	Susceptible to Sybil attacks. High communication complexity of O(n^2).
Ripple based BC	The iterative procedure meant for maintaining the agreement correctness of the network. Transactions are pushed forward in batches to all the other nodes when almost 50% of nodes approve the transaction [31]. Transactions are written on the ledger only when 80% of the nodes approve it [31].	Less latency, attack tolerant, less energy intensive.	List to who you want to reach in consensus with must be maintained properly and if they are broken you will fail in various ways. Ripple is path dependent, i.e., it memorizes the past which increases its memory complexity to maintain the chain.
Tendermint based BC	Bears only up to 1/3rd of the failures, i.e., a block can be passed only if 2/3rd of the validators/BC participants pre-commit it in one round [32].	With the assumption that no more than 1/3rd of validators can be byzantine, Tendermint assures safety. Provable liveliness in a partially synchronous network. Instant finality of 1-3 seconds.	Communication complexity is the same as that of ripple, i.e.,O(n^2). When the tolerance threshold increases, things start to blow up.

Figure 2.2 shows that the third party takes heavy transaction fees of $2 out of the total $100. Also, it is clear from figure 2.3 that without verification from the bank or some other central intermediary there is no way Kevin can know if James has sent the same amount to Paul as well. Bitcoin solves these issues by having:

- *Decentralized Power:* Bitcoin makes any individual entering into the system a very powerful person. When a transaction happens, its information gets broadcasted to all the people that form the BC network or as they say in [34] "Everyone sees everything". As such, the power is distributed and not centralized like banks, which alleviates the problem of single-point-of-failure. The single-point-of failure node is the one which if goes down takes the entire system with it and if it gets hacked, the entire network is exposed to danger.
- *Immutable Transactions:* Financial organizations are prone to assaults. Since BC transactions are immutable and the ledger is encrypted, transactions in BC are secure and valid, if successful [16].

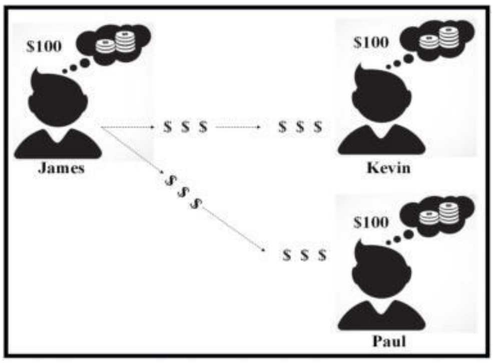

Fig. 2.3: Doubling spending problem.

If a hacker attempts to modify even a single transaction detail, its request gets rejected because everyone in the network has an updated and a valid copy of the block. Consequently, if James sends $100 to Kevin today and then tries to send the same $100 to Paul tomorrow, the transaction will be rejected without having to consult any central intermediary like a bank.

3. Applications of Blockchain in sectors other than Finance. The use of BC outside finance is still in the experimental phase. Some of the most promising non-finance applications of BC include:

1. Voting System.
2. Supply Chain Management.
3. Internet of Things (IoT) Security.
4. Healthcare.
5. Intelligent Transportation System (ITS).
6. Government services
7. Tourism.

These regions are seemingly solid fits for BC. To properly reckon the advantages of using BC in these fields, we analyze the contemporary technologies that are used instead of BC in these areas. These are explained in the following sub-sections.

3.1. Voting System. One of the central pillars of modern democracy is voting [35]. The success of a democracy relies on the level of fairness and reliability of its elections. Electronic voting machine (EVM) tampering allegations and electoral frauds (like inaccurate or invalid votes, multiple registrations, etc.) always surface whenever there is an election season in various countries. This happens because EVM' s suffer from substantial weaknesses like [36]:

- Absence of transparency and auditability of the system.
- Lack of understanding of the system which prompts loss of trust and undermines its entire sense.
- Absence of widely acknowledged standards in voting systems.
- Danger of tampering and fraud by insiders.
- Increased expenses of ballot infrastructure in terms of power supply, communication technology, etc.
- Use of malicious hardware and software [37]. The elections could be maneuvered in the favor of a particular candidate by using techniques like replacing the circuit board with a look-alike, manipulation of the memory unit or manipulating stored votes by vote stealing attacks remotely, etc.

How BC can help: Blockchain-based voting system will bring the following key benefits in voting systems:

- Blockchain-based voting system shall bring auditability to the voter level, i.e., instead of insider officials and specific organizations, voters themselves would be able to audit the e-voting system.
- The voting scheme will have the properties of decentralization and self-management as well. This shall reduce the expense [38].
- The Blockchain voting system will also improve the security of voting; any break-ins into the voting

system can be detected easily.

- Blockchain-based voting systems solve the multiple-vote registration problem by offering only one "votecoin" to an individual who uses his/her private key to access his/her voting right and public key to choose his/her preference. Once this votecoin is exhausted, the vote will be registered in the system after verification by all the blockchain stakeholders. Hence no more voting can be performed by the individual [38].

Literature survey on current work: This sub-section highlights the current work being done on blockchain voting, as well as the progress and challenges of this widespread adoption.

Blockchain based voting frameworks are proposed in numerous papers [39],[40]. [39], proposes a blockchain architecture that advocates a different blockchain to each applicant taking part in the election.

In [40], to improve the security level asymmetric encryption utilizing RSA is performed on the information before it is put in the blockchain. In [41], an E-Voting framework is created utilizing smart contracts. It additionally assesses three diverse blockchain structures, Exonum, Quorum and Go-Ethereum, dependent on how reasonable they are for an E-Voting framework.

Application specific e-voting frameworks utilizing blockchain are additionally proposed in [42], [43]. In [25], a PIN based scheme is used for authentication that is utilized to check the voters and empower them to check their votes after the election process is over. Two distinct Blockchains are utilized to record the votes and the voter IDs of the voters who had made their choice. In [27], a centralized Authentication Server (AS) is utilized to check the voters, and a decentralized, blockchain based Arbitration Server (AR) is utilized to store the votes. BronchoVote [44] is a web-based platform that uses Ethereum Blockchain technology and smart contracts to provide authentication, anonymity and voter verification benefits in e-voting. BroncoVote has been implemented on a university scale. It has also worked on to achieve the voter privacy by making use of homomorphic encryption. Similarly, [45] uses Zerocoin to enhance the anonymity of voters. However, when critically analyzed, [45] has the tendency for centralization and it does not handle exceptions.

[46] presents Shamir secret sharing approach for giving a new definition to cryptic e-voting by using the Blockchain technology. It does not require any middleman to improve the voting processes of auditability and traceability.

Other recent research works include university projects like Voteboook (New York University) [47], Vote-Watcher [48], Openvotebook network (New Castle University), and the proposal of university of maryland [43]. A common limitation of crypto-currency based systems, however, is they are very volatile [49]. A huge monetary risk is involved for the organizer. Tassos Dimitriou [50] has proposed a universally verifiable secure blackchain based voting system with least computational and communication overhead on the voter. The system makes use of a randomizer token (black box representing a voter) for achieving security for each voter. To make the system more secure, author proposes to use a consortium blockchain for the implementation of a bulletin board, but this would require the intervention of impartial observers, thus increasing the overall computational complexity of the system and dependence on third party.

3.2. Supply Chain Management (SCM). The supply chain can range over numerous vertical stages, several horizontal connections, different geological areas, varied financial frameworks, various individual characters and elements included, and with changing chronological stresses relying upon the item and market. These measurements are hard to oversee and normally all the better we can do is make them at first powerful and effective with consistent improvement as an objective [51].

The primal objectives of SCM include the optimal quality, less cost, better speed, risk reduction, dependability, transparency, accountability, sustainability, and flexibility [53]. SCM has taken advantage from another famous paradigm called Internet of Things to achieve these objectives and righteously so IoT did transform this sector by helping in the identification, and tracking of goods using sensors, Radio Frequency Identification (RFID) tags, Global Positioning System (GPS) tags, barcodes, and chips. Nonetheless, it suffers from a lot of problems in identity management, and governance of these goods. The challenges include:

- *Ownership and Identity of IoT devices:* In its lifetime, a device moves from the ownership of a manufacturer to a supplier and then from supplier to a retailer and finally into the dominion of a consumer. Furthermore, if the device is compromised, decommissioned or resold, then the consumer ownership gets either revoked or changed [54].

- *Attribute and Relationship Management of IoT devices:* Attributes of a device can include the manufacturer name, its make, the type, serial number, deployment GPS coordinates, location, etc. In addition to these attributes, they have relationships. IoT relationships may include device-human, device-device, or device-service. The examples of IoT device relationships may include relationships like deployed-by, used-by, shipped-by, sold-by, upgraded-by, repaired-by, sold-by, etc. [55].

Employment of blockchain can easily and securely deal with these challenges with its reliable and authenticated identity management. It can ascertain "who is doing what" and at what time is s/he doing that [56]. The other advantages that blockchain technology can bring into SCM include:

- *Better Performance and Trust Evaluation:* BC technology can effectively and validly measure the results obtained, and evaluate the performance of the SCM process. The moment any SCM input data finds its place on the BC distributed ledger; there is no way it can be changed, i.e., it is immutable. This brings trust among suppliers. The BC procedure also eliminates auditors implying reduction in costs, and increase in efficiency. The suppliers can perform checks on their own processes in real-time [57].
- *Assessment of Quality of Product during its Transportation:* BC solutions can be used to assess the travel duration and paths which can help in assuring the quality of the product. For example, products that require refrigeration must not be held in warm conditions for a long duration. If that happens, their quality is compromised [53]. The BC solutions, therefore, give a sense of security to the consumers who use the products.
- Blockchain advocates transparency, speed, openness and non-falsifiability as the foundations of this new worldview. Blockchain innovation can make it significantly more difficult, if not completely impossible, for unlawful or fake items, for instance, adultered or infringing excipients, or merchandise whose processing is naturally unfavorable to enter authentic inventory chains. It would empower end clients to confirm precisely how, where and by whom the item they plan to buy has been gathered and made, accordingly denying a business opportunity for unlawful and fake items [57].

Literature survey on current work: [51] identified the top motivators and barriers to the adoption of BC technology in SCM. It identifies organizational barriers (lack of knowledge on BC, and dearth of tools and standards to implement BC.), supply-chain linked barriers (paucity of end-user awareness regarding BC technology, lack of supply chain partner collaboration and coordination.), technological (infancy of the technology itself and finite available infrastructure) and external barriers (uncertainty on how market will respond to BC adoption, lack of involvement of industry in BC adoption) as the four major categories of barriers to BC adoption in SCM. It also identified reducing operation cost, increased security and improved information traceability as the top drivers of BC adoption in SCM.

In their work, Mattila et al. [52] investigated the chances of utilizing blockchain to help product-centric information management so as to give an effective engineering to gather information on items over their whole life-cycle. The consolidated utilization of RFID and blockchain is additionally investigated by [58], to empower track and tracking of items in the Chinese agri-food market to upgrade security and quality while decreasing food squander.

Start-ups are using BC for improving traceability [59]. For Instance, an industry partner Provenance started to work with Co-Op, a UK based retailer in 2016 to track fresh foods through its BC based supply chain. An agreement was signed between the enormous retail associations Wal-Mart, IBM, and Tsinghua University in October 2016 for investigating the chances of blockchain in food authentication and supply chain tracking. With this, in March 2017 Walmart became one of the 400 IBM customers testing blockchain innovation. One more striking example of the industry initiative is by the company called Modum.Io (a pilot project initiated in June 2016). The motivation for this project is the monitoring of humidity and temperature measurements of the medical items that do not require refrigeration during their transportation. This information is transferred to the Ethereum BC upon reaching the destination.

Sara et al. in [60] provide a detailed analysis of data (regarding the use of blockchain by various companies) gathered from 173 companies of Association of Supply Chain Management (ASCM). The study helps to understand various barriers for the use of blockchain in supply chain management. The study concludes that there needs to be more expertise regarding the application of BC in supply chain management, increased

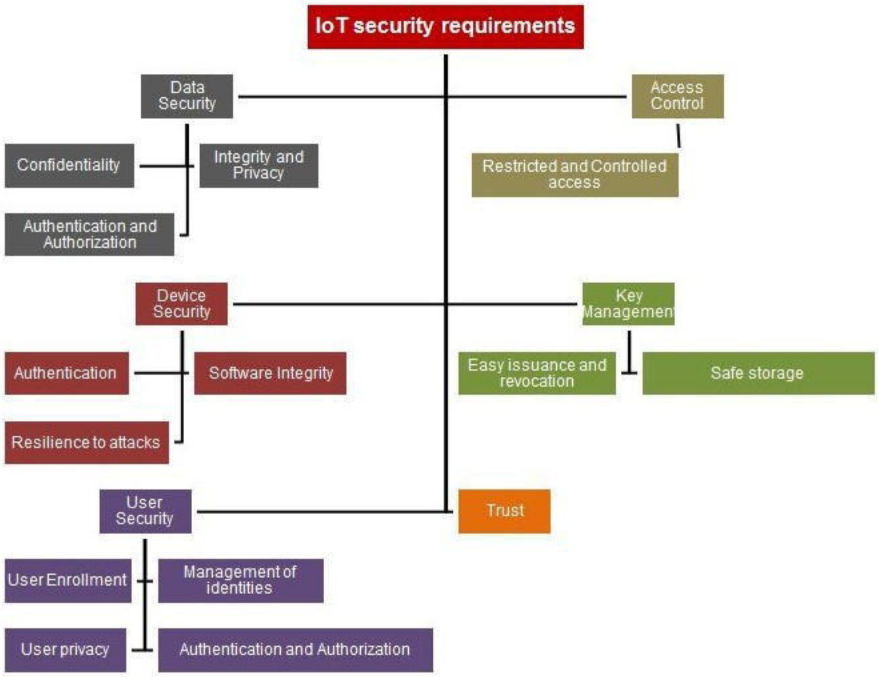

Fig. 3.1: IoT security requirements.

collaboration with the supply chain partners and enhancement of information security.

3.3. IoT Security. IoT is a technology that has revolutionized the world by offering services in almost all domains. On the other hand, presently, IoT devices suffer from a lot of Security and Privacy (S&P) issues.This is because the developers of IoT devices focused mainly on their tempting features and left their security as an afterthought [61]. BCs are computationally expensive and involve high bandwidth overhead, and delays, which are not suitable for IoT devices [5]. The security professionals from all around the world, however, are vouching on the BC to settle down these S&P issues for its peculiar benefits like decentralization, fault tolerance, pseudonymous identities, cryptographic security, authentication, and data integrity [62].

3.3.1. Security requirements for IoT and related work. The parameters that need to be taken care of for ensuring a secure IoT environment are summarized in figure 3.1. These requirements are described as under [55, 62].

- *Data Security:* Since there are no boundaries in IoT networks (data can travel through numerous hops), encrypting the data is extremely important to ensure confidentiality. The devices are highly vulnerable to attacks, and thus an attacker may modify the data to accomplish his/her heinous crimes thus compromising the integrity. Moreover, because of the huge diversity of devices and services, privacy violations could happen by compromising the devices present in the IoT network. To check the work done on the confidentiality in IoT using BC, one can refer to PriWatt [63], Axon et al. [64], Dorri et al. [5], [65], Hardjono et al. [66], IBM Hyperledger [67],[68], Munsing et al. [69], Neha et al. [70], Ouaddah et al. [71], Shafagh et al. [72], Tourancheau et al. [73],Guan et al. [74], Mettler [75]. End-end security, optimized for IoT data requirements is provided by a lightweight and scalable BC mechanism offered by the authors of [76]. This instantiation allows the nodes that have high resources to manage the network. The public blockchain is maintained by the cluster heads to make the system distributed.
- Authentication and authorization of the systems are equally important. While authentication spots “who is who?” authorization establishes “who can do what?” An IoT security mechanism must be

able to perform both. Given the huge number of available IoT architectures, it is crucial to ensure that a standard global protocol for authentication and authorization is established for IoT. Ghuli et al. [77], Hashemi et al. [78], Huh et al. [79], AuthCoin [80], IBM Hyperledger [67],[68], Wu et al. [81], English [82] have proposed various authentication and authorization techniques for IoT devices using Blockchain.

- *Access Control:* There is a whisker between access control and authorization. An Access Control System (ACS) makes sure that any specific node has all the essential requirements fulfilled for it to claim the right to be authorized. It certifies that a particular node falls within the bounds of a local network while as authorization assures that a node is good enough to access it. In [78], the authors have designed a system that allows users to give access to their data by issuing tokens. The Chain-anchor [66] architecture offers commissioning of the resource-constrained IoT devices into cloud systems using a permissioned Blockchain. [5],[65] also propose an access control mechanism for IoT devices by creating an access control list stored in the header of BC. Since, multiple parties like manufacturers, users, operating platforms, etc. are involved in IoT, it becomes imperative to establish a collaborative trust amongst all of them. This is made possible by the IoT passport framework proposed by the authors of [83]. IoT passport is a decentralized trust framework that includes BC based authorization, authentication, and trust as its foundation stones.
- *Device Security:* The devices used in any IoT environment are prone to be compromised as they are usually deployed in public places, and essentially lack the inherent capability to include security themselves. Hence, it is important to ensure device authentication, its software integrity, and its resistance to any hardware or software tampering. Jason and smart contract based security policy has been proposed in [84]. The authors of [61] have orchestrated a multi-faceted solution called Neuromesh to IoT device security using the Bitcoin protocol. Neuromesh is able to identify and remove any IoT device malware, and blacklist any suspicious IP address to allow secure communications.
- *Key Management:*Efficient key management is essential in IoT that allows safe storage, an easy revocation of compromised keys and updating of old ones as and when necessary. In [62], the researchers have proposed a scheme called "blockchain based distributed key management architecture (BDKMA)". It uses BC technology to fulfill the decentralization, auditability, and high scalability requirements, as well as the privacy-preserving principles for hierarchical access control in IoT.
- *Security of User:* User security is a pivotal requirement for establishing the holistic security of IoT networks. It shall include the identity management of users, their enrollments, authentication, authorization, and privacy. The security of user has been discussed in papers like [66],[85] and [86].
- *Trust:* All the nodes of the system should have a certain degree of trust on each other. This trust must be established both ways, i.e., a higher level node (fog/cloud node) must be sure that the device sending it the data or asking for its services is legitimate while as the IoT devices must also establish that the node (cloud/fog) to which they are sending their data is secure. The current work on BC in this field include PriWatt [63], Axon et al. [64], Bahga et al. [87], Herbert et al. [85], IBM Hyperledger [67],[68], Nehai et al. [70], Zhang et al. [86], English [82], Mettler [75].

3.3.2. Categories of IoT Security Issues. The security issues of IoT paradigm could be categorized into three levels: Low-level, medium-level and top-level security issues for the reason that these IoT devices range in their functionality, and size from simple processing chips to huge high-end server [55]. The IoT security issues are summarized in Table 3.1.

3.3.3. Blockchain Solutions to these Issues. IoT's security and privacy issues could be resolved by taking advantage of BC benefits listed in figure 3.2.

The decentralized operation of BC along with its immutability offers a perfect solution for IoT systems that operate in highly vulnerable environments [62]. In table 3.2, we explore the additional advantages that BC-based IoT architecture would bring to the IoT's S&P. It gives a comparison between cloud-based IoT systems and BC-based IoT systems.

Blockchain offers a 160-bit address space [108] and therefore can generate an address for almost $1.46 * 1048$ IoT devices. This reduces the address collision probability as it provides 4.3 billion addresses more than IPv6. This makes BC a more scalable solution for IoT than IPv6 [55]. Moreover, most of the attacks on IoT devices

Table 3.1: Security issues prevalent in IoT.

Security Issue	Level	Description	Reference
Jamming	Low	Wireless IoT devices are targeted by degrading the network. Jamming of channels is performed by emitting radio frequency signals without following any standard protocol.	[88, 89]
Insecure Initialization	Low	When the IoT network is not initialized properly at the hardware layer, privacy violation and disruption of various network services can happen.	[90, 91]
Sybil	Low	Sybil nodes are defined as the ones that use fake identities to bring down the functionality of a network. At this level, Sybil nodes deplete network resources and starve the legitimate devices from using them.	[92, 93]
Insecure Physical Interface	Low	If the software that gives physical interface is insecure, its weakness could be used to target nodes in the network.	[94]
Sleep Deprivation	Low	These attacks cause the IoT nodes to always remain in the “wake-up-state.” This causes unnecessary battery drainage.	[95]
Replay Attack	Medium	IoT networks follow the 802.15.4 protocol which gives a Maximum Transmission Unit (MTU) of 127 bytes. This makes fragmentation of IPv6 packets mandatory. Their re-assembly consumes resources. Hence, if replay attacks are launched, extreme resource wastage can happen. Moreover, the processing of legitimate packets will be affected.	[96, 97]
Buffer Reservation Attack	Medium	For re-assembling the fragmented packets, the IoT receiver nodes maintain some buffer space. This attack depletes that space by sending incomplete packets leaving no space in the buffer for the actual ones.	[97]
Sink-hole Attack	Medium	The attacker node quickly responds to the routing requests for luring the sender to route all its packets through it. It then performs its malicious activities.	[98, 99]
Transport level end-end Security	Medium	It ensures that data is received in the exact form and shape by the receiver as sent by the sender.	[100, 101]
Session Management	Medium	If the transport layers session is hijacked, it can result in Denial of Service (DoS).	[102, 103]
Constrained Application Protocol (CoAP) Security with Internet	Top	CoAP is a web-transfer protocol which is vulnerable to a lot of attacks and therefore requires: Encryption for securing the communication. Efficient key-management and authentication procedures for its multicast support.	[104, 105]
Insecure Interface	Top	IoT services accessed through mobile, web, and cloud will be prone to multiple data privacy attacks if the interface is insecure.	[94]
Insecure Firmware	Top	The codes written in languages like TSON, XML, XSS, etc. require proper testing. The updates need to be performed securely.	[94]

Table 3.2: Advantages of BC over Cloud based IoT architectures

Comparison Parameter	Cloud IoT	Blockchain IoT
Architecture [62]	Centralized.	Decentralized.
Trust [106]	Put on the cloud.	Distributed in the network.
Existence of single-point-of-failure [107]	Yes.	No.
Mutation [34]	Data manipulation is possible.	It is immutable.
Data Sharing [62]	Un-authorized data sharing is possible.	Access control is user defined based on smart-contract technology.
Cost [62]	Expensive.	Less-expensive.
Transparency [62]	The Users have no idea about the way intra-cloud transmission happens.	An unforgeable log of transmissions and events is created and maintained.
Latency [55]	High latency, hence it is unsuitable for applications demanding quick responses.	Offers edge devices to store data and perform computations, hence producing quick responses.

are launched because of their memory and other resource constraints. Running an IPv6 stack becomes an additional liability.

Sybil and spoofing attacks are launched when the attackers use pseudo-identities. The creation of Sybil identities could be restricted only by the incorporation of a strong trust relationship [55]. There is an inherent trust in the BC because of its distributed power, and decentralized control. BC is typically popular for its reliable and authorized identity registration, ownership tracking, and monitoring of items [55].

Attacks on buffer and session managements could be prevented by blockchain's data authentication and integrity. The data sent by the IoT devices in a BC at all times remains encrypted as well as signed by the

Fig. 3.2: Blockchain for IoT

original sender, who holds a unique public key, and its unique identifier. The attacker can neither use his/her signature; nor can take anyone else's identity. Hence, these attacks could be avoided.

The protocols widely used in IoT environments like Routing Protocol for Low-Power and Lossy networks and IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) need a security wrap from other protocols such as DTLS and TLS for messaging because they are not inherently secure. Likewise, for routing RPL and 6LoWPAN need a wrapping from IPSec. All these protocols, i.e., DTLS, TLS, and IPsec are heavyweight and complex in terms of memory needs and computational requirements [55]. Their complication comes from the central management and governance of key management and distribution that uses the famous PKI protocol.

BC offers secure communication in the manner that it eliminates the need to have any key management and distribution procedures which bring up security issues in IoT networks. In BC, every IoT device gets an asymmetric key pair and a Global Unique Identifier. As such, the messaging protocols DTLS and TLS would not require the exchange of PKI certificates in the handshake phase.

3.4. Intelligent Transportation System (ITS). The manner in which the Internet of Vehicles (IoV) connects vehicles with each other and the Road Side Units (RSUs) brings peculiar security challenges into the picture [107]. The black-hats can hijack a vehicle, which can result in compromising passenger safety, endangerment of the public property and putting at-risk the life of others on the road [109]. For example, an attack was launched by the white-hats Miller and Valesek on the vehicle infotainment system to remotely control its functions [110]. Also, the vehicles share some critical information with each other which if hacked brings about privacy issues.

Table 3.3 analyzes the issues with the classical Security and Privacy (S&P) methods that are used in smart cars and why they remain ineffective to solve them. It also sketches out how BC can achieve the same purpose effectively.

Literature survey on current work: Ensuring the reliability of messages exchanged between vehicles is a major challenge in ITS. Motivated to address this concern, Yang et al. [111] designed a BC based distributed trust management scheme for ITS. Experimental results demonstrate that the proposed system is efficient and practical for facilitating trust in smart vehicular systems. Similarly, authors in [112] proposed a BC based system for ensuring secure and trusted communication between vehicles in ITS. Simulations show that the

Table 3.3: Comparison of Conventional and BC-based methods in Smart cars.

Parameter of Comparison	**Conventional S&P Approach**	**Benefits brought about by BC**
Architecture [107]	Centralized, and non-scalable.	Decentralized, and scalable.
Participation [107]	Partial, not all devices contribute to S&P.	End-End participation.
Privacy [109]	Lacks privacy. Driver's privacy can be at-risk because of a direct link between the vehicle, and the Original Equipment Manufacturer (OEM).	Privacy assured.
Verification of activities [107]	Performed by OEM	Events publicly verified.
Integrity [107]	Data exchange is insecure which compromises integrity.	Secure and privacy preserving exchange of data is ensured.
User control [107]	No control can be exercised by the user over the data exchange.	The user enjoys full control and transparency over data exchange.
Payments and accounting [109]	Centrally controlled.	Payments and accounting have distributed security, and happen privately.
Tracking of customer [109]	Both location and behavior could be tracked.	Information about location and behavior remains private.

Table 3.4: Comparison of traditional and BC-based methods in Healthcare.

Parameter	**Traditional Systems**	**BC Systems**
Management [118]	DDBMSs are intrinsically centrally managed. The applications requiring independent control over the repository cannot function.	Every node runs independently of others, i.e., they are decentralized. Gives full independence to applications.
Mutability of audit trail [119]	Traditional systems only offer functions like create, read, delete, and update which makes them prone to mutation attacks.	BC systems allow create and read functions, making them feasible for recording critical information that requires immutability. BC guarantees that nobody, neither a doctor nor the patient her/himself can change the records.
Data provenance [120],[121]	Administrators enjoy the power of shifting the ownership of digital assets. The assets cannot be traced, i.e., data records cannot be confirmed. No way to deny false records.	Only the owner can modify the ownership credentials and that too by following the standard cryptographic protocol. Assets can be traced. Records are always signed by the source. False records are denied.
Reliability [34]	No single-point-of-failure, since DDBMSs are distributed.	No single-point-of-failure.
Availability [34]	To maintain entire histories of records, DDBMSs become costly.	BC offers continuous access to and availability of data.
Security and Privacy [122], [123]	No security mechanism is employed. BC utilizes 256-bit Secure Hash Algorithm (SHA) for assuring anonymity and privacy. Here every user gets a unique hash value instead of an IP address.	BC uses 256-bit elliptic-curve-digital signature algorithm for ensuring data integrity in the form of digital systems.

study was able to resolve three major challenges: authentication, trust, and validation in ITS. In [113], authors designed a distributed framework for efficient key management in ITS. Simulations conducted in the study reveal that the proposed framework provides better flexibility than centralized Key Management Schemes. Dorri et al. [107] proposed a decentralized BC based architecture in order to ensure user privacy and safety of smart vehicular systems. Due to the privacy concerns in ITS, the users are reluctant to forward traffic announcements. To this purpose, the authors in [114] proposed CreditCoin, a BC based system that encourages the users to share their traffic information. Experiments carried out in the study demonstrate that the proposed system is efficient and easy to implement. Qilei et al. [115] designed a BC based ITS that gathers information about the traffic conditions and detects accidents. Cebe et al. [116] designed a BC based forensic framework called as Block4Forensic to resolve a dispute while investigating accidents. The framework resolves the dispute by involving the crucial factors like conditions of the road, details about manufacturing company and maintenance centers, other vehicles, etc. Performance analysis conducted in the work reveals that the framework is effective for dispute resolution. Rajat et al. [117] proposed a BC based framework for efficient and secure energy trading in electric vehicles. Performance evaluation carried out in the study demonstrates that the proposed framework is effective and resource-efficient.

3.5. Healthcare. Majority of the developed countries spend more than 10% of their GDP on their Healthcare systems [124].The systems that were traditionally used for healthcare applications include Distributed Database Management Systems like Oracle [125], and Apache Cassandra [126]. The key advantages offered by BC over these are tabulated in Table 3.4.

Moreover, the Blockchain offers solutions to contain all the properties that the health data of an individual must display. These include:

- Right from the time a person is born, his/her entire health, disease, and treatment information must be summed up in it. BC is an affordable gateway to store redundant information/histories of data which if recorded with any other technology becomes costly [34].
- The data must strictly adhere to the procedures of security like anonymity, confidentiality, integrity, etc. The BC is inherently designed for offering these security advantages [123].
- It must include only one instance of truth. Multiple instances of truth cannot exist in BC, as any record that finds its place in the distributed ledger of BC goes through a complicated verification procedure [120, 121]
- The down-time of this data must be zero.
- It must remain strong against attacks. BC is more secure in comparison to its contemporary technologies in healthcare [122, 123].
- It must rebound easily, i.e., if the owner loses her/his key, they must be able to make access to the same. BC data is always available [34]. Moreover, its transparency feature will allow for this rebound to happen quickly.
- The data must be ubiquitous. Public Blockchains will make the data ubiquitous.
- The views of health data should be distinct for different players.
- It should be immutable. The BC's foundation is laid on this feature [119]-[123].

Literature survey on current work: By designing a BC based healthcare data gateway, the authors of [119] have tried to mitigate the user privacy issues that arise in healthcare data. Privacy is the focal point of establish who and whom should be given access to patient's health data [127]. Similarly, the authors of [128, 129, 130] have given solutions to enhance the security of patient's health data which is otherwise prone to misuse.

Some of the most famous blockchain based initiatives that have been taken for managing electronic heath records include the names like Medric [131], Patientory [132], HealthSuite Insights Philips Healthcare, Medshare [133], Iryo, Gem Health, FHIR Chain [134],OMNI PHR [135], Medicalchain, Doc.ai and Hearthy [136].

Similarly, The BC based projects that are focused on genomics include Factom, Encrypgen, Nebula Genomics, lunaDNA, Zenome, Genomes.io and Shivom [136].

ETDB-Caltech [137], Patel et. al 2018, OPU Labs, MedX Protocol, Dermonet [138] are the examples of BC based initiatives in the field of dermatology. The BC based projects initiated in the direction of managing pharmaceutical supply chain solutions like track and trace regulation, track of temperature, humidity, etc. of the pharmaceutical products, and bringing transparency in trade records, include Mediledger project, Ambrosus, Modsense T1, Blockverify, DHL collaboration with Accenture, Authentag, Hejia, GFT collaboration with MYTIGATE, and IEEE pharma supply BC forum [136].

For prescription management, BC initiatives like BlockMedx, Project Heisenberg, ScriptDrop,and ScalaMed [136]. BlockMedx Allows a pharmacist to verify the prescription issue by the doctor by accesing the created immutable BC. Project Heisenberg manages the prescription process by giving different portals to doctors, patients and pharmacists. In ScriptDrop authors have worked to deliver the medicines at the doorsteps of the patients, relieving their burden of visiting the pharmacies once the prescription is issued. ScalaMed offers a patient-centric model for managing this process. ScalaMed keeps a track of all the patient's prescription to avoid cases of cross-reactions of prescribed medicines.

The BC based solutions for billing and claim management include Gem, Change Healthcare, HSBlox, Pokitdox, solve.care, Smartillions, HealthNautica with Factom, and Robomed Network [136].

3.6. Government Services. Gone are the days when criminals would crack safes and loot bank vaults. Today governments all around the world face the wrath of cyber-attacks. Tax frauds happen everywhere which hinder the development of nations. BC has the potential to tackle both of these issues [139]. These along with some other use cases and opportunities provided by BC in the government services are discussed in the following sub-sections.

Securing important public infrastructure from cyber-attacks. Every nation's critical public infrastructure is implanted with one or the other digital technology and a significant number of the frameworks are also connected through the internet [139]. This opens them to the likelihood of hacking assaults. The countries that have established strong cyber security defenses can also launch the attacks, and go undetected. For example, it is possible to snatch the control of critical routers, monitor, and manipulate them. This would permit the information from any government association behind routers to be caught. Other cyber-attacks to which the e-governments are vulnerable include malware, DDoS, probes, packet sniffing [140]. The motivation for launching these attacks could be to bring political differences, extortion, race for supremacy, and cyber-terrorism [141].

Additionally, as several other digital technologies are incorporated in public infrastructural frameworks like railways, bridges, flood channels, and energy establishments, the possibility that such assaults could cause loss to property and human life increases substantially.

How BC can help: BC's distributed ledger characteristic can make sure that the software and other firmware embedded on the infrastructure has not been meddled with. It can moreover track the state and integrity of the firmware for ensuring integrity and protection of human life.

Financial frauds suffered by the governments. The government departments face issues like [142]:

- Monetary losses because of errors and frauds.
- Problems in efficient policy delivery and complete financial inclusion of poverty-stricken people.
- How to put the public money on a sustainable footing.
- Verifying the true identities of users.
- Problems in the distribution of international aid in the conditions of crisis.

How BC can help: BC can help to tackle these issues in the following manner:

- BC can offer full financial inclusion to people who cannot afford the inclusion barriers like heavy transaction costs, access to customary financial products, etc. BC can include the people easily and in an affordable manner into the benefits system.
- BC will make the forgery of identities extremely difficult and almost impossible [143, 144]. It has the intrinsic building characteristic that it can verify the identities of users through distributed ledgers that run on extremely secure devices. This will slash the level of fraud and errors that are issued in the delivery of benefits.
- The tax-payers can easily check how their money is being invested by the government in the BC-based systems.
- BC's distributed ledgers have no boundaries based on geography, i.e., their modus-operandi remains the same in any part of the world. This feature can offer great relief in removing the bureaucratic hurdles of classical banking systems as the international donors can donate coins. This will not only ease the suffering one faces in sending money overseas but also reduces the international aid exchange fees [145].
- Moreover distributed ledgers can curtail the cash fungibility, i.e., the property of an item whose single units are indistinguishable and have the same value.
- BC solves the problem of double-spending which in the case of international aid reception or tax reception is important to avoid.
- BC's distributed ledger can trace how the currency has been spent and by whom [139]. This assures the aid being spent on purposes other than for which it was provided.

Integrating the resources of a decentralized nation. China, for example is a massively decentralized nation from the perspective of responsibilities and resources given to the local governments [146] which makes the integration of its resources a hurricane task.

How BC can help: Blockchain records every transaction which makes it simple to track the parties that approve transactions and comprehend the extent of the exchange. It additionally implies that information can be all the more effectively and securely moved between various associations, in this manner advancing the incorporation of data among various associations. Moreover, the BC technology primarily relies on a consensus mechanism for its working. This implies that decentralized governments can choose entities that can make additions to a particular BC using a consensus mechanism, thereby developing trust among these entities, and integrating their resources on one platfor [146].

*Literature survey on current work:*In 2016, the government of United Kingdom affirmed the Fintech startup Credits to be the provider for Blockchain innovation for government organizations, and endorsed the utilization of Block-as-a-Service [147]. The motivation for this adoption was five-fold [148]:

1. for protecting the public infrastructure,
2. It could lead to the development of secure payment frameworks for work and pensions,
3. Reinforcement of international aid systems,
4. document verifications,
5. Managing European VAT system.

Similarly, Dubai government along with some other private entities has established a council called Global Blockchain Council that integrates elements from government, local and international startups to boost the BC technology with various experiments [147]. The authors of [149] have proposed a BC based e-government framework for bringing security and privacy in the operation of various public sectors. Grech et al. illustrate in [150] how BC could be employed in the national identity management systems. However, proper implementation of the proposal has not been given. [151] have described the self-sovereign digital Id system of Canada that is based on BC. However, again no evaluation criteria have been used. [152] suggests the replacement of the bureaucratic government with a BC based government for transparency.

3.7. Tourism. As per the world travel and tourism council's annual report for 185 countries and 25 regions, Tourism industry has contributed a whopping $8.8 trillion to the global economy in the year 2018 [153]. The report published that the industry reckoned for 10.4% of the global economy, 10% of total employment, 6.5% of global exports, and 27.2 % of global service exports. The economic impact of travel and tourism for the year 2019 marked a 3.9% increase over 2018, giving a boost of 2.9% to the total global economy [153]. The Internet has abled the tourists to book their products and other travel related requirements online [142]. From the literature review, it is observed that since the time blockchain caught worldwide consideration in 2017, its potential adoption has progressively changed different ventures. Among these areas, the tourism industry right now leads in blockchain investment [154]. The following sub-sections describe the issues present in the tourism sector and how BC can help to alleviate them.

- Online customer reviews about their travel highly clout the buying choices of tourists. Amateur tourists especially consider the online reviews to be the sincere sentiments of genuine travellers [155]. However, the reliability of these reviews cannot be ascertained completely as there can be the manipulation of centralized systems handling these reviews by hotel and restaurant owners as well as by the customers.
  How BC can help: For having fair reviews, BC can provide a common rating and audit framework that provides reviewers with traceable identities. This, however, does not require giving up the anonymity but that all entries are marked with a private key that is unique to every specific user. Subsequently, tourists would be unable to make duplicate reviews with one identity. Also, nobody will be able to change their reviews ex-post.
- Buying and selling of tourism-related products involve the exchange of money between parties who do not know each other beforehand and money transfers across country borders. To establish trust in these situations, intermediaries are used who charge commissions.
  How BC can help: Bitcoin and other crypto-currencies do not require any third party for money exchange. This empowers the development of new types of client-client exchanges for tourism items.
- Heterogeneous payment gateways are used to pay for availing tourism services. Such gateways in turn open the gates to malicious users for launching attacks like hacking into wallets, theft of identities, attacks on payment clearance cycles, etc. [156].
  How BC can help: Blockchain offers a decentralized architecture for payments that establishes reliance and reputation management among the various parties involved in the tourism industry like, banks, travel agencies, hotel, cabs, etc. [157].
- The market power of Online Travel Agencies (OTAs) and Global Distribution System (GDS) are the intermediaries whose removal is a must from the tourism supply chain [158] for the reason that they encourage the custom of commission and move the market according to their whims, and wishes. The powerful members of the GDS formulate rules and fees that every small tour operator has to comply

with to be competitive.

How BC can help: BC is an open source and decentralized platform which has the potential to do away with these intermediaries. Examples of BC-based online tourism platforms include HotelP2P, and WindingTree [159].

- Small Island Economies (SIEs) are exceptionally reliant on the tourism industry as a critical supporter of their economic development. However, their economic development is encroached by various external financial and ecological factors, their small size and insularity [154]. To beat these inherent difficulties, SIEs need to assemble strength, diversify their economy and create the tourism schemes that encourage economic development [160]. Such an opportunity will be provided by the adoption of blockchain innovation.

  How BC can help: Aruba, a small island economy is building up a blockchain platform to permit local companies to directly associate with tourists, accordingly recovering loss revenues from the monopoly of foreign agencies [154]. While, the Caribbean Tourism Organization is elevating crypto-installment to help the travel industry [154].
- The other tourism related challenges which can be tackled by using the inherent characteristics of BC include the avoidance of overbooking , coordination among hotels and transport systems, assistance in baggage tracking, and verification of travel ID's [156].

Literature survey on current work: [156] proposed a BC based framework called BloHosT (Blockchain Enabled Smart Tourism and Hospitality Management). BloHost uses a single crypto currency enabled application to register the tourists as well as the various tourism stakeholders. For interoperability, it uses smart contracts. Onder and Treiblmaier proposed in 2018 [142] three propositions about blockchain in tourism industry that would bring a completely new look to the tourism industry. Firstly, new forms of evaluations and review technologies will eventually form reliable rating systems; secondly, the extensive adoption of crypto-currencies will pave way to the development of new C2C markets, and finally the BCT will lead to increased disintermediation in the tourism industry. They have argued that answers to these propositions would bring a new look to tourism industry in blockchain perspective. In [161] Leung and Dickinger have dissected how European explorers use Bitcoin as a digital currency to buy tourism products. Besides eliminating the intermediaries, their system offers an uninterrupted service along with the safety of data via immutable encryption. In their work [162], authors have tried to relate the trust in blockchain with the trust in tourism. Pilkington and Crudu [163] have taken a shot at how blockchain can be utilized for diminishing poverty in a poor nation like Moldova with the tourism 2.0. They have contended that because of the high corruption rate in Moldova, there is a requirement for trusted systems. The researchers have exhibited that the immutable nature of blockchain can help mitigate destitution with the tourism 2.0 by wiping out defilement issues in Moldova.

4. Challenges in the way of total realization of Blockchain. To gain a holistic view of the strength of Blockchain technology, it is imperative to discuss the challenges that need to be overcome for its successful implementation in these key areas. This section puts a stress on the limitations of the BC technology.

The first problem area will be the harm to privacy. Bitcoin transactions may be allied to user details which can then be associated to IP addresses, suggesting a lack of anonymity for users. The likelihood of a loss of privacy could undermine the general protection of blockchain infrastructures. Online voting systems, for example, place excessive value on security as a main blockchain property, both to protect voters and to ensure the correctness of the election result. The second problem in the paradigm of voting emerges in the consensus algorithms used in BC with regard to speed and energy consumption. Bitcoin's PoW has an estimated energy intake of 45.8 TWh per annum, according to [164].

The challenges that a company which wishes to adopt Blockchain for improving its food supply chain must overcome relate to the development of smart contracts and endorsement policies, channel configuration and data management. A paper contract consists of different clauses. In order to define constraints for a data model, these contractual clauses can be defined by textual language. These constraints can later be converted into a more formal language. For a smart contract, they can even be translated into code. Once the constraints are in a formal grammar, they can also be tested for consistency, completeness and accuracy using software tools. Blockchain ledger is a database of historical transactions [165]. Mapping a supply chain process into a series of successive transactions that are conducted in an ordered sequence is necessary to incorporate a process on a blockchain system. While intuitive, there are challenges to operationalizing this approach. The terminology of regulatory policies in plain text, in particular, can be very complicated and such policies are not easy to map into an executable language with the right semantics. The need to ensure that the smart contract code represents the parties' intent and contains no inadvertent coding errors is another major concern. However, ensuring that the software code is bug-free is virtually impossible. Danger is thus not completely removed [166]. This is obviously a weakness of the blockchain technology.

From the viewpoint of IoT security, at present, the Bitcoin block size is limited to 1 MB and a block is mined about every ten minutes. Subsequently, the Bitcoin network is restricted to a rate of 7 transactions per second. Thus BC is unable to deal with high-frequency trading [167]. The small block capacity means the delay of smaller transactions as the miners would prefer the transactions with higher fees. However, larger block sizes mean larger storage space and slower propagation in the network. This will lead to the branching of blockchain. This makes scalability a huge challenge. The prime feature of IoT is the multitude of devices, hence, overcoming this scalability issue will be a major challenge.

The integration of blockchain into ITS provides data manipulation security and prevention through its ability to guarantee data immutability. Blockchain cannot however, directly guarantee security and privacy, as blockchain is based on various methods. Some of the techniques are modern cryptographic techniques, pseudonyms, and off-chain storage. That can ensure the security of content within blocks (transactions or records) and the privacy of users and devices [168]. Moreover, the incorporation of blockchain in ITS may involve the ability to manage a large number of data and transactions in a highly complex moving vehicle environment. This is a current blockchain application weakness to accommodate into IoV directly [169]. Therefore, the performance metrics of the blockchain enabled IoV network are as critical as its protection and privacy due to the reliance of massive data and mobility. These matrices of performance include latency, consumption of energy, scalability, and throughput. Collusion attacks could be launched in BC-enabled IoV networks because of the issues in consensus algorithms. The active validators may collude with other false validators in this attack [170].

The important challenges that exist in BC-based healthcare systems include scalability, security and privacy of electronic health records because of the 51% attack, heavy processing power requirement, and huge investment by providers to lay down the BC infrastructure in their domains. Keeping the nodes alive in such a BC-based healthcare system across the nation needs enormous socio-technical changes, and alignments [171]. Moreover, BC applications are created to be HIPPA and GDPR compliant. However, as separate social, economic and healthcare structures would be combined, it is problematic for both the patient and the healthcare provider to lack the legal or compliance code to obey the results of the applications [172].

For adopting BC in government services, in addition to the heavy sustainability costs, complicated, expensive, and extensive software upgrades across all the mining computers in the nation is required. Sometimes, due to the existence of a software error, or anomalies in the blocks of a single user that can cause the entire blockchain to break prematurely, protocol changes cannot roll smoothly. All the users in the network will have to rollback their updates in such situations to maintain continuity in the entire blockchain [173]. Next, it is often difficult to introduce deliberate software protocol changes, and seasoned network users must be vigilant and sometimes forcefully avoid such actions. Another big problem that can occur in BC is the loss of cryptographic keys. If any user loses the public/private key package, is stolen or expires, those blocks cannot be recovered [174]. Also, in the long run, BC will display a poor economic behavior because with time the reward that one will get for mining will be less profitable compared to the extensive resource investment [175]. The Proof of work algorithm is highly susceptible to DoS attacks. Critical government infrastructure will be put at risk. Double spending attacks could be launched if one user gets the control of 33% of network computational resources [176].

In the sector of tourism, the usage of blockchain technology by customers would be restricted to those who are tech-savvy and educated about its process, thus limiting its use to just a small demographic group. In addition, in the event of an unexpected shock to the economy, the lack of regulation over blockchain and cryptocurrencies poses a concern for tax evasion and exchange rate volatility. Cryptocurrency value instability may also pose a danger to market stability for potential tourists [177] . Moreover, given the huge energy consumption of blockchain networks, the environmental cost implications for SIEs would require attention to the production of renewable energy and the related policy reforms [178].

Risk posed by Quantum Computers to Block-chain technology: Block-chain technology uses one-way mathematical functions to generate digital signatures that are required for authenticating the users in the network. These functions are easy to calculate, but very difficult to forge, for the reason that it is extremely hard to calculate the inverse of these functions. However, the advancements in the field of quantum computing are posing a serious threat to the security of block-chains [179]. It is anticipated that in the near future, the quantum computers would be able to calculate the inverse of one-way functions easily, making the encryption using these functions obsolete. Hence, investigating the encryption methods that are hard to break even using quantum computers is highly crucial for the block-chain security.

5. Conclusion and Future Directions. Blockchain is a decentralized, persistent, distributed, immutable, transparent, secure and auditable database technology. Currently, it is viewed as a concept that has tremendous potential to transform the finance industry, but its potential in other areas remains unexplored. In this paper, we examined the integration of BC with seven key scenarios. In each of these scenarios, we highlighted the problems that exist in the classical systems which they use and the solutions that Blockchain technology can provide. We have also highlighted some current issues that require careful analysis and professional research. This research proposes two aspects of the blockchain definition in these sectors at the theoretical level: explicit and implicit. The functional aspects of the blockchain define the explicit dimensions. While most of the scarce research in the field of blockchain is technology-driven, suggesting new protocols and algorithms, attention is not given to the major drawbacks that come with it. This paper in addition to the implicit advantages of using blockchain has highlighted the key challenges that come with its adoption in any of these sectors. It can be used as a guiding torch by the researchers to take up a research challenge in the domain of blockchain. The future directions are given as:

1. *Scalability:* Researchers can shift their focus towards finding a tradeoff between block size and security.
2. *Privacy violation:* According to [180], BC does not assure the transactional privacy maintenance. This is because of the public visibility of all the transaction values and public keys. Moreover, [181] has proved that the Bitcoin transactions carried out by an individual could be served and analyzed to expose the information of a user. Also, a method has been proposed by [182] to attach pseudonyms of users (a key feature of BC) with the IP addresses even in the case when they are secured behind the firewalls or the Network Address Translation (NAT).
   Researchers can go in the direction of finding improvements in the anonymity of BC.
3. *Attacks by miners:* There is a consensus on the statement that if 51% of the computing power of the BC combines, it can reverse the BC and subsequently reverse the successful transactions [167]. Therefore, if the miners become successful in carrying out the collusion attack or otherwise called the 51% attack, the consequences could be heavily dangerous. Moreover, the researchers are vouching on the statement that much less than 51% power is required to cheat in BC [183].
   Other than 51% attacks, stubborn mining [184] where the miners launch network-level eclipse attacks are possible in BC. Researchers can work in the direction of finding approaches to let the honest miners work without just wasting their resources, and in letting them find a BC branch which is neither selfish nor stubborn.
4. *The movement towards centralization:* BC is depicting a trend where miners become centralized in the mining pool. For example, in the Bitcoin network [185], only the top 5 mining pool own more than 51% of the entire hash power.
   Since the BC's strength lies in its decentralized architecture, this trend has to be stopped and for that methods need to be proposed.
5. *Smart contract attack analysis:* Smart contract is a fragment of code that can be automatically executed by the miners. If this code is tampered with, even with a small bug, disastrous damage can happen. An example is the loss of $60 million by the recursive call bug in the DAO- Smart contract.
   Researchers need to focus on the analysis of smart contract attacks.

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A REVIEW OF DESIGN APPROACHES FOR ENHANCING THE PERFORMANCE OF NOCS AT COMMUNICATION CENTRIC LEVEL

MISBAH MANZOOR,* ROOHIE NAAZ MIR,† AND NAJEEB-UD-DIN HAKIM‡

Abstract. As the trend of technology shrinking continues a vast amount of processors are being incorporated in a limited space. Due to this almost half of the chip area in Multi-Processor Systems-on-Chips (MPSoCs) is under interconnections, which pose a big problem for communication. Network-on-Chips (NoCs) evolved as a significant scalable solution for removing wiring congestion and communication problem in MPSoCs. NoCs provide the advantage of customized architecture, increased scalability and bandwidth. NoC is a structured framework where communication is the prime concern. In this review paper we present an overview of research and design approaches in the communication centric areas of NoCs. Here we have tried to discuss and iterate most of the available work done for communication in 2D NoCs. This paper gives the insight of different attributes and performance parameters of NoCs. Further it gives a detailed description of how topology, flow control and routing mechanisms can affect the qualitative aspects (performance) of NoCs. It then explains how various attributes of routing can help in increasing the efficacy of NoCs. Subsequently a brief review of different simulators used for NoCs is given. All of this is provided based on the survey of academic, theoretical and experimental approaches presented in the past. Finally some suggestions for future work are also given.

Key words: Network-on Chips (NoCs), 2D NoCs, Performance, Throughput, Latency

AMS subject classifications. 68M10

1. Introduction. As the trend of Moore's law continues, hundreds of billions of transistors are getting incorporated on a single chip. As a result of this the count of transistors and processors on chips is soaring tremendously. This decreased the scalability of buses and posed various problems. Buses caused wiring congestion and delays, due to which communication suffered [1]. As such shared buses were replaced by multiple bridge buses and then they further by crossbars, but still communication demands of growing multi-chip designs could not be met. With the exponential rise of components and IPs, the communication infrastructure began to crumble. Communication in Multi-Processor System on Chips (MPSoCs) became a much costly asset than computation. Hence new communication architecture was needed and thus Network-on-chip (NoC) was welcomed. NoCs enhanced communication and provided higher bandwidth. NoC eases the communication design for System-on-chips (SoCs) as it gets rid of earlier congested and complex communication structures [2]. Table 1.1 shows the qualitative advantages of NoCs over earlier conventionally used buses. As can be seen in Fig 1.1, NoC is made up of building blocks namely routers (which implement routing algorithm), links (which make physical connection between routers), network interface (that connects core and network), processing element (functional blocks which run some application). Each router is connected to a processing element and its neighboring routers through links. The data flows over the links through routers to reach the particular destination. NoC's performance is characterized by different parameters. These parameters are briefly discussed below:

1. *Latency:* It is the time in which a packet goes from source to destination in a network. In other words it is the time frame from the packet generation and packet arrival at destination. Latency depends on topology as well as routing. A network should have lower latency for better performance.
2. *Throughput:* It is the rate of successful arrival of packets to a destination for a certain traffic pattern. It means how many packets are received in a particular simulation time. It is used to measure the

*Department of Electronics and Communication, National Institute of Technology Srinagar, India (misbah@nitsri.net)
†[2]Department of Computer Science and Engineering, National Institute of Technology Srinagar, India (naaz310@nitsri.net)
‡[3]Department of Electronics and Communication, National Institute of Technology Srinagar, India (najeeb@nitsri.net)

Table 1.1: Qualitative Advantages of NoCs over Buses

S.No	Parameter	Bus	NoC
1	Scalability	Less	More
2	Throughput	Less	More
3	Frequency	Less	More
4	Gate Count	More	Less
5	Power	More	Less
6	Area	More	Less
7	Energy Efficiency	Less	More
8	Testability	Less	More

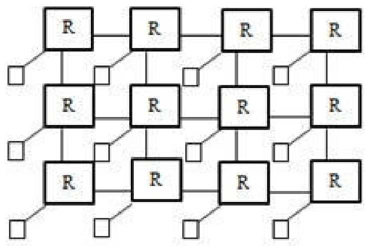

Fig. 1.1: Basic 2D Mesh Network-on-chip

performance of entire NoC network. Maximum throughput is calculated when maximum channels get saturated in a network. A network should have high throughput for fruitful performance.

3. *Adaptivity:* It is the property through which packets can take different routes to reach the same destination. It is related to path diversity. More the number of paths to a particular destination more adaptive the routing can become. Adaptivity helps in balancing load in a network. It also provides fault tolerance. This is because there can be multiple paths to reach destination by avoiding the faults. A network should have more adaptivity for good performance.
4. *Power Efficiency:* It is the property of reducing power consumption in the network. It can be done at different levels in NoCs but usually it is done at router architectural level as it consumes more power. A network should consume low power and should be energy efficient.
5. *Fault Tolerance:* It is the network's ability to perform its intended function in presence of faults. Faults can occur either at links or nodes or cores. Fault tolerance deals with successful operations even in presence of breakdowns in the system. It is closely related with reliability. Greater the fault tolerance more reliable is the network. A system should have high fault tolerance.

1.1. Contribution and Structure of Paper. In the previous year's many survey papers have been presented. They are very useful in understanding the NoC's communication architecture and working. But there is still a lack of broad review in the communication centric areas of 2D NoCs. The main aim of the communication centric design approach is to be able to achieve greater design productivity, performance and reliability. So in order to enhance this vision, we are providing an extensive overview of research and design approaches at the communication centric level in Network on chips. This research will help the researchers to get a clear perspective of how to enhance the performance and productivity in NoCs.

We have organized our survey as follows. Section 2 presents the related work. Section 3 introduces the communication centric areas of NoCs (Topology, Flow Control and routing). It discusses different attributes of topology and different types of topologies. Further different flow control schemes presented in the past are discussed. Then routing along with its attributes is introduced and discussed. Different types of routing and their impact on certain important aspects of NoCs such as adaptivity, power, area, fault tolerance and performance of NoCs is presented. Section 4 presents and compares different simulators used for NoCs. Lastly section 5 concludes the paper and presents some suggestions for future work.

2. Related Work. The authors in [3] presented a paper in which they discussed the performance of wires in scaled technologies. According to them under technology scaling total number of wires were growing exponentially, global wires posed serious problems to designers, as they do not scale in length. The delay across these wires remained constant. The effect of wire capacitance, resistance and inductance was described in detail. Finally they suggested that new structured communication architecture was needed. Then a new concept was introduced, which is considered as the base for understanding network on chips. It laid emphasis on routing packets rather than wires [4]. According to authors routing packets will simplify the layout and structure. It will also increase the performance and modularity. They said that topologies must balance power efficiency with wire utilization. They also explained that a well-developed network interface is essential for high performance. The survey presented in [5] stated the problems of earlier technologies followed by the evolution of network on chips. The authors briefly explained router micro architecture and routing protocols. They also explained different switching techniques followed by different architectural issues and NoC implementation. In another review [6] the basic background of NoC architecture and its design characteristics were presented. Then brief discussion of three types of router designs i.e. circuit switched router design, virtual channel router design and wormhole router design was given. The paper was concluded by considering that virtual channel designs are most efficient. The authors in [7] presented a review and discussed network on chips with its different functional layers followed by different design methodologies. They gave a brief idea of routing and arbitration techniques. Then they shared some quality of service metrics. Finally they introduced a new NoC architecture i.e. Bidirectional network on chip (BiNoC). Another survey of NoC architectures was presented which described the characteristic behavior of different NoC architectures [8]. A brief explanation of switching in different architectures followed by different types of routing was given. It was followed by some insight on different connection types in different NoC architectures and different buffer management techniques.

3. Communication Centric Areas of NoC. As NoC is all about communication between different resources, hence here communication is the supreme concern. There are broadly three communication centric areas of NoCs namely: topology, flow control and routing as shown in Fig 3.1. To target the specifications and performance of an application in NoCs, the designer has to deal with different constraints in these three communication centric areas. Each of the three above mentioned areas play an important role in the communication, as well as maintaining the performance of network since various performance parameters depend on them. These areas have a broader inner classification and relation which is shown and discussed as under. We will continue with the flow given in the Fig 3.1.

3.1. Topology. Topology defines how the network nodes are physically connected. Selecting a good network topology is very important as it has a great impact on cost, performance and fault tolerance. An efficient topology should have less latency and larger bandwidth. Topology selection depends on communication requirements of an application. Applications can use basic NoC topologies or more robust recent ones depending on their specific needs. In this section we will elaborate different types of NoC topologies, their attributes and architectural designs, which make them more robust and performance efficient [9].

Based on the networks regularity and layout, 2D NoC topologies are divided into two broad types namely Regular and Irregular topologies. In regular ones each router is connected to a processing element or core and to a fixed number of other routers e.g. Mesh, Torus, Octagon etc. In irregular ones each router is not connected to its processing element, here some routers are used for transmitting packets only e.g. fat-tree, 3 stage-butterfly etc. as shown in Fig 3.2. Regular topologies have low cost and less design time. However they suffer from scalability as certain real time applications are complicated designs. Reports show that about 60% NoCs employ mesh or torus topology [10]. To meet the complex SoC applications nowadays customized topologies with heterogeneous cores are used. In customized NoCs each router has different number of ports and other hardware internal components for implementing different topologies in different regions. It has proved to increase the performance than regular topologies [11]. Thus NoC topology modeling can be seen as a potential candidate for customized heterogeneous NoCs. Customized NoCs increase the performance by reducing delay and power overheads otherwise caused by regular NoC topologies [12].

A topology has various attributes few of which are discussed below.

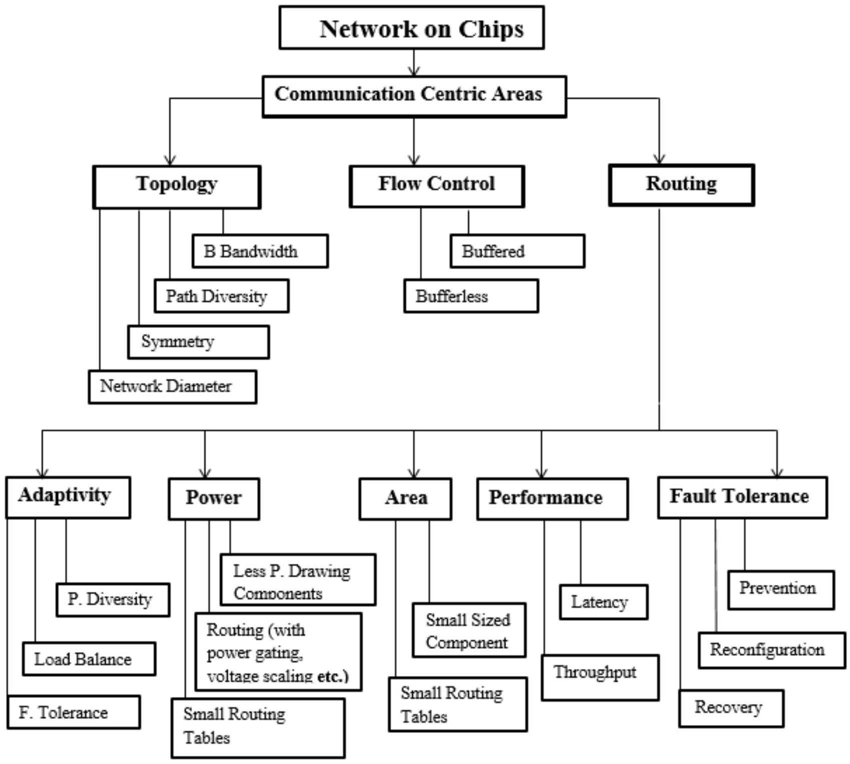

Fig. 3.1: Communication Centric areas of Network-on-chip and their attributes

Bisection Bandwidth: Bisection of a network is a cut that divides the network and nodes into two equal halves. It is the minimum bandwidth for all the bisections in a network. Larger bisection bandwidth implies more paths between two half sub networks and thus increases throughput, performance and fault tolerance.

Pathdiversity: Path in a network is the way formed by the channels from one node to another. Path can be minimal (minimum number of hops) or maximal. The more paths or routes in a network, the more robust it is to faults. More number of minimal paths in a network, lesser the latency and better the performance. It also helps in load balancing.

Symmetry: It represents the uniformity in the structure of a network (nodes and links). It plays very important role in load balancing which in turn affects performance. A symmetric network balances load uniformly and makes routing easy as every node can share same routing space in the network.

Network Diameter: It represents the maximum number of shortest paths between all pairs of nodes in a network. It is calculated by number of hops (no. of links it has to pass to reach destination). Smaller network diameter implies smaller hop count and less latency. It helps in managing traffic flow.

Mesh is commonly adopted topology as it is simple and regular but it suffers from scalability at times. Different topologies are being introduced day by day to enhance the performance of NoCs. We are discussing some of them here and then compare their architectural advantages and performance. The work in [13] introduced Cross by Pass Mesh. It combines the regular mesh with some by pass links. The additional links are efficient for reaching longer distances easily with less hop count. These additional links improved symmetry and scalability than regular mesh and torus. Another topology called as centrally connected Mesh (C^2 Mesh) was introduced in[14]. It had four additional links connected to the center. For designing $n \times n$ (C^2) mesh first centre is found, for odd n, one center node is connected to 4 corner nodes while for even n, four center nodes are connected to four corner nodes. It increased scalability and performance as compared to simple mesh. In

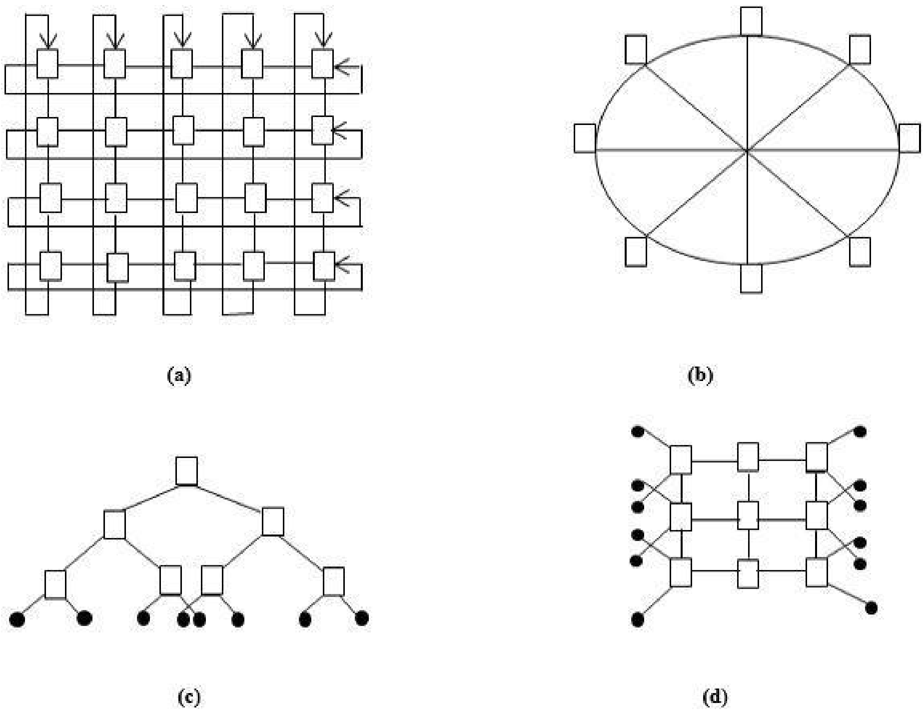

Fig. 3.2: Regular Topologies: (a) Torus (b) Octagon: Irregular Topologies (c) Fat-Tree (d) 3-Stage Butterfly

[15] the authors introduced an area and power efficient NoC named as Diagonally Linked Mesh (D-Mesh). It added additional diagonal ports to router for Quasi-minimal routing. It evenly distributed saturation load. Simulations proved diagonal links are more area and power efficient than normal links. Another novel hybrid topology was proposed in [16]. It was a combination of mesh, torus and folded torus topology. It used three types of links namely torus links, folded tori links and mesh links. These reduced hop-count and increased performance in comparison to regular mesh, regular torus and regular folded torus. Then Quad spare mesh topology was introduced in [17]. It was a simple mesh which was divided into smaller 2×2 meshes and each 2×2 mesh was provided with a spare router for fault tolerance. It was specially used for router and link failures. It re-configures itself in case of failures. It increased fault tolerance with little increase in latency. Another new topology called as Multi Level Mesh was put forward in [18]. This topology differs from simple 2D Mesh by the fact that it has several meshes that share common routers. It resulted in less latency, less power consumption than regular 2D mesh. The authors in [19] proposed a new NoC topology named as PentaNoC. It actually involves cascading any number of pentagon shape blocks using various wrap around links. This reduced hop count and increased path diversity which in turn resulted in good performance. A new NoC topology called as SlimNoC was presented in [20]. It was a scalable, energy and area efficient topology. It had a diameter of 2 which reduces buffer area which again in turn reduces power consumption and also gives better performance. A new star type NoC topology to overcome latency issues of long distance data transmission was introduced in [21]. Here a $n \times n$ mesh is taken and n is assumed as a multiple of 3. Then it is divided into many 3×3 sub meshes and central node of each is connected to the diagonal nodes. These central nodes constitute a second level mesh. Choosing central nodes for long distance communication reduces the latency. It reduced hop count and gave much better performance for large sized NoCs. Table 3.1 highlights the architectural advantages and performance improvements using different topologies.

3.2. Flow Control. It is the mechanism that does the sequencing of data in the path from source to destination. It also allocates different resources like channels, bandwidth, buffers etc. Flow control mainly

Table 3.1: Architectural Advantages and Performance Improvements of Different Topologies

S.No	Architectural and Performance Improvements	CB Mesh	C^2 Mesh	D Mesh	Hybrid Mesh	Quad Spare Mesh	Multi Level Mesh	Penta NoC	Slim Noc	Star NoC
1	Scalability	Y	Y	Y	Y	Y	Y	Y	Y	Y
2	Network Diameter	Y	-	-	-	-	-	Y	-	Y
3	Increased Bisection Bandwidth	Y	Y	-	-	-	-	Y	-	-
4	Reduced Implementation Complexity	-	Y	-	-	-	-	-	-	Y
5	Reduced Area	-	-	Y	Y	-	-	-	Y	Y
6	Reduced Cost	-	Y	-	-	-	-	-	Y	-
7	Increased Throughput	Y	-	-	Y	Y	Y	Y	-	Y
8	Reduced Latency	Y	Y	Y	Y	Y	Y	-	Y	Y
9	Incresed Fault Tolerance	-	-	Y	-	Y	Y	Y	-	-
10	Reduced Power	-	-	Y	Y	-	-	-	Y	Y
11	Adaptivity	Y	Y	Y	-	-	-	Y	-	-

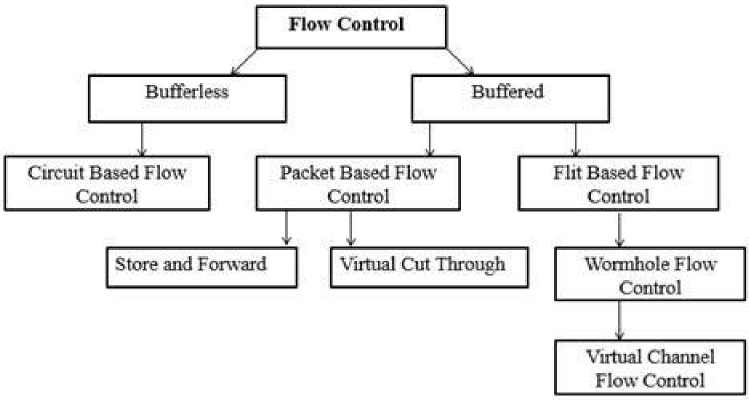

Fig. 3.3: Flow Control Mechanisms

deals with resource allocation and resolves the contention for resources. An efficient flow control mechanism can increase the propagation speed of the packets in the network. It can also help in removing deadlocks and livelocks, as it removes the long waiting periods for packets to share the network resources. Switching forms a part of flow control as it decides how the data flows within the routers and channels. Broadly switching is divided into two types namely circuit switching and packet switching. Circuit switching is a buffer less flow control mechanism whereas Packet switching is a buffered flow control mechanism as shown in Fig 3.3. Adding buffers efficiently increase the flow control. Buffers can be allocated either in terms of packets or flits. If it is allocated in terms of packets then it either forms Store and Forward or Virtual Cut Through flow control mechanisms. On the other hand if it is allocated flit wise it forms wormhole flow control mechanism. Wormhole flow control in turn includes Virtual channel flow control as it is associated with virtual channels. The most commonly used among all these is wormhole flow control as it gives better buffer utilization and less latency. It allows using idle bandwidth, in terms of virtual channels over the same physical channel.

The authors in [22] compared the buffered and bufferless flow control mechanisms and suggested various ways of how these can be optimized. Buffered flow results in high power while bufferless causes deflection, which at times can degrade network performance. Bufferless flow control mostly gives advantage at lower loads while buffered gives better performance at medium and higher loads. Buffered flow can use buffers which serve to

Table 3.2: Advantages of Different Flow Control Techniques

S.No	Architectural and Performance Improvements	Clumsy FC	Prediction Based FC	Distributed Flit Buffer FC	Improved FC	Injection Level FC	Flit Level FC	QLT FC	Fault Tolerant FC
1	Reduced Area	-	-	Y	-	-	-	Y	Y
2	Reduced Cost	-	-	-	-	Y	-	Y	-
3	Reduced Design Complexity	-	-	Y	-	-	-	-	-
4	Increased Packet Injection Rate	Y	Y	-	Y	-	-	-	-
5	Reduced Latency	-	Y	Y	-	Y	Y	-	-
6	Increased Throughput	Y	-	-	-	-	Y	-	-
7	reduced Power	-	-	-	-	Y	-	Y	Y
8	Congestion Control	-	Y	-	-	Y	-	-	-
9	Fault Tolerance	-	-	Y	Y	-	-	Y	Y
10	Better Buffer Utilization	-	Y	-	-	-	Y	Y	-

maximize energy efficiently while bufferless can use a better routing algorithm for reducing latency. A predictive closed loop flow control method was introduced in [23]. The authors here introduced a router model which tells the state of neighbor router based on amount of flits present in their input buffers. Based on this they predict availability of routers locally and as a whole globally. Using this information the packet injection rate in network can be controlled and congestion can be prevented. Thus better performance can be achieved. Further a distributed flit buffer flow control technique was introduced in [24]. The authors merged ack/nack protocol with relay stations distributed on channels. It provided advantage of using smaller router and long wires with ease in physical design. By combining these two approaches better performance was achieved. The authors in [25] introduced a flow control technique named as clumsy flow control. Their aim was to reduce the impact of deflection routing in bufferless NoC routers. So they employed pipelining mechanism which used two stages. One stage was used for calculating the output link and another for assigning that link. It resulted in less deflection with increase in performance. The authors in [26] presented an improved flow control for implementing Minimal Fully Adaptive routing in NoCs. According to duato's theory there are two virtual channels i.e. escape virtual channels (EVCs) and adaptive virtual channels (AVCs). AVCs can be used at any time but EVCs can only be used for packets which follow deadlock free algorithm. There is a constrain of atomic reallocation on AVCs. This paper enhances flow control by demolishing AVC reallocation constrain from various ports on the router. It proposed router architecture where packet exchange occurs from escape virtual channels to adaptive virtual channels non-atomically and hence performance is improved. An injection level flow control was introduced in [27] which was based on calculating the status of paths between source and destination. Destination node only sends the path information to source node and accordingly source adjusts the packet injection rate in the network. Hence injection rate is controlled at different levels in accordance with network payload and thus performance is improved. Another flit reservation flow control mechanism was presented in [28], where the impact of using control flits ahead of data flits was enhanced. Due to this buffers were reserved in advance for upcoming data flits. The advance reservation results in immediate buffer reuse unlike existing techniques which hold the buffer until credit is received. It thus reduces delay and increases throughput. Another flow control method namely Quarter load threshold for wormhole switching was introduced in [29]. Here the authors say when the network saturates, congestion occurs and the buffer state becomes full. According to them congestion can be controlled if only some buffer slots of the total buffer space are used. So they put a limit on buffer state of network and this limit was its quarter load value i.e. quarter buffers of a node should be used. As such balance was achieved between latency and throughput and performance was enhanced. The authors in [30] proposed a fault tolerant flow control for NoCs. Here they handle soft errors and recover these errors at link level. Dynamic packet fragmentation is used here. Upon error detection faulty flits are fragmented and then re-transmitted through new virtual channels. They introduced a router for this which gives 97% error coverage with little area and enhanced reliability. Table 3.2 summarizes and compares the advantages of above mentioned different flow control techniques at architectural and performance level.

3.3. Routing. Routing determines the number of possible paths a message can take to traverse to its destination. It is like a road map. A good routing algorithm should choose smaller (minimal) paths, balance the load and increase the throughput of the network. Also a good routing algorithm should have greater path diversity so that it can provide adaptivity and fault tolerance. Taxonomically routing is classified as deterministic, oblivious and adaptive. In deterministic routing always the same path is used to send the data between source and destination. In oblivious routing data is send through some random path without considering the network state. Deterministic routing is a part of oblivious routing. Adaptive routing uses the information of the network to send the data to destination. It considers factors like congestion, faults etc. and then routes the data accordingly. Routing is the backbone of communication in NoCs as it affects various qualitative metrics or attributes which are discussed below:

3.3.1. Adaptivity. Adaptive routing can be seen as the future of NoCs. Adaptive routing takes into account the network conditions by using the local information from neighbors. This information could be link or node failures, packets waiting for resources (congestion), load information etc. It increases path diversity, balances load and provides greater flexibility and fault tolerance. Adaptive routing gives better performance especially for non-uniform traffic patterns. Adaptive routing mostly results in lower latency and higher throughput along with congestion control. It greatly impacts power consumption in network.

An adaptive routing algorithm for NoCs was proposed in [31]. In it the importance of proper buffer management for increasing throughput was explained. The authors combined two attributes i.e. adaptivity and buffer management and introduced a modified XY routing algorithm. In this algorithm the paths are chosen locally by calculating the available bandwidth in each direction. The direction with highest weight or bandwidth is chosen and accordingly blocks of buffers are arranged in that route and the packet is transferred. It was compared to normal XY, OE and DYAD and gave better performance results than XY and OE. A destination adaptive routing (DAR) based on delay estimates was proposed in [32]. This routing algorithm determines global congestion than local congestion. It is done in two stages; firstly queuing delay from every node to every other node is calculated in a distributed manner. Secondly this delay contributes to the determination of ratios so that traffic can be distributed to the destination between ports of a router. Router architecture for this algorithm was also introduced. As a result of congestion awareness and adaptivity, performance was improved. Another author in [33] proposed a fully adaptive routing algorithm and region based approaches for 2D and 3D NoCs. This algorithm relies on congestion determination and adaptivity. It first detects congestion and then routes the packets. Here the network is divided into clusters and congestion is detected by a group of clusters. Each cluster consists of four routers and a fifth router named as cluster agent. Each cluster firstly gathers congestion information from local routers, and then it distributes the same to neighboring clusters. Hence each router is aware of congestion about every other router and takes the routing decision accordingly. As such performance was improved. The authors in [34] proposed an algorithm called as Adaptive look ahead algorithm. This algorithm is a combination of full adaptive and partially adaptive algorithms. It determines next two hops on a single node (next hop and look ahead hop) and routes the packet region wise. According to it a router is surrounded by four regions. If destination is in region 1, 2 or 3 then look ahead algorithm is followed else a fully adaptive algorithm is chosen. It does not take congestion into account but gives less computational complexity. It gave better results compared to XY and OE. Another adaptive routing namely Dynamic and Mixed routing (MIXROUT) was introduced in [35], which works according to the load status of the network. It actually combines an adaptive routing Multiple and Load-Balance Path Routing (MULTI) and deterministic routing (XY). When the load is high MULTI is used otherwise XY is followed. MULTI works well and mitigates congestion in high loads while XY operates well in low loads as it does not suffer from power and thermal optimization issues unlike MULTI. As such balance is maintained and performance is enhanced. An adaptive table routing, based on hierarchical clusters called as C-routing was presented in [36]. It combines cluster approach and turn model approach. Here a node does not have the cost of all the nodes in the network rather it has its own information and cluster information. First intercluster routing is followed than intracluster. It combines XY and partially adaptive routing. The former is followed in north direction and latter in east, west and south directions. This routing reduces table size and improves performance. The authors in [37] proposed an adaptive routing used specially in MPSoCs. It finds maximum shortest paths between

Table 3.3: Performance Enhancement due to adaptive routing

S.No	Architectural and Performance Improvements	AdR with Buffer Utilization	Destination Adapt. Routing	Region based AdR	Adap. Lookahead Routing	MIX Routing	C Routing	AdR For MPSoC	Centra. AdR	AdR for Reliab.
1	Less Latency	Y	Y	Y	Y	Y	-	Y	Y	Y
2	High Throughput	Y	Y	Y	Y	Y	Y	-	Y	-
3	Congestion Control	-	Y	Y	-	Y	-	-	-	-
4	Reduced Power	-	-	-	-	-	-	Y	-	Y
5	Reduced Cost	Y	-	-	-	-	-	-	Y	-
6	Reduced Area	Y	-	-	-	-	Y	-	-	-
7	Reliability and Fault Tolerance	-	-	-	-	-	Y	-	-	Y
8	Thermal Temperature Stability	-	-	-	-	Y	-	-	-	-

each source destination pair. It is an odd even based deadlock free unicast/multicast routing that works on Hamiltonian method. There are specific routing rules for even and odd rows. Since it is a hamaltonian odd even routing, it is highly adaptive and balances load evenly in the network. An interesting centralized adaptive table based routing for NoCs was introduced in [38]. It monitors traffic effectively in the network and balances load evenly. It is done by two modules namely feedback module (which monitors traffic) and control module (which decides routing path). Based on traffic congestion XY or YX routing is followed by toggling according to congestion. This method balances load very well as compared to distributive adaptive routing. The authors in [39] presented an adaptive routing algorithm which improves the reliability of NoCs. This technique reduced the effect of electron migration, hotspot carrier injection and negative bias temperature instability (NBTI) on lifetime of NoCs. It introduced a concept of packet per port i.e. a metric which balances the stress in the network. It affected the ageing of NoC components and tried to age the components evenly which in turn increase the reliability. Table 3.3 given below summarizes the performance enhancement due to different above mentioned adaptive routing techniques.

3.3.2. Power. Future SoCs require power efficient NoC architectures. Power from NoCs point of view is related to different factors like hop count, complex routing functions and power drawing components of NoCs architecture. If the number of hops taken to reach destination is large, more power will be consumed by the system. So it is preferred to choose minimal routing for minimizing power consumption. Also routing algorithms constituting complex routing tables should be avoided as they consume more power and energy. Moreover as technology is shrinking, leakage power continues to grow and leads to higher power consumption in NoCs. Continuous switching and transactions increase power consumption. Also various NoC components such as routers, buffers, crossbars etc. are all power drawing components and contribute to enhanced power consumption. So the design of power and energy efficient NoCs is the need of the hour.

A number of techniques have been presented for power efficient NoCs. Power consumption can be decreased by making more robust router and link architectures. The main components which contribute to NoC power are the routers and links. So power saving can be done in these two areas from architectural point of view. For routers techniques like buffered and buffer less architecture are applied and for links power gating and voltage scaling can be applied [40]. It was observed that routers consume a significant amount of power, particularly, when they are idle. In routers buffers are the main source of power dissipation. So an alternative was put forward in the form of bufferless routers [41]. In a router without buffers, flow control deflection algorithms are used, where in packets have to be transmitted on their arrival only. Thus, the only required buffers are few pipeline registers. They do result in low power dissipation but they decrease network performance as the load increases. As such they brought a trade off between performance and low power. The authors in [42] proposed a scalable power gating method Turn on-on Turn (TooT) for routers. In NoCs some routers remain idle for a long time, so when they wake up they consume power. (TooT)reduces wake ups and thus reduces power. It avoids powering on a router when a straight packet is forwarded or ejected and powers on only when packets come from other directions. As such it improves static power and energy. The authors in [43] reported that link power dissipation contributes a greater portion of overall power consumption. Reducing link voltage reduces square times power consumption, so they changed the link voltage based on the communication urgency. NoC with two different kinds of links δ links and λ links were setup. The δ links used the normal voltage and the λ links used a lower voltage. The data packets with the robustness flag high are transmitted on δ links, whereas those with the robustness flag low are transmitted on λ links. This reduced power consumption. Another power saving method was proposed in [44]. It allowed transferring flits rapidly between adjacent routers in half clock cycles by utilizing both edges of the clock. This method leads to link and buffer power reduction along with latency improvement. The authors in [45] have shown the impact of routing algorithm on power and performance. Routing algorithm has impact on buffer size, hop count and router logic. Their power modeling and comparison of different routing algorithms showed more buffer depth more power drawn, more virtual channels more rapidly energy increases, more adaptive algorithm more power it consumes than deterministic ones. A new and hybrid first in first out (FIFO) architecture for reducing power in NoCs was introduced in [46]. Here the authors used a Complementary metal oxide semiconductor (CMOS) Memristor in FIFO which is a non-volatile, scalable and area efficient device. According to them for increasing performance in NoCs, FIFO depth has to be increased which in turn increases power and area. So to overcome this they used CMOS Memristor in it. They used it in RAM block. On implementation it served better results in terms of power and area than conventional FIFOS. A new slow silent virtual channel method for low power NoCs was put forward in [47]. Adding virtual channels increase throughput but as long as bandwidth is not saturated, after that leakage power starts. So they incorporated low power techniques with virtual channels. They used run time power gating for each virtual channel, sleep control methods for different wake up periods, routing techniques to overcome standby power in addition to voltage and frequency scaling. The authors in [48] introduced a new low power router architecture namely centralized buffer router. They used centralized buffers plus elastic buffered links in its router architecture. The centralized buffer in router is used only when a packet from input buffer cannot go to its output buffer. It has many pipelining stages, and the control and data information splits in the links. They also provided a deadlock avoidance method. The technique gave much improvement in power and latency.

3.3.3. Area. Area is also an important factor as far as high performance NoCs are considered. Area increases power also increases. Area can be minimized by many methods like by using smaller routing tables for routing, by minimizing the size of VLSI components and resources, by using less complicated reconfigurable designs etc. A new router architecture for area reduction and power efficiency was introduced in [49]. It presents a new virtual channel sharing technique named as partial virtual channel sharing. According to it sharing of resources is essential for minimizing chip area. Here virtual channel buffer is shared by other ports in a router based on communication needs. As such buffer utilization increases without causing significant area overhead. The authors in [50] presented an area efficient partially reconfigurable crossbar switch for NoCs. Reconfigurable NoCs usually have larger area because they have more complex crossbar switch design. Here a partially reconfigurable crossbar switch design is presented which has smaller area and less delay. It is made up of look up tables (LUTs) and reconfiguration takes place by changing these LUTs which in turn reduce area. They also proposed an algorithm for making connections in crossbar switches. A new router architecture which reduces area and increased speed in NoC architectures was introduced in [51]. The authors modified three components inside a router namely crossbar switch (replaced with less number of LUTs), buffers(instead of 16 bit used 8 bit buffers) and a decoder(instead of decoder used two input one output OR gate). The area is measured in terms of number of LUTs used. This resulted in large area improvement as compared to conventional NoC router. Ihe authors in [52] also presented an area and power efficient router for NoCs. This router used wormhole routing, with a simple deterministic algorithm, followed by flow control and decoding techniques. They used two types of crossbar switches namely multiplexer and matrix for area efficiency. They showed that multiplexer type crossbar gives better efficiency than matrix type in terms of area and power. A low area router architecture for NoCs based on HDL was proposed in [53]. Here it uses two crossbar switches instead of one. The concept is a router which has many small crossbar switches performing same function as that with a large crossbar. It consumes less area with small overhead in latency. The latency here is minimized by providing a low latency algorithm named as predominant routing algorithm. This combination reduced area to a greater extent. Again a new router architecture named as Inter-Router Dual-function Energy and Area efficient Links (iDEAL) for area efficient NoCs was proposed in [54]. For optimizing NoCs in terms of area buffer plays an important role. Reducing number of buffers in a router reduces area and some performance. So here in this technique number of buffers is reduced to reduce area at the same time some adaptive dual function links are introduced in router architecture. They store as well as transmit data as per requirement. Hence reduction in area and compensation for performance was obtained. The authors in [55] proposed a new area and energy efficient architecture for NoCs. They took advantage of circuit switching and multistage circuit-switching network (CLOS) network and combined it. Furthermore they proposed a heterogeneous router architecture which used a combination of buffered and bufferless routers. They also incorporated lane division multiplexing in router. On implementation, combination of CLOS and circuit switched switch performed better than normal crossbar with a large reduction in area. A new area efficient reconfigurable router architecture for NoCs was introduced in [56]. Design was carried using hardware description language. It had a dedicated channel for each direction i.e. (E,W,N,S) along with it buffers and multiplexers. Each channel has 5 multiplexers. Fixed priority arbiter is used for reducing area of this router. It showed improvement in area and latency. An area efficient table based routing for irregular NoCs was presented in [57]. The authors lay stress on finding paths, which could find higher similarity by routing methods. This surpassed the problem of region based routing along with area reduction.

3.3.4. Performance. Performance in NoCs can be determined by latency and throughput. By achieving low latency or high throughput or both we can enhance the performance. Lower latency is much needed as we are in fast communication era. By designing low latency networks we can enhance the speed and also get high throughput. We can enhance performance by working on different NoC architectures, using adaptive routing algorithms, using smaller routing tables, routing architectures (buffers, allocators) etc.

An adaptive routing called zigzag routing was introduced in [58]. In it packets move in alternate x and y directions. Initially distance to destination is calculated and compared. The data is first send in the direction which has greater distance until the distance in both the dimensions becomes the same, then data alternates between x and y dimensions. It decreases latency and power and increases the performance. The authors in [59] presented an FPGA based NoC architecture. They also made it easy to interface it with a bus protocol like wishbone. They made it flexible for implementing into any topology and used wormhole routing to reduce latency. This NoC architecture was optimized for Vertex 5 FPGA and achieved low latency, high throughput and low area. A new NoC architecture for high throughput and high performance called as High Throughput Butterfly Fat Tree (HTBFT) was proposed in [60]. It is modification of butterfly fat tree architecture. It gives efficient performance in parallel machines. It has a four array tree with switches connected to four down links and two uplinks. Its switch architecture is less complex than normal butterfly tree structure (BFT). It was synthesized in Xilinx ISE and was seen that throughput increased with marginal latency changes as compared to BFT architecture. Another NoC router architecture was proposed in [61], which helped in achieving low latency and high throughput. The authors modified normal router by injection and ejection ports, spilited a packet into two halves, implemented two different DOR routing methods along some changes in hardware design. All the changes combined to increase the path diversity and increased performance as well. Likewise another high throughput router for NoCs was introduced in [62]. Stress was laid on bond between neighboring routers. The authors designed a router in which buffer and allocators were modified. They also put forward neighbor flow regulation algorithm which worked in coordination with modified structures. Simulation results show improvement in throughput and latency due to coordination between neighboring routers. X-Network which is a high performance wormhole switching network was proposed in [63]. In this network a router is shared by four processing elements and is also in contact with other routers in different directions (E,W,N,S). As a result of this hop count decreases. It was compared to conventional NoC architecture on different routing algorithms and traffic patterns. It performed better and hence increased performance. In [64] proposed high throughput router architecture for NoCs. There are different components in router architecture which affect the performance, switch allocator being one among them. They modified the arbiters of first stage switch allocators. They replaced simple round robin arbiter with a predefined priority based round robin arbiter in first stage which in turn reduces the contention in the second stage. As a result throughput increases linearly with number of virtual channels. It also reduces design complexity and latency. A new heterogeneous topology for achieving low latency and high throughput was proposed in [65]. They combined tree and mesh topology

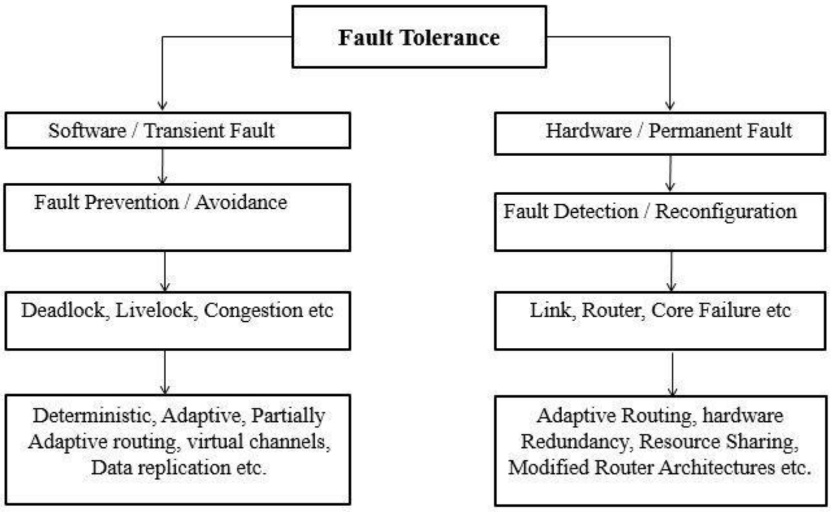

Fig. 3.4: Fault Tolerant Methods

to design a hybrid topology. Tree network provided low latency and mesh network a high throughput. As a result they obtained the advantages of both. They also provided an algorithm based on hop count to manage contention and latency. The algorithm was tested for different traffic patterns and gave very good performance and energy consumption.

3.3.5. Fault Tolerance and Reliability. It has been observed as the number of processors and transactions increase in MPSoCs, a large number of components fail during manufacturing and integration and another huge lot during the operations. It happens because faults may occur in different forms at different levels. This leads to a decrease in performance and reliability. Thus fault tolerance is required at different levels of abstraction. Adopting fault tolerant approaches is imperious for maintaining the required and appropriate performance of NoCs. Fault tolerance increases the reliability of the system. Reliability is a measure to determine how many times the network works correctly performing its task of delivering messages. To design a reliable network its error handling capability should be increased.

Fault tolerant routing is classified on the basis of faults it tolerates. First category includes faults that can be prevented or avoided. These are software faults like deadlock, livelock, congestion etc. The second category includes faults which need detection and reconfiguration i.e., hardware faults like link, node or core failures. For the prior one, routing techniques which avoid these faults are designed and for the latter one different routing techniques plus reconfiguration is needed (fault tolerance and reconfiguration) as shown in Fig 3.4. Reconfiguration and recovery are also as important as prevention. It includes methods and means to bring back a system from faulty to functioning state. It involves the circuit components like routers, re-configuring routing paths, re-configuring using various redundancies like component or information redundancies etc. The most basic fault tolerant routing used for deadlock prevention is deterministic XY routing, where a packet is first routed horizontally until it reaches the column of destination and then routed vertically. YX follows the opposite of XY, it routes packet first vertically until it reaches destination row and then horizontally. The authors in [66] introduced turn models which were partially adaptive in nature. They restricted certain turns in certain directions to break the cycles which otherwise created deadlocks. They presented negative first turn model (restricted positive to negative turns), west first turn model (restricted west last turns) and north last turn model (restricted north first turns). Their simulations showed that partially adaptive algorithms perform better for non-uniform traffic than deterministic ones. In [67] the author introduced odd even turn model which is fully adaptive and deadlock free. It restricted some of the locations where some of the turns were forbidden. There are separate routing rules for even and odd columns and it resulted in uniform adaptivity. Results showed

Table 3.4: Type of Fault Tolerance provided by different techniques

S.No	Architectural and Performance Improvements	XFA	Basic TM	Odd Even TM	Non-Mini. Fully AdR Using VCT	Selec. Extension Rout. Alg. Based TM	Fault. Tolerant Deadlock free Rout.	Fault. Tolera. Reconf. NoC	Traffic Aware Reconf. Architecture	Reliable NoC Architecture	Fault. Toler. NoC Relia. Improvement
1	Deadlock Freedom	Y	Y	Y	Y	Y	Y	-	Y	-	-
2	Congestion Control	Y	-	-	-	Y	Y	-	-	-	Y
3	Livelock Freedom	-	Y	Y	-	-	Y	-	Y	-	-
4	Router Failure	-	-	-	-	-	-	Y	Y	-	Y
5	Link Failure	-	-	-	-	-	Y	-	-	Y	-

that adaptive algorithms give better performance for non-uniform traffic patterns. Another deadlock free fully adaptive routing was presented in [68]. It uses non minimal paths. It avoids deadlocks using turn models but with the help of arbitration and output selection support of routers. It allowed packets to select an output port in minimum time after arrival, even if it is not the shortest path. Also throughput improvement was achieved. The author in [69] introduced a deadlock free XY fully adaptive (XFA) routing. It is an adaptive form of XY routing and sends data through minimal paths. It gives less latency and better throughput than regular XY routing for non-uniform traffic patterns. A novel method of increasing the adaptivity and deadlock free property of turn models was presented in [70]. The authors redesigned odd even and a Low Weight and Highly Adaptive Routing (LEAR) algorithms. They released some turn restrictions of adaptive algorithms. They also used a mixed switching technique, mixing virtual cut through and wormhole switching. This provided different paths and logical separation of data along with fault tolerance and latency improvement. The authors in [71] proposed fault tolerant scheme which is deadlock and livelock free. This scheme also combats congestion and link failures. For deadlock prevention a timeout scheme is used along with packet reinjection by a virtual source. An algorithm for livelock avoidance is also given. This technique proved more reliable and efficient for removing deadlocks and livelocks. A reconfigurable fault tolerant technique was presented in [72] which can handle single or multiple router failures. Here routers are modified which recover the cores connected to faulty routers. It uses routing tables for network updates. If a router fails, it gets detached to the core and the routers surrounding this faulty router use their unused ports and attain the abandoned core and maintain the performance. In [73] the authors proposed a reconfigurable rerouting algorithm for faulty links. Here a test is carried out for detecting faults, once a fault is detected every switch reconfigures itself for finding rerouting alternative paths to bypass faulty links. It uses transaction level model platform for simulation. The work in [74] presented a fault tolerant reconfigurable NoC architecture. It is used for saving cores attached to faulty routers. Here a core is attached to two routers, master router (original router) and slave router (neighboring router). If a master router fails, the slave router reconfigures and saves the core. This fault tolerant architecture reduced latency and improved reliability as compared to normal mesh. The authors in [75] presented a reconfigurable fault tolerant technique for bypassing faulty routers. It modified the router structure and used Dynamic XY (DyXY) routing which makes it robust for deadlock and livelock also. Its router contains additional reconfiguration control unit which helps in reconfiguration. It uses two virtual channels and an adaptive minimal routing for bypassing the faulty routers. Table 3.4 given below summarizes the type of fault tolerance provided by different techniques.

4. Network on Chip Simulators. This section presents some of the commonly used simulators for Network on chips. Fig 4.1 below presents a general block diagram of a NoC simulator. A general NoC simulator should atleast have an application package, a simulation package and a performance model. To select a particular NoC tool the user must know what operating system or installation platform he needs, what kind of topology he needs to work on, what traffic patterns he needs, what output performance parameters he needs to calculate and accordingly select a particular tool. Given below we have presented some of the commonly used NoC tools. Their comparison is presented in Table 4.1.

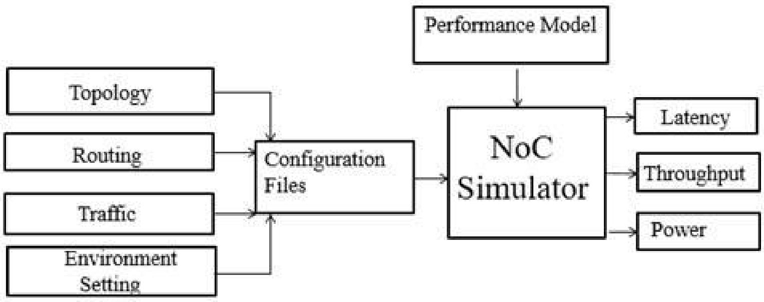

Fig. 4.1: Block Diagram of a general Network on Chip Simulator

NS 2 It is an open source event driven simulator. It is used for research in communication networks and simulating Network on chips. It uses C++ and oTcl language. The simulation process in NS 2 includes topology generation, model development, node and link configuration, execution, performance analysis and graphical visualization. It provides simulation in wired as well as wireless networks.

Nostrum It is a highly customizable Network on chip simulator. It has a command line interface. In addition to routing, finding performance parameters it also supports application mapping to networks. The user has the flexibility to configure different simulation parameters. It provides best effort and guaranteed communication results. It is a packet switched communication platform.

Nirgam It is an open source cycle accurate event driven simulator for Network on chips. It uses System C language and takes log file input for simulation. Earlier it was developed and used for 2D mesh and torus but now it is extended to 3D. It very flexible and allows the user to configure various parameters according to need like no. of virtual channels, buffer size, clock frequency etc.

Noxim It is a system C based cycle acuurate Network on chip simulator. It has a command line input interface. It is also a highly configurable tool and allows configuration of parameters by user. It uses Orion power model to calculate the power. It supports both wired and wireless NoC architectures.

DARSIM It is a parallel, highly configurable cycle accurate Network on chip simulator. It has a parallel simulation engine which enhances the speed and synchronization. It also supports parameterized table based designs. It supports static, oblivious and adaptive routing. It simulates both 2D and 3D mesh.

Gem 5 It is an open source discrete event driven simulator for computer system architecture, system level architecture and microarchitecture level in Network on chips. It takes a command line input. It provides the flexibility of rearranging, parameterizing, extending and replacing the components according to the need.

NoCTweak It is an open source System C based Network on Chip simulator. It works in command line. It is a very flexible, parameterizable tool and provides faster simulation speed. It calculates performance (latency, throughput, power) as well as energy of NoCs. It also facilitates calculation of area, timing and router components.

Booksim It is a cycle accurate simulator for network on chips. It offers the capability of modifying a large number of network parameters. It also allows network component designs especially router microarchitecture. It is capable of implementing almost all the algorithms. It is one of the most widely used simulators. Table 6 given below gives the comparison of NoC simulators presented.

5. Conclusion. This paper emphasizes the role of NoCs for communication in many core MPSoCs. Different performance parameters are discussed as they determine the efficiency of NoCs. Then stress is laid on communication centric areas, which include topology, flow control and routing. They being the backbone for effective NoC communication, their different types, their attributes, and their impact on performance are discussed. Different types of routing for increasing adaptivity, performance, fault tolerance and reducing power

Table 4.1: Comparison of NoC Simulators

S.No	Simulator	Year	Company	Installation Platform	Language	Topology	Traffic Pattern	Performance Metrics
1	NS 2	1995	DARPA	Windows with Cygwin	C++ and oTcl	Wide range	Synthetic	Latency and Throughput
2	Nostrum	2005	Royal Institute of Technology Stockholm	Linux	System C	2D mesh and Torus	Synthetic	Latency, Throughput and Link Utilization
3	Nirgam	2007	University of Southampton UK and MNIT Jaipur	Linux	System C	2D Mesh and Torus	Synthetic and Embedded	Latency, Throughput and Power
4	Noxim	2010	Catagne University	Linux	System C	2D Mesh	Synthetic	Latency, Throughput and Power
5	DARSIM	2010	Massachusetts Institute of Technolgy	Linux	C++	2D and 3D Mesh	Trace driven injector or Cycle level MIPS Simulator	Latency and Throughput
6	Gem 5	2011	Joint Collaboration of AMD, ARM, HP, MIPS, Princeton, MIT and Universities of Michigan,Texas and Michigan	Linux, Solaris, MacOS	C++	Wide range	Synthetic and Embeded	Throughput and Energy
7	NoCTweak	2012	ST Microelectronics, UC Micro, Intel and University of California, Davis	Linux	System C	Mesh, Torus and Ring	Synthetic and Embeded	Latency, Throughput, Power and Energy
8	Booksim	2013	National science foundation and Stanford Pervasive Parallelism Laboratory	Linux	C++	Wide range	Synthetic	Latency and Throughput

and area are discussed. Also some NoC simulators are briefly discussed. By analyzing the work done in the past and the survey presented above, we have come to the conclusion that performance of NoCs can be enhanced by working in communication centric areas. Analyzing in depth different attributes of each communication centric area major improvement in performance can be achieved. Also we should lay stress and effort on following research areas in future.

1. NoC topology modeling for irregular networks can be interesting area to work.
2. Customized topology modeling for heterogeneous NoCs needs research.
3. For flow control an important side to look and do research is fairness (schemes which fairly allocate resources in the network).
4. Flow control is closely related to router microarchitecture and pipelining, so these can also be important areas of research.
5. Customizing routing algorithms which would enhance quality of service (QoS) metrics (less latency, high throughput,congestion control, increased adaptivity etc.) can be an area of research.
6. Power aware routing (routing algorithms and techniques which reduce network activity for reducing power) can be taken as area of highly needed research.
7. Fault tolerance and reliability at communication centric level (fault tolerant topologies, fault tolerant flow control schemes, fault tolerant routing) can be taken as an area of research.
8. NoC traffic modeling can be future area of research so that realistic performance of NoCs can be obtained and analyzed.
9. Also development of different real traffic simulation platforms and tools for giving the on ground performance of NoCs can be taken as an important research area.

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REVIEW OF RESEARCH ON STORAGE DEVELOPMENT

HONGHONG ZHANG* AND GUOGUO ZHANG†

Abstract. The development of computer external storage has undergone the continuous change of perforated cassettes, tapes, floppy disks, hard disks, optical disks and flash disks. Internal memory has gone through the development of drum storage, Williams tube, mercury delay line, and magnetic core storage, until the emergence of semiconductor memory. Later RAM and ROM were born. RAM was divided into DRAM and SRAM. Due to its structure and cost advantages, DRAM has gradually developed into the widely used DDR series. At the same time, the low-power LPDDR series has also been advancing. At present, with the development of NVRAM technology, non-volatile random access memory with both internal and external storage functions is born. Dual-space storage based on NVRAM combines internal and external storage into one, and large capacity dual-space storage has become the development trend of storage.

Key words: external storage, internal memory, hard disk, DDR, dual-space storage

AMS subject classifications. 68M99

1. Introduction. The storage is an important part of the computer system, and its function is to store programs and data. The world's first computer "ENIAC" was born in the University of Pennsylvania in 1946. In 1945, von Neumann's "stored program" design idea played a key role in the invention of computers. In fact, the appearance of storage predates the birth of computers. The punch card invented by the Frenchman Joseph Jacquard in 1801 was the earliest storage [1]. From punch cards to mercury storage, to magnetic core storage, then to hard disks, optical disks, U disks, RAM and ROM, until now NVRAM, storage continues to advance with the development of computers. This article details the complete process of storage development. Based on the latest non-volatile random access memory, a large-capacity dual-space storage architecture is designed and constructed. The main contributions of this article are as follows:

1. Study the complete process of storage development;
2. The future development trend of storage is predicted;
3. Designed a large-capacity dual-space storage structure.

2. Related research. Guo Jianqing of the Technology Department of China Huajing Electronics Group Co., Ltd. once reviewed the technological level and development status of domestic and foreign storage in 1993, and predicted the future development trend of storage [2]. Increasing areal density is the development direction of hard disks, and there is still room for development of tape storage technology [3]. Jiang Xinghua from the Department of Audio-visual Education of Hebei Normal University introduced the development of semiconductor integrated circuit storage applications in computing in 1999 [4]. He Cang of CST in the United States and Huang Xinyu and Li Peng of Dongfang Integrated Electronic Commerce Network introduced the development trend of storage for different types of equipment in 2000 [5]. Compared with DRAM, Flash Memory is easier to shrink in size and easier to manufacture. Therefore, its cost reduction is relatively faster [6]. The use of storage is becoming diversified, with high speed, large capacity and low power consumption, and the demand for storage is greatly increasing [7]. Tang Haiyan pointed out in 2005 that low power consumption and high integration are the development trend of mobile phone storage [8].

Liu Ming from the Institute of Microelectronics of the Chinese Academy of Sciences discussed the development status and challenges of non-volatile memory in 2012, and introduced the research work of emulation,

*Shanghai University, Shanghai, 200444, China; Henan University of Animal Husbandry and Economy, Zhengzhou, 450044, China(zhhh7921@126.com).
†Shanghai University, Shanghai, 200444, China.‡

reliability, materials, devices and integration of emerging memories [9]. Magnetic random access memory (MRAM) is a potential replacement product for the memory of most digital products such as mobile phones, mobile devices, notebook computers, and PCs, and is the new star of storage [10]. Resistive random access memory is a special application of memristors in binary conditions. Because of its simple structure, high density, high speed, low power consumption, compatibility with CMOS technology, and three-dimensional integration capabilities, it has become one of the next generation non-volatile memory technologies with the most potential for development [11]. The ferroelectric random access memory (FeRAM) has the main characteristics of many erasing times, low operating voltage, low power consumption, fast reading and writing, etc. It also has radiation resistance. This intrinsic radiation resistance is suitable for national defense, military, aerospace, satellite communications and other fields [12]. The phase change memory and storage materials developed by Song Zhitang's team have reached the international advanced level in comprehensive performance indicators, and are said to herald the arrival of the next generation of storage [13].

Many simple physical devices can be used to store information, the best storage to use is the acoustic delay line and drum [14]. A small ring-shaped ferromagnetic core with appropriate "rectangular" characteristics can be used as a storage device, and the storage unit is selected at the intersection of two or three spatial coordinates, and then assembled into a two- or three-dimensional storage system [15]. Among many different types of memory such as punched cards or tapes, films, magnetic tapes and drums, the drum has an outstanding feature, which is suitable as an internal memory for machines that are not too fast [16] . The analog-to-digital conversion controller and MOS shift register buffer form a unit, although it is customized for a special computer, it can run on different systems [17]. The IBM 650 calculator uses a magnetic drum storage program for control, and punch cards for input and output, gaining the flexibility of computers required in the field of commercial and scientific computing [18]. A perfect memory system can immediately provide any data requested by the CPU. However, this kind of ideal memory cannot be actually realized because the three factors of memory capacity, speed and cost are directly opposed [19]. Hard disk drives are an important bottleneck of system performance. Intel Turbo memory solves these problems by adding a new layer, non-volatile disk cache based platform, to the storage hierarchy [20]. Researchers are exploring the use of several emerging storage technologies, such as embedded DRAM, spin transfer torque RAM, resistive RAM, phase change RAM, and domain wall memory [21]. Compared with traditional DRAM and flash memory, phase change memory (PCM) is becoming more and more popular in next-generation systems [22].

At present, with the continuous development of non-volatile random access memory (NVRAM) and its technology, various NVRAMs have emerged. Because NVRAM has both the random access of memory and the permanent preservation of external storage, Jin Yi et al. proposed a dual-space storage based on NVRAM technology [23], which combines the current internal memory and external storage into one and integrates them into a storage body on NVRAM.

3. The development of external storage. The earliest external storage was punched cards (Fig. 3.1), but the invention of punched cards was much earlier than the birth of computers. In the 18th century, French weavers invented tandem punched cards when printing patterns. Joseph Jacquard invented the Jacquard Loom in 1801, which used punched cards to automatically control the pattern of weaving. American statistician Herman Hollerith used punched cards to store population data, and then used a tabulating machine to perceive the cards, helping the United States quickly complete the census. The tabulation machine company founded by Herman Hollerith later became part of IBM [24]. The non-perforated and perforated punched cards are precisely the expression of binary information 0 and 1. Jacquard and Herman used punched cards for automatic control and data processing respectively, which can be regarded as the prototype of computer software. In 1928, IBM used punched cards of 12×80 array to store information in its tabulating machine system. In 1935, IBM launched a punch-card computer, the 601 model, which could calculate multiplication in one second. The world's first programming language, FORTRAN, used punched cards to represent programs (Fig. 3.2). Until 1970, punched cards were used still as storage media in computer equipment. For computer systems, punched cards seemed to be chaos beginning. It can be used as an input device or an output device for a computer. The calculation result is printed on the punched card so this is the attribute of the external storage for it. Furthermore, the program and data stored on the card can also be regarded as the "predecessor" of the internal memory.

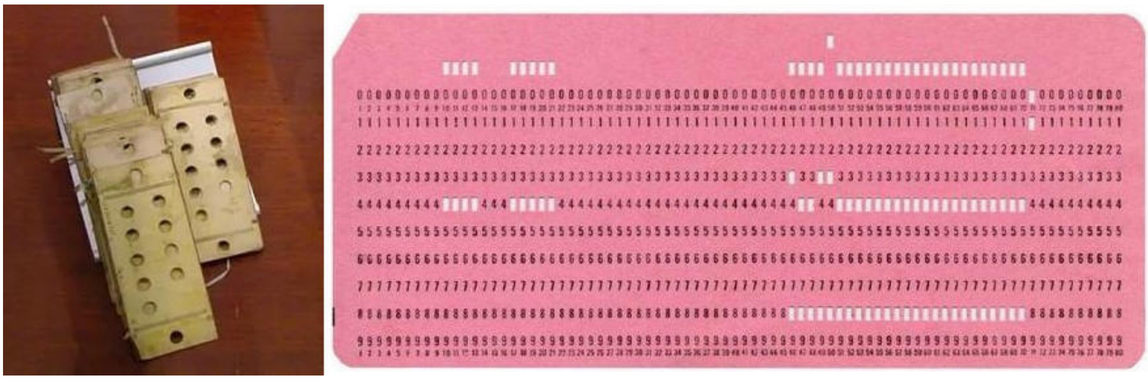

Fig. 3.1: Punched cards.

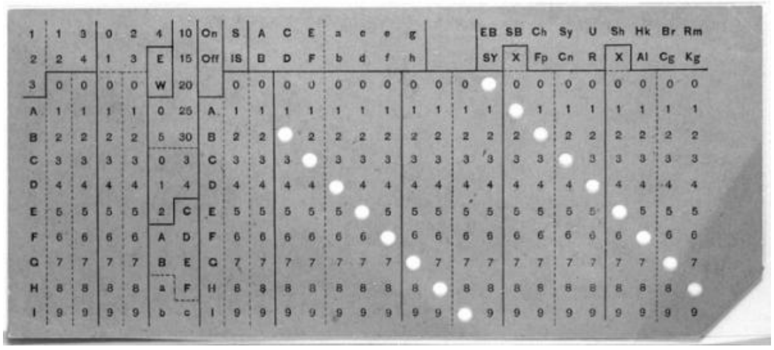

Fig. 3.2: Punched cards of FORTRAN program.

Due to the ever-increasing data and results to be processed, punched cards naturally evolved into punched paper tapes (Fig. 3.3). Punched paper tape was also born in the French textile industry. In the textile industry, it even predates punched cards. The aforementioned series of punched cards are improved on the basis of punched paper tape. In 1846, British physicist Alexander Bain invented a telegraph device[25] that used punched paper tape to send telegrams. In 1857, British scientist Charles Wheatstone used perforated paper tape for data storage and transmission. The principle of storing data in a punched paper tape is the same as that of a punched card. A punched paper tape row can be pierced 8 holes in a row to represent a character. Some systems also use parity check perforation method, using the 8th column whether to be perforated to ensure that the number of holes in a row is even (even parity).

Following punched cards and paper tapes, magnetic tapes had become the most important external storage. The birth of the tape started with the phonograph. In 1877, the American inventor Edison invented the phonograph, which can store sounds and restore them for playback. In 1898, the Danish scientist Valdemar Boll stored the sound on the magnetized piano strings. After repeated adjustments, the steel wire was replaced with a paper tape coated with metal powder. This was the embryonic form of the magnetic tape. In the 1930s, the German companies "Falben" and "Wireless Telecom" improved the metal paper tape, coated the plastic tape with iron oxide, and wrapped the plastic tape around the reel. Thus, the tape (Fig. 3.4) was officially born. In 1951, UNIVAC (UNIVersal Automatic Computer) used magnetic tape as a data storage device for the first time [26]. Since then, magnetic tape has developed rapidly, and later it has been widely used in the fields of recording and imaging. With the development of disk technology, tape has slowly withdrawn from the consumer field. Because the tape is very long, the access speed is very slow. However, tape also has many advantages. One is that it is cheap. with the same amount of data, the cost of tape storage is one-sixth that of

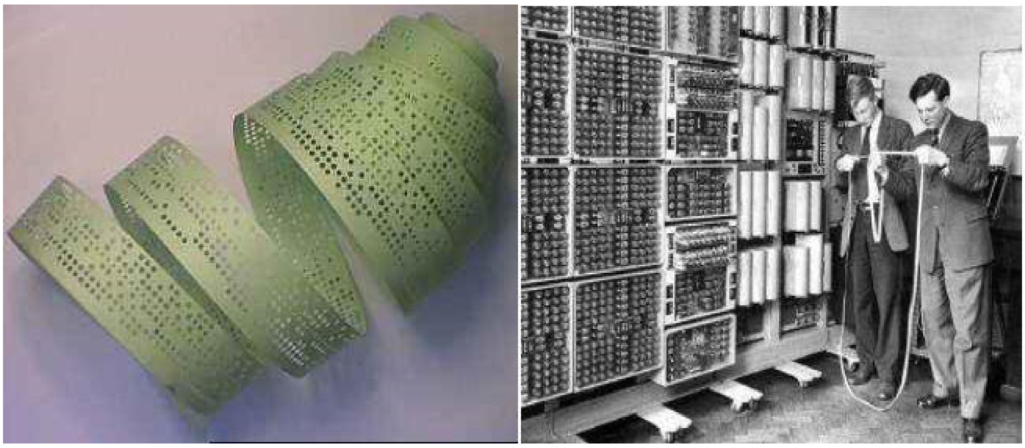

Fig. 3.3: Punched paper tapes.

Fig. 3.4: Tape.

hard disk storage. The other is security. The off-line characteristics of tape make it very defensive. Moreover, with the development of magnetic tape storage technology, the capacity of magnetic tape continues to increase, and the cost continues to decrease, so magnetic tape still has a strong vitality.

The operating instructions of the IBM System370 computer were stored in the semiconductor memory and were lost once shut down. Therefore, it was necessary to develop a cheap and portable device that could store and transmit the operating code of the computer. In 1967, the storage team of IBM's SanJose Lab started the road to their development of floppy disks (Fig. 3.5). Four years later, in 1971, Alan Shugart (who later left IBM to found Seagate) invented a plastic disk coated with oxide on the surface. This was the world's first floppy disk launched by IBM. The floppy disk [27] had a diameter of 8 inches and a capacity of 79.7KB. It was read-only. A readable-writable floppy disk appeared a year later. In fact, as early as 1952, Dr. Yoshiro Nakamura (Japan), the world's great inventor, who enjoyed the reputation of contemporary Edison, invented the floppy disk, but this was not recognized by IBM. In 1976, IBM introduced a 5.25-inch floppy disk (often called a 5-inch disk) with a capacity of 180KB (single-sided low-density) and 360KB (double-sided low-density). Later, the capacity was increased to 1.2MB (double-sided high-density). Although the volume was smaller than the 8-inch disc, it was still not convenient to carry, and the packaging was fragile and easy to break. In 1980, Sony first introduced 3.5-inch floppy disks (commonly called 3-inch disks) and floppy drives (Fig. 3.6), which were smaller in size and larger in capacity, reaching 1.44MB. It has 80 tracks, each track has 18 sectors, 512 bytes are stored in each

Fig. 3.5: Floppy disks of different types.

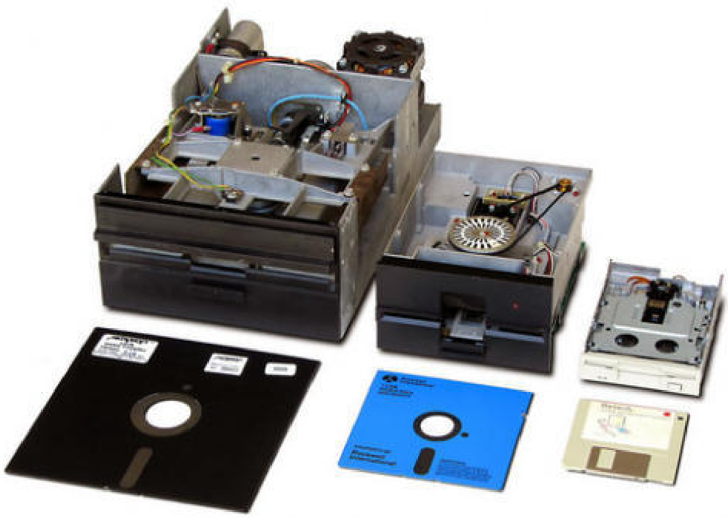

Fig. 3.6: Floppy drives of different types.

sector, and both sides can be stored. 80×18×2×512B=1440×1024B=1440KB 1.44MB. But at the time, 5-inch disks were still popular on the market. It wasn't until 1987, when IBM deployed 3.5-inch floppy drives on its personal computers, that 3-inch disks officially became popular. Because the previous computer programs were very small and the floppy disk was very cheap, it occupied the mobile storage monopoly for 20 years. Until the beginning of this century, many people still prepared floppy disks as system startup disks to install and restore operating systems. Moreover, many college and technical secondary school students used 3-inch disks to submit various computer assignments. In 2010, Sony discontinued production of floppy drives, and stopped selling floppy disks in March of the following year. Until then, the floppy disk had completely withdrawn from the storage market.

In 1956, IBM introduced 350 RAMAC [28] (Random Access Method of Accounting and Control) (Fig. 3.7), which was the world's first hard drive. The hard drive used 50 24-inch platters with a capacity of only 5MB. In 1968, IBM invented the Winchester technology, which sealed the magnetic head, seek mechanism and disk in a closed body to form a Head Disk Assembly (HAD) (Fig. 3.8). This enclosure is not a vacuum, it just isolates the dust from the external environment. This technology uses a lightly buoyant small head slider to implement contact start and stop, that is, the head does not touch the disk surface until it starts and stops. To prevent data from being destroyed, no data is stored in the start-stop area. Relying on ingenious aerodynamic design, when accessing data, the disk rotates at high speed, and the magnetic head flies at a height of 0.2

Fig. 3.7: The first hard drive.

Fig. 3.8: Hard disk.

to 0.5 m on the disk surface. Moreover, the surface of the disk is coated with lubricant, which can better protect the head and disk. This is the prototype of modern hard drives. In 1979, IBM introduced a thin film induction magnetic head, which reduced the weight of the magnetic head, thereby speeding up the access speed and increasing the storage density. In 1980, the 3380 hard drive manufactured by IBM had a total capacity of 2.52GB, but it was twice the size of a refrigerator and weighed 250KG. By the end of the 1980s, IBM invented the Magneto Resistive (MR) head, which was another major contribution to storage. Because magnetoresistive heads are very sensitive to data changes, the storage density of magnetic disks has been increased by tens of times compared with the past. In 1991, IBM applied magnetoresistive heads to its 3.5-inch hard drive, and the hard drive capacity exceeded 1GB, and the hard drive entered the GB era. In 1997, IBM introduced Giant Magneto Resistive (GMR) heads, which have higher sensitivity than MR heads, thus further increase the storage density. In 2003, IBM sold its hard-disk division to Hitachi of Japan, ending its glorious history in the disk field. Hitachi thus established Hitachi Global Storage Technologies (Hitachi GST, HGST for short).

The main part of a hard disk is a circular disk and a magnetic head. Each disk has a magnetic head on each side. Each disk has the same size and is divided into the same number of circular tracks, from the outside to the inside numbered from 0 , and the tracks with the same number form a cylinder. For example, the hard drive with the model number "HGST HTS545050A7E680" is a Hitachi hard drive. The parameters are: 969021 cylinder, 16 heads, 63 sectors/track, 512 bytes/sector. The number of sectors of the hard disk = head × cylinder × sector = 16 × 969021 × 63 = 976773168, this value is the number of LBA sectors. LBA is logical block addressing. In this mode, parameters such as head, cylinder (track), and sector are not actual physical parameters. In the old hard disk, the number of sectors in each track is the same, which will cause a great waste of outer track storage space. Later, in order to increase the capacity of the hard disk, the number of sectors set for each track is no longer the same, and the outer track will have much more sectors than the inner track. But in order to be compatible with the previous addressing mode, logical block addressing is adopted.

Because hard disks have the advantages of large storage capacity, convenient use, and high cost performance, they are still widely used until now. The parameters of the hard disk include capacity, rotation speed, average seek time, transmission rate, cache and so on. Rotation speed refers to the maximum number of revolutions of the disc in one minute, that is, the rotation speed of the spindle motor, and the unit is Revolutions Per minute (RPM). The common revolutions are 5400 or 7200 revolutions. The larger the revolutions, the faster the hard disk speed. Average Seek Time refers to the average time it takes for the head to move from the starting position to the specified track. The shorter the time, the faster the hard disk speed. Data Transfer Rate refers to the speed at which the hard disk reads and writes data, in megabytes per second (MB/s). The transmission rate is divided into internal transmission rate and external transmission rate. The internal transfer rate refers to the data transfer rate from the head to the hard disk cache, which mainly depends on the hard disk speed. The external transfer rate refers to the data transfer rate between the hard disk cache and the system bus, which mainly depends on the cache size and interface type. The cache is a memory chip on the hard disk controller [29], which has a fast access speed. It is a buffer between the internal storage of the hard disk and the external interface. A large cache can increase the external transmission rate of the hard disk. Interface types include ATA (Advanced Technology Attachment), SATA (Serial ATA), SCSI (Small Computer System Interface) and SAS (Serial Attached SCSI), etc. The ATA interface uses a traditional 40-core cable to connect to the motherboard. It is a parallel interface, which is different from the serial ATA later, also known as PATA (Parallel ATA). Usually known as IDE (Integrated Drive Electronics) hard disk, originally meant the hard disk drive that integrates the controller and the disk body, and also indicates the hard disk interface, commonly known as the PATA interface. SATA is a serial interface developed on the basis of ATA, which overcomes the crosstalk of the PATA interface, and the external transmission rate has reached 150MB/s. SATA also has stronger error correction capabilities and has basically replaced the traditional PATA interface. The SATA interface was later developed into SATA and SATA , and the transmission speed continued to increase, reaching 600MB/s. The SCSI interface is not an interface specifically produced for hard disks, but a high-speed data transmission interface for small computer systems. The SCSI interface is connected by a 50 or 68-core cable, which is a parallel interface, supports multi-tasking, hot-plugging, and has a low CPU occupancy rate. But it is not compatible with ATA and the price is high, so it is mainly used for advanced servers. SAS is a serial SCSI, which improves the transmission speed and is compatible with SATA.

RAID (Redundant Arrays of Independent Disks) is a disk group with huge capacity composed of multiple independent disks. This technology expands the disk capacity, improves data access speed by accessing data in blocks or accessing several disks at the same time, realizes redundant backup of data through mirroring and so on. The concept of RAID was proposed by David Patterson, Garth A. Gibson, and Randy Katz of the University of California at Berkeley in 1987 [30], but the original I was not independent, but inexpensive, which can be seen from their paper "A Case for Redundant Arrays of Inexpensive Disks (RAID)" published in June 1988. In fact, the essence of RAID technology can be traced back to the patent US4092732 in 1978. This is the patent "SYSTEM FOR RECOVERING DATA STORED IN FAILED MEMORY UNIT" invented by Norman Ken Ouchi of IBM. The patent proposes technologies such as disk mirroring and special parity check codes. RAID is divided into multiple levels according to the technology and structure used, including RAID 0, RAID 1, RAID 0+1, RAID 2, RAID 3, RAID 4, RAID 5, RAID 6, RAID 7, RAID 53. RAID 0 mainly realizes data striping access, at least two disks, but no redundancy; RAID 1 mainly realizes disk mirroring, at least two disks, but the utilization rate is 50%; RAID 0+1, as the name implies, is the two technologies are combined, divided into RAID 01 and RAID 10, according to the order of using RAID 0 and RAID 1. It is a highly reliable and efficient disk structure, but at least four disks are required and the cost is high; RAID 2 uses Hamming code calibration; RAID 3 adopts bit-wise parallel transmission technology with parity check code; RAID 4 adopts

Fig. 3.9: CD and DVD.

data block transmission technology with parity check code; RAID 5 uses distributed parity check; RAID 6 uses two kinds of distributed parity check; RAID 7 adopts optimized high-speed data transmission technology; RAID 53 is a combination level like RAID 0+1, however it is not a combination of RAID 5 and RAID 3, but RAID 0 and RAID 3 The combination.

CD (Compact Disc) is what we usually call optical discs (Fig. 3.9), which use optical storage media that are different from previous magnetic media, rely on laser principles to read and write storage devices. In 1972, Philips of the Netherlands successfully developed the use of laser beams to record and reproduce information. In 1978, the Laser Vision Disc (LD) was put on the market [31]. What LD stores is the analog signal of image and sound. In 1982, Philips and Sony jointly formulated the CD-DA (Compact Disc-Digital Audio) standard. CD-DA records the analog signal on the disc after PCM (Pulse Code Modulation) digital processing. The advantage of digital recording is that it is not sensitive to interference and noise. Although the thickness of a CD disc is only 1.2mm, it is a multilayer structure: substrate, recording layer, reflective layer, protective layer and printing layer. Since the laser wavelength is 780nm, the numerical aperture (NA) of the objective lens is 0.45, and the distance for the laser beam to converge to a point needs 1.2mm, so the thickness of the CD disc is 1.2mm, too thick or too thin will affect the data access . The substrate is a circular polycarbonate (Polycarbonate, high molecular polymer containing carbonate base, PC plastic for short)sheet with a diameter of 12cm and a hole in the middle, which is the appearance of an optical disc that is usually seen. Regarding the diameter of the disc, Philips recommends 11.5cm, which can record for 60 minutes, which is suitable for car audio systems on the European market. Sony believes that it should be set to 12cm, recording 74 minutes and 42 seconds. Because Norio Oga, who leads Sony, is a musician, he believes that "it is incomplete for the recording of Beethoven's Ninth Symphony to be difficult." In the end, Sony's claim was passed. The recording layer is the place where information is recorded. The substrate is coated with special organic dyes. When burning information, the laser burns the organic dyes into "pits" one after another. Both pits and no pits represent the information "0", the edge of the pit Represents information "1". Since these pits cannot be recovered, this is a non-rewritable CD. For rewritable optical discs, the substrate is coated with carbonaceous material, which changes the polarity of the carbonaceous material during recording. Since the polarity of the carbon substance can be changed repeatedly, this forms a rewritable optical disc. The reflective layer is the third layer, which is used to reflect the laser beam of the optical drive. The reflected laser beam is used to read the information in the optical disc. The material of this layer is 99.99% pure silver, aluminum or copper. When light reaches this layer, it will be reflected back, making the disc look like a mirror. The protective layer is a light-curing acrylic material to protect the reflective layer and the dye data layer from damage. The printing layer is where the information and capacity of the optical disc are printed, that is the back of the optical disc, and it also protects the optical disc.

VCD is a video compact disc. The difference between it and CD is that it records film and television information, so it is commonly called video disc. There are different standards for the compression of data on optical discs. According to the color of each standard package, it mainly includes the following types: 1) Red Book, a CD-DA disc jointly developed by Philips and Sony for storing audio sound tracks Standard, contains only audio sector tracks. 2) Yellow Book, the CD-ROM data disc standard jointly developed by Philips and Sony, contains only data sectors. 3) Green Book, the CD-I (Compact Disc Interactive) standard developed in 1986.

4) Yellow Book Advanced, the CD-ROM/XA (CD-ROM eXtended Architecture) disc standard supplemented in 1989, can interlace data or audio and video storage. 5) The Orange Book has formulated a standard for rewritable discs. The disc is divided into data area, data area is divided into tracks, and the track is divided into sectors. 6) Blue Book stipulates the CD-Extra in extra mode, the first track is CD-DA music, and the second track is CD-ROM data. 7) White Book, which defines the VCD standard, and the video CD mentioned here is the white paper standard. VCD uses MPEG-1 compression method to compress images. MPEG is the Moving Picture Experts Group, an organization that specializes in formulating international standards in the multimedia field. It includes three parts: MPEG video, MPEG audio, and MPEG system (audio and video synchronization). The audio format of VCD uses 44.1KHz sampling frequency, 16 Bit sampling value and Stereo, before uncompressed, such audio format is CD sound quality. The CD restored by this compression method has the same sound quality as the original CD, and even professionals cannot hear the difference, so this is a lossless compression. MPEG-1 layer 1 and layer 2 are compression processing methods that are specially designed to deal with the audio format of VCD, and layer 3 is the MP3 music format that we know well. MP3 uses 192Kb/s Audio Bit Rate compression. Compared with the original music, there is some slight distortion after restoration, so MP3 is a lossy compression, which is compressed by as much as 10 times. VCD can be played directly on a VCD player, or on a computer equipped with an optical drive. But because VCD has strict format regulations, sometimes the discs burned by oneself cannot be played on the VCD player.

DVD (Fig. 3.9) is a digital versatile disc, with MPEG-2 as the standard, with a capacity of 4.7G, which can store 133 minutes of high-resolution full-motion movie and television programs, and the image and sound quality is beyond the reach of VCD. The surround channel adopts Dolby Digital technology, which is a new generation of home theater surround sound system released by Dolby Laboratories. The digital sound includes front left, center, front right, surround left, and surround right. The signal of 5 channels, plus a single subwoofer effect channel namely 0.1 channel, is called 5.1 channel together. The difference between DVD and VCD is as follows: 1) The color of VCD discs is aluminum white, or slightly light blue, light green, etc.; while DVD discs are very obvious dark purple, which is the color of alumina after treatment. After the data has been burned, the color of the inner circle becomes darker, making it easier to see if there is data on the DVD disc. 2) The capacity of CD/VCD discs is about 600-700MB, while that of DVD is much larger, reaching about 4.3GB. 3) CD/VCD discs use a near-infrared invisible laser with a wavelength of 780nm for reading and writing data, and DVD discs use a red laser with a wavelength of 650nm for reading and writing operations. 4) The image resolution of VCD is only 352×240 (NTSC: National Television Standards Committee in Japan and the United States) or 352×288 (PAL: Phase Alteration Line in China and Europe). The DVD with MPEG2 standard image compression technology has a resolution of up to 720×480. MPEG2 also has dynamic stream control technology, which can flexibly adjust the video reading rate. In 2002, Sony Group led the planning and development of Blu-ray Disc (BD). The English name of BD is Blu-ray Disc, not Blue-ray Disc. This is because the word Blue-ray Disc is too colloquial in Europe and the United States and cannot be approved for trademark application, so the trademark registration is completed by removing the letter e. Blu-ray discs are named because they use a blue laser beam with a wavelength of 405nm for reading and writing operations. Since the blue light has a shorter wavelength, the focal diameter after focusing is smaller, and the use of different reflectivity for multi-layer writing, so the Blu-ray disc has a larger capacity. A single-layer Blu-ray disc has a capacity of 25 or 27GB and can burn up to 4 hours of high-resolution video.

Hard disks and floppy disks are magnetic media storage, optical disks are optical storage, and semiconductor storage is now widely used. Flash memory is a long-life memory that does not lose data (non-volatile) when power is off. It was invented by Dr. Fujio Masuoka when he was working at Toshiba in 1984 [32]. It is named flash because the memory erasing process is reminiscent of a camera's flash. Flash memory technology uses charges stored on a piece of floating polysilicon (floating gate) placed on a gate oxide layer to achieve storage. In 1988, Intel and Toshiba introduced NOR-type and NAND-type flash memory respectively. The NOR type belongs to the internal memory described later, and the NAND type flash memory is described here. So far, NAND flash memory has various forms (Fig. 3.10), including SSD (Solid State Drive), U disk, CF (Compact Flash) card, SD (Secure Digital) card, TF (Trans-Flash) card, memory stick and so on. The naming of the U disk comes from the use of the USB (Universal Serial Bus) interface, which supports hot swap. From 1998 to 2000, many companies claimed that they were the first to invent USB flash drives, including China Netac

Fig. 3.10: Various forms of flash memory.

Fig. 3.11: Different interfaces of USB.

Technology (Netac), Israel M-Systems, Singapore Trek Company. However, it is China Netac [33] that has obtained the basic invention patent of the U disk. Netac has registered the trademark "USB flash drive", so many people also call the USB flash drive "U Disk". The USB 1.0 standard was proposed in 1996, and the speed was only 1.5 Mbps. Two years later, the USB 1.1 speed reached 12 Mbps. The speed of USB 2.0 introduced in 2000 reached 480Mbps, and the maximum speed of USB 3.0 used today can reach 5.0Gbps. The color of the plastic sheet of the U disk interface can help us identify its version, the black one is 2.0, and the blue one is 3.0. The USB interface has only 4 wires, 2 power wires and a pair of differential signal wires, so it is serial transmission. The package of the USB interface (Fig. 3.11) includes Type A (usually USB flash drive interface), Type B (square ladder type port), Mini B type (small square ladder type port), Micro USB type (smaller than Mini B type, the previous Android phone charging interface), Type-C (current Android phone charging interface, regardless of direction) type. The Type-C interface puts an end to the worries of people plugging in the wrong direction. According to the half probability that one billion people in the world make mistakes every day, and each error takes extra 2 seconds, which can save more than 277777 hours, a total of about 31.7 years. SD card was jointly launched by Panasonic, Toshiba and SanDisk in 1999. It has a size of 32mm x 24mm x 2.1mm and supports hot swap. It is widely used in portable devices such as digital cameras. Ordinary computers can use a USB card reader to access the SD card, and some notebooks come with an SD card interface. The memory stick is a memory card developed by Sony. Its early size was 50mm x 21.5mm x 2.8mm, which was similar to chewing gum. Unlike other flash memory cards, the interface standard of the memory stick is non-public. SSD is a solid state drive (Fig. 3.12). Unlike traditional hard drives that require high-speed rotating disks and moving heads, SSD uses microchips and has no moving parts, so it has strong shock resistance, low noise, short read and write and short delay times. And it has the same interface as traditional hard disks, it is easy to replace traditional hard disks, but the current price is still relatively high.

4. The development of internal memory. The earliest internal memory can be traced back to Magnetic Drum [34], which was invented in 1932 by Gustav Tauschek, an Austrian engineer from IBM. After 20 years, the drum memory technology was widely adopted, and it was the first computer memory to be widely used. The

Fig. 3.12: Solid state drive.

magnetic drum (Fig. 4.1) uses a magnetic material coated on the surface of a circular aluminum drum to store data. The drum rotates at high speed during operation. A set of fixed magnetic heads are arranged close to the surface of the cylinder to read and write data. The magnetic drum adopts saturation magnetic recording, from fixed magnetic head to floating magnetic head, and from magnetic glue to electroplated continuous magnetic medium, which laid the foundation for later disk storage. The drum was first used in IBM 650 as internal memory. The drum is 16 inches long, has 40 tracks, can rotate 12,500 revolutions per minute, and can store 10KB of data. The biggest disadvantage of the magnetic drum is that the storage capacity is too small. A large cylinder has only one surface layer for storage. More than ten years after the invention of the drum memory, some other types of memory have also been born. One of them is the Williams tube [35] in 1947, the full name is Williams-Kilburn tube, a kind of storage device composed of cathode ray tube (CRT) . The name of the Williams tube comes from the developers Freddie Williams and Tom Kilburn. Williams tubes store data as charged points on the surface of the cathode ray tube. Since the electron beam of the cathode ray tube can read and write the points on the electron tube in any order, it is random access, which is in line with the characteristics of our current internal memory. The capacity of Williams tubes is only a few hundred to about 1,000 bit. The Manchester Baby [36] computer (also known as Small-Scale Experimental Machine, SSEM for short) that appeared in 1948 successfully ran an electronic storage program for the first time, using a Williams tube. Although the Williams tube was not designed for SSEM, the use of SSEM had verified its reliability.

Another well-known early memory is the Mercury Delay Line [37], its principle is very simple, a stone is thrown into the water to form a wave, and the wave head can spread to a distant place after a period of time. In other words, the pulse is transmitted from one end of the mercury-filled tube to the other, assuming that it takes one second to propagate, the data will be stored in this second. Since no ready-made devices were available at that time, in order to find a suitable memory, researchers explored almost all physical phenomena-electricity, magnetism, light and sound. Finally, because the acoustic impedance of mercury is close to piezoelectric quartz crystal, when the signal is transmitted from the crystal to the medium and then back, the energy loss and echo are minimized. Therefore, although mercury has defects such as weight, cost and toxicity, mercury is still used to make memory. Moreover, in order to make the acoustic impedance as close as possible, the mercury must be kept at a constant temperature, that is, the mercury must be heated to 40 degrees Celsius above room temperature. In March 1951, the first universal automatic computer UNIVAC-1 designed by Mauchly and Eckert (the main designers of ENIAC) used a mercury delay line memory device [38]. The mercury delay line (Fig. 4.2) is a tube with a length of 150cm and a diameter of 10 mm, filled with mercury. There are converters at each end for electrical-acoustic conversion and acoustic-electrical conversion. In this way, the pulse signal enters from one end of the tube and is converted into ultrasonic waves. After 960ms, the ultrasonic waves reach the other end of the tube, and then are converted into electrical signals for output. The mercury delay line is the heaviest internal memory in history, and each mercury tank weighs more than one ton.

Magnetic-core memory was invented by Wang An of Ethnic Chinese in 1948. Magnetic-core memory is usually called core memory [39], so until today, people are used to calling memory as core because of this. A wire is inserted into the ferrite magnetic ring. When currents in different directions flow through the wire, the

Fig. 4.1: Magnetic drum memory.

Fig. 4.2: Mercury delay line memory.

magnetic ring can be magnetized in two different directions, and the information representing "1" or "0" is stored in the form of a magnetic field. Each core has wires in two directions that are perpendicular to each other, x and y, and there is also a readout line that traverses diagonally. As shown in Fig. 4.3, x and y are addressed in two different directions.When a certain current flows through the wire, the magnetic core will be magnetized or the direction of magnetization will be changed. The minimum threshold value of the current that can magnetize the magnetic core can be obtained through experiments in advance. When writing data, input a current slightly higher than 50% of the magnetization threshold of the magnetic ring on the x and y coordinate lines corresponding to the magnetic core to be written, so that only the magnetic core corresponding to the x and y coordinates will have current in both lines at the same time. And the threshold will be exceeded after superposition, and the magnetic core will be magnetized or change the direction of magnetization, thus writing one bit of data. At the same time, the current passing through all other magnetic cores is either 0 or 50% of the magnetization threshold, and cannot be magnetized, so no data is written. The process of reading data is more troublesome. A read current slightly greater than 50% of the magnetization threshold is sent in the x and y directions. The direction of the read current is known in advance, so that the core corresponding to the x and y addressing coordinates will have current exceeding the threshold. If its original magnetic field direction is the same as the direction of the magnetic field corresponding to the read current, magnetic state of the magnetic core will not change, and there will be no induced current on the readout line traversing diagonally. It can be seen that the data stored in the magnetic core and the read signal are the same. On the contrary, if its

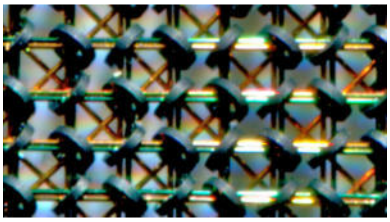

Fig. 4.3: Magnetic-core memory.

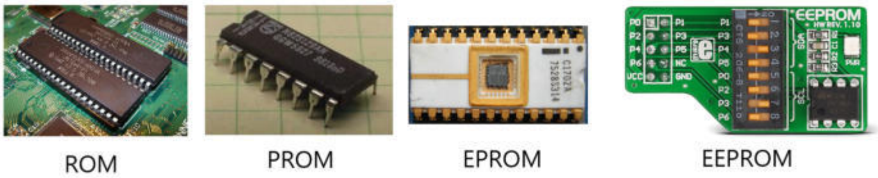

Fig. 4.4: ROM of Various types.

original magnetic field direction is opposite to the direction of the magnetic field corresponding to the read current, magnetic state of the magnetic core will be reversed [40], there will be a huge magnetic flux change, so there will be a large induced current on the readout line traversing diagonally. It can be seen that the data stored in the magnetic core is opposite to the read signal. However, the reading process is destructive. After reading the data, the magnetic core is written with the same read data. The way to recover the data is to write back the original data in the cache. Magnetic core memory is different from ordinary internal memory in two points: first, reading data is slower than writing data, because reading data also includes one-time write recovery; second, data is not lost when power is off, which is similar to the non-volatile random access memory that is being developed today. IBM purchased the magnetic core memory patent with a huge amount of money from Wang An in 1956, in order to solve the problem of data storage in large computers at that time. However, the magnetic core memory also has its shortcomings. The magnetic core is easily damaged, expensive, and slow in operation. In order to solve these problems, IBM has conducted research more than ten years. In 1961, IBM established the Thomas Watson Research Center in New York State, with semiconductors as the direction, and its semiconductor device supplier was Fairchild. Gordon Moore from Fairchild published an article in the ”Electronics” magazine in 1965 and predicted: when the price remains the same, the number of transistors that can be accommodated on an integrated circuit will double about every 18 months, and the performance will also be increased doubled [41]. This prediction was later called ”Moore’s Law”.

With the increase in storage density, smaller magnetic cores and wires are required, and the difficulty of manufacturing is also increasing. By the end of the 1960s, when the first generation of semiconductor memory chips came out, the magnetic core memory market began to suffer. Semiconductor memory can be divided into read only memory (ROM) and random access memory (RAM) according to functions. As the name suggests, ROM (Fig. 4.4) can only read the content of the memory. The content stored in it is written in one time by the manufacturer using mask technology and stored permanently. ROM is generally used to store fixed and dedicated programs and data. It is a non-volatile memory. Once the information is written, it will not be lost due to power failure. The content of read-only memory required by different users is different. For ease of use and mass production, programmable read-only memory [42] (PROM: Programmable ROM) has been further developed. PROM is generally programmable once, and each memory unit is all 1 or all 0 when leaving the factory. When the user uses it, use the programming method (electricity or light) to store the required data. For example, bipolar PROM has two structures: one is the fuse blown type, and the other is the PN junction breakdown type. They can only be rewritten once, and once the programming is completed, their content is permanent. In order to overcome the drawbacks of programming only once, EPROM (Erasable Programmable

Read Only Memory) was born. EPROM allows users to write content according to their needs, and can erase and rewrite the written content. It is a ROM that can be rewritten multiple times. Because it can be rewritten, the user can correct the written information and rewrite it after correcting the error. EPROM can use high voltage to program and write data, and the data can be cleared by exposing the circuit to ultraviolet light when erasing. To facilitate exposure, a transparent quartz window is reserved on the package shell, but usually, the window is sealed with an opaque sticker or tape to protect the data. In 1979, Intel introduced the first electrically erasable programmable read only memory [43] (EEPROM, also known as E2PROM), which solved the inconvenience of EPROM operation. The erasing of EEPROM is carried out by electronic signals, without the help of other equipment, and the minimum modification unit is byte, so there is no need to clear all the data and write it. EEPROM is a dual-voltage chip. When writing data, a certain programming voltage must be used, and the content can be easily rewritten by using the dedicated refresh program provided by the manufacturer. BIOS can prevent viruses by virtue of the dual-voltage feature of the EEPROM chip: when refreshing, turn the jumper switch to the "on" position, and apply the programming voltage to the chip; in normal use, turn the jumper switch to the "off" position, prevent viruses from illegally modifying the BIOS chip.

In 1964, the original Fairchild semiconductor company(known as the cradle of Silicon Valley talent) developed a 64-bit metal oxide semiconductor (MOS) static random access memory [44] (SRAM: Static RAM). In 1966, Dr. Robert H. Dennard of 34 years old from the IBM Thomas Watson Research Center, proposed the idea of using MOS transistors to make memory chips. The principle is to use the amount of charge stored in the capacitor to represent whether a binary bit is 1 or 0. Each bit only needs one transistor and one capacitor (1T/1C structure). In June 1968, IBM registered a patent for transistor DRAM (Dynamic RAM) (Patent No. 3387286). The dynamic here is relative to the static state. DRAM needs to be charged and refreshed every certain period of time, otherwise the data will be lost, but the SRAM can save the data without refreshing. SRAM does not need to cooperate with memory refresh, so it has high working efficiency and high speed; but its unit circuit is complicated, the integration level is low, and the price is high. Because IBM was undergoing an antitrust investigation by the US Department of Justice at the time, it delayed the commercialization of DRAM. In August 1968, Fairchild's general manager Bob Noyce and head of R&D department Gordon Moore resigned from Fairchild. They pulled 2.5 million US dollars from venture capitalist Arthur Locke and registered a company, which is now the famous Intel company. The word of "Intel" means wisdom and integrated circuits in English, and the trademark was bought from a hotel for $15,000. At that time, the company had only two employees, Noyce and Moore, and they recruited Andy Grove, a process development expert from Fairchild. Then in 1969, Fairchild's marketing director Jerry Sanders pulled 7 employees to form AMD (Advanced Micro Devices) company. Due to financing difficulties, Sanders pulled $1.55 million in investment from Intel's Noyce. Over the next half century, Intel and AMD have become a pair of intractable competitors. In 1969, Intel Corporation developed the first 256-bit SRAM [45], named the 1101 chip, which was officially launched in 1971. The 1101 chip was the world's first mass-produced MOS internal memory using silicon semiconductor technology. The 1101 chip was later improved into the DRAM chip 1103. 1103 was Intel's first star product, so that all companies at that time had to be compatible with this immature chip. For example, due to a design error in 1103, three kinds of voltages have appeared. For compatibility, other companies can only design 3 voltages. This small step by Intel can be said to be a big step in memory history. At that time, the memory was directly installed on the motherboard's DRAM socket in the form of a DIP (dual in-line package) chip, and the package interface was 30-pin SIPP (Single In-line Pin Package) interface. With a capacity of only 64KB to 256KB, the memory is not easy to expand, but it is sufficient for the processors and programs at the time. Until the emergence of 80286, software and hardware put forward greater demand for memory, so the memory module was born, and the package interface was upgraded to 30pin SIMM [46] (Single In-line Memory Modules). The pin definition is actually the same as SIPP. Golden fingers of both sides transmit the same signal. Although SIMM quickly replaced SIPP, the two forms of memory coexisted for a long time. The first-generation SIMM memory with only 30 pins, a single memory data bus has only 8 bits, a 16-bit data bus processor requires two, and a 32-bit data bus processor requires four, which is costly and frequently fails. The emergence of 72pin SIMM memory solves these problems. The bit width of a single memory is increased to 32 bits, and a 32-bit data bus processor only needs one memory. The early memory frequency is not synchronized with the CPU external frequency. It is asynchronous DRAM, including fast page mode dynamic memory

Fig. 4.5: DDRx.

(FPM DRAM: Fast Page Mode DRAM) and extended data output memory [47] (EDO DRAM: Extended data out DRAM). Operating voltage is all 5V. FPM DRAM is improved from the early Page Mode DRAM. When reading the same row of data, it can continuously transmit the column address without the need to transmit the row address. This is much more advanced than that of Page Mode DRAM, which must transmit the row address and column address every time it is accessed. The common capacity of 30pin FPM DRAM is 256KB, and the capacity of 72pin FPM DRAM ranges from 512KB to 2MB. EDO DRAM improves the access mode of FPM DRAM, without waiting for the completion of read and write operations, as long as the specified valid time expires, the next address can be output. EDO DRAM is 72pin, and the capacity of a single EDO memory ranges from 4MB to 16MB. A processor with a 64-bit data bus needs to use two EDO memories.

With the development of processors, memory technology has also undergone changes. The socket has been upgraded from the original SIMM to DIMM (Dual In-line Memory Module). The golden fingers on both sides transmit different data and enter the era of classic synchronous dynamic random access memory (SDRAM: Synchronous DRAM). Synchronization refers to the synchronization of the memory frequency with the CPU FSB, which greatly improves the efficiency of data transmission. The first is the single data rate synchronous dynamic random access memory SDR SDRAM [48] , which was born in 1993. Here, SDR is relative to the later double data rate DDR (Double Data Rate). The DDR X (Fig. 4.5) mentioned in the article is actually the abbreviation of DDR X SDRAM. The interface of the SDR SDRAM memory socket is 168Pin, and the number of pins on one side is 84. It uses a 64-bit data bus. A 64-bit data bus processor only needs a single memory. The frequency of the first generation SDR SDRAM is 66MHz, usually called PC66 memory [49]. Later, as the frequency of the processor increased, PC100 and PC133 memory appeared one after another. SDR SDRAM has a standard operating voltage of 3.3V and a capacity ranging from 16MB to 512MB. In order to further increase the transmission rate, an upgraded version of SDR SDRAM, double data rate synchronous dynamic random access memory (DDR SDRAM) appeared in 1996. SDR SDRAM only transmits data on the rising edge of the clock period, while DDR SDRAM transmits the signal at the rising edge and the falling edge of the clock cycle respective [50], making its data transmission speed twice that of SDR SDRAM, and it will not increase power consumption. So until now the technology used in memory is still DDR, but the version has been upgraded from DDR1 to DDR4, and DDR5 is also being developed. Corresponding to the synchronous dynamic random access memory (SDRAM), the synchronous static random access memory (SSRAM) is also developing synchronously. And the speed of SSRAM is faster, but due to its complex unit structure, the integration is not as high as SDRAM, which brings about a cost increase. This limits its popularity, mainly used in caches and some servers.

DDR SDRAM uses a 184pin DIMM slot. The fool-proof notch is changed from two for SDR SDRAM to one. The operating voltage is 2.5V. The initial DDR memory frequency is 200MHz, and then 266MHz, 333MHz and mainstream 400MHz are slowly born. The capacity ranges from 128MB to 1GB. DDR2/DDR II (Double Data Rate 2) SDRAM is a new generation memory technology standard developed by JEDEC (Joint Electron

Device Engineering Council) in 2003. The biggest difference between DDR2 and DDR is the use of 4bit data prefetching, that is to say, DDR2 memory can access data at 4 times the speed of the external bus per clock cycle. DDR2 uses a 240pin DIMM slot, the working voltage is reduced to 1.8V, which is more energy-efficient than DDR. The mainstream frequency is 800MHz, and the capacity ranges from 256MB to 4GB, mostly with a single 2GB capacity. In 2007, JEDEC developed the DDR3 memory standard. Compared with DDR2, DDR3 has made new specifications in many aspects. The DDR3 core voltage drops to 1.5V, and the data prefetching increases from 4bit to 8bit. The bandwidth of DDR3 at the same core frequency is twice that of DDR2. DDR3 also uses 240pin DIMM slots, the frequency ranges from 1066MHz to 2400Mhz, and the capacity ranges from 512MB to 8GB. In 2011, JEDEC developed the DDR4 memory standard. Compared with DDR3, DDR4 also made some new specifications. The DDR4 operating voltage is further reduced to 1.2V, and the data prefetching still maintains 8bit, because it is too difficult to increase the prefetching to 16bit. However, DDR4 has increased the number of banks, using Bank Group (BG) design, 4 banks as a BG group, you can use 2 to 4 BGs. If 2 BGs are used, the data of each operation is 16bit, and 4 BGs can reach 32bit operations. It can be said that the number of prefetch bits is increased in disguise. DDR4 uses a 288-pin DIMM slot, and the location of the fool-proof notch is also different from that of DDR3. In addition, the gold fingers of DDR4 have a slight curve—the middle is slightly protruding and the edges are shortened, while the previous memory gold fingers are straight, which can ensure that there is enough signal contact area between DDR4 and DIMM slot, so the signal is more stable. And it will be easier to remove the memory module.

LPDDR is called Low Power Double Data Rate SDRAM, which is a type of DDR SDRAM, also called mDDR [51] (Mobile DDR SDRAM). LPDDR is a low-power memory standard drafted by the JEDEC Solid State Technology Association. It is characterized by low power consumption and small size, specially used for mobile electronic products. The JEDEC released the second-generation low-power memory technology LPDDR2 standard in December 2010, and the LPDDR3 standard in May 2012. Its working voltage is 1.2V, which is lower than the 1.5V of DDR3. Compared with LPDDR3, the first-generation LPDDR4 standard released in 2014 has an operating voltage drop of 1.1V, which can be said to be the lowest power solution for mobile devices such as large-screen mobile phones and tablets. Currently, the faster LPDDR5 is also being developed and implemented.

The flash memory mentioned in the external memory above is divided into Nor(or not) Flash and Nand(and not) Flash, the difference is as follows. The first is the interface: address and data bus of Nor Flash are separated; but that of Nand Flash are shared. The second is the reading and writing unit: Nor Flash is read and written by byte; but Nand Flash is read and written by page. The third is the composition structure: the structure of Nor Flash is sectors and bytes; while Nand Flash is divided into blocks and pages, and only supports page-level writing. Even if only one byte is changed, the entire page must be rewritten. The fourth is the erasing unit: the erasing unit of Nor Flash is sector, which takes about 5 seconds, and the maximum number of erasing is 100,000; that of Nor Flash is block, which only requires 4 milliseconds, and the maximum erasing number is 1 million times. The fifth is the application scenario: Nor Flash is mainly used for program storage in the industrial field; Nand Flash is mainly used for large data storage in the consumer field. Nor Flash can be used as internal memory.

In recent years, with the continuous development of non-volatile random access memory (NVRAM Non-Volatile RAM) and its technology, various NVRAMs have emerged. Ferroelectric RAM (also known as FeRAM or FRAM) uses a layer of ferroelectric material to replace the original dielectric, making it also have the function of non-volatile memory [52]. Ferroelectric memory can be traced back to 1952. The master's thesis "Digital Information Storage and Data Exchange of Ferroelectrics" by MIT graduate student Dudley Allen Buck discussed "ferroelectric memory". But it was nearly 40 years later that the Jet Propulsion Laboratory of the National Aeronautics and Space Administration put this technology into practice in 1991. However, the research and development of new FeRAM chips is still the current research topic of major research centers. FeRAM can be divided into destructive readout and non-destructive readout according to the working mode. The destructive readout mode is to use the capacitance effect of the ferroelectric film, replace the conventional capacitor with the ferroelectric film capacitor, and use the polarization reversal of the ferroelectric film to realize the writing and reading of data. Data needs to be rewritten after destructive reading, so FeRAM is accompanied by a large number of rewriting operations in the information reading process. Non-destructive readout replaces the gate silicon dioxide layer in the MOSFET with a ferroelectric thin film, and modulates the source-drain current through the gate polarization state. The stored information can be read according to the size of the source-drain current value. Because the polarization state of the gate does not have to be reversed, the readout method is non-destructive. However, this approach is still in the research stage.

Magnetic RAM (MRAM) stores data by magnetic field polarization instead of electric charge. The memory cell of MRAM includes a free magnetic layer, a tunnel gate layer and a fixed magnetic layer. The direction of the magnetic field of the fixed layer is unchanged, and the polarization direction of the free magnetic layer is variable. When the direction of the magnetic field of the free layer and the fixed layer are parallel, the memory cell exhibits low resistance; on the contrary, it exhibits high resistance. By detecting the resistance of the memory cell, It can be judged whether the data is 0 or 1. Since the magnetic properties of ferromagnetic materials will not disappear due to power failure, MRAM is non-volatile. Theoretically, ferromagnets are permanently effectual, so the number of writes is also unlimited. Currently commonly used is the current-driven spin transfer torque MRAM (STT-MRAM). This technology originated in 1996. Slonczewski and Berger theoretically predicted a purely electrical magnetic tunnel junction writing method called spin transfer torque [53]. STT-MRAM can achieve a good compromise in terms of speed, area, and power consumption, so it has a wider range of applications. In 2008, Siemens Industrial Automation Division adopted 4Mb MRAM for human-computer interaction interface for industrial control. In 2009, French Airbus decided to replace the original SRAM and FLASH with MRAM in the flight control computer of the A350 XWB aircraft. In 2013, Buffalo Memory announced the use of STT-MRAM instead of traditional DRAM as a high-speed cache in solid-state hard drives (SSDs). In 2018, IBM introduced 256Mb STT-MRAM chips into the latest generation of enterprise SSDs.

Resistive RAM (RRAM) consists of two metal electrodes sandwiching a thin dielectric layer, which serves as an ion transmission and storage medium [54]. The storage medium ion movement and local structural changes caused by external voltages, which in turn cause resistance changes, RRAM uses this resistance difference to store data. Different media materials have different storage effects. The materials selected for RRAM are mostly metal oxides. In addition, sulfides and organic dielectric materials have also received a certain degree of attention. At present, the most accepted is the conductive filament, because it does not depend on the area of the device, and the potential for miniaturization is huge. The memory matrix of RRAM can be divided into passive matrix and active matrix. The memory cell of the passive matrix is connected by a resistive element and a diode. The function of the diode is to prevent the memory cell information from being lost when the resistive element is in a low resistance state. The advantage of the passive matrix is simple design and good miniaturization; the disadvantage is that there is inevitably interference between adjacent units. The active matrix is just the opposite. The transistor controls the reading and writing of the resistive element. The advantage is to isolate the interference of adjacent cells; the disadvantage is that the design is complicated and the miniaturization is poor. In addition, some of the resistive random access memory materials also have multiple resistance states, making it possible for a single memory cell to store multiple bits of data, thereby increasing the storage density.

Phase-change RAM (PRAM or Phase-change memory: PCM) is made of Chalcogenide glass containing one or more chalcogenides [55]. Chalcogenide glass can change its state after heating and become crystalline or amorphous. Different states have different resistance values and can be used to store different values. In fact, as early as 1969, Charles Sie of Iowa State University discussed this memory technology in his doctoral thesis. Intel's co-founder Gordon Moore also published an article in 1970 describing phase change memory. However, due to the complexity of the technology, many research centers are still under development. At present, only Samsung, Micron, and Intel have launched phase change storage products in the world. In May 2017, Intel released Optane storage products based on 3D Xpoint, which is phase change memory. The Song Zhitang research team of the Shanghai Institute of Microsystems, Chinese Academy of Sciences, has been devoted to phase change memory research for 15 years. They have cooperated with SMIC(Semiconductor Manufacturing International Corporation) to achieve a major breakthrough in the research and development of phase change memory at the 130nm technology node. Industrialized sales have been realized through the phase-change memory chip for printers developed in collaboration with Zhuhai Apex Microelectronics Co., Ltd.

The development history of external storage and internal memory is detailed above, and the development

Fig. 4.6: Memory development history.

context is shown in Fig. 4.6.

5. The development trend of memory. It is generally believed that the reason why memory is divided into internal memory and external storage is due to the significant difference between the computing speed of the CPU and the access speed of the memory. In order to match the computing speed of the CPU as much as possible and improve the computing efficiency of the CPU, the memory is divided into internal memory and external storage, and the high-speed memory communicates directly with the CPU, and the low-speed external storage communicates with the memory. The memory speed is fast, but the capacity is small and the data is lost after power failure; the external memory capacity is large, and the data is permanently stored, but the speed is slow. Since computer memory has been divided into internal memory and external storage for a long time, most people think that the existence of internal and external memory is determined by the structure of the computer itself, and the computer should have internal and external memory. This can actually be called a misunderstanding of computer storage. The characteristics of computer memory are non-volatile and random access. Since no storage medium with these two characteristics has been found before, scientists cleverly used non-volatile storage and random access memory respectively.

At present, with the continuous development of non-volatile random access memory (NVRAM:Non-Volatile RAM) and its technology, various NVRAMs have emerged, and the theory of dual-space storage has also been born. This is precisely because NVRAM memory has both random access of internal memory and permanent preservation of external storage. The dual-space storage combines internal memory and external storage in the same storage body, which will change the situation that the computer memory has been divided into two for many years, eliminate the data copy between the internal and external storage, and greatly speed up the

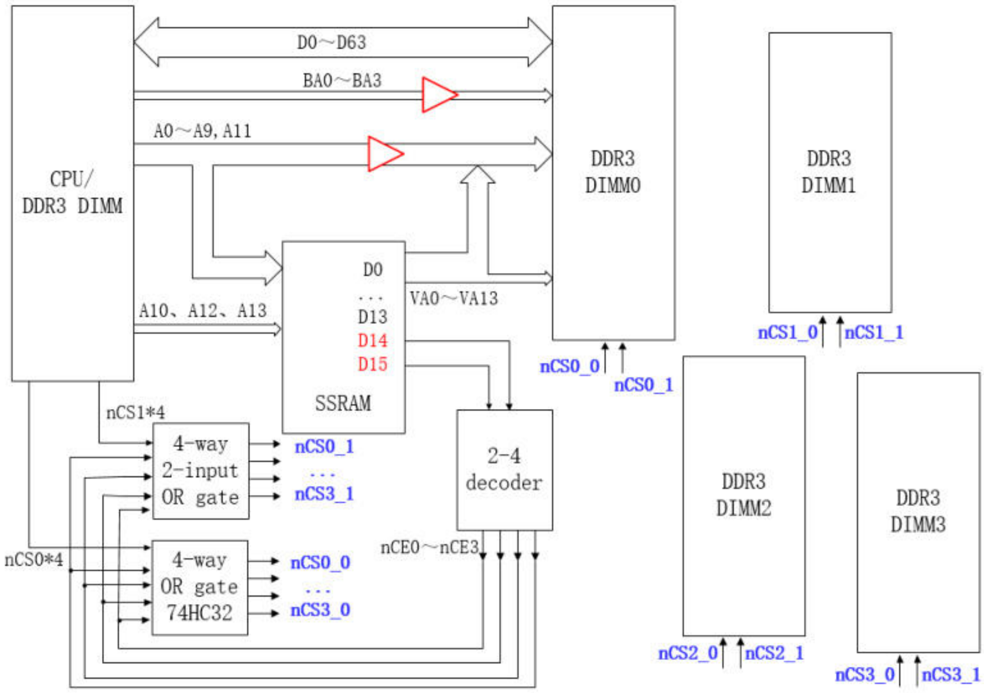

Fig. 5.1: Large-capacity dual-space storage architecture diagram.

operation of the computer. Our team has developed the structure and theory of dual-space storage, and has carried out memory shift experiments to verify it.

The dual-space storage uses NVRAM as the storage body. The basic idea is to use the random access of NVRAM to construct the word space of the dual-space storage to replace the current memory; use the permanent preservation of NVRAM to construct the block space of the dual-space storage to replace the current external storage. So the current internal and external memory is integrated into a storage body, which we call dual-space storage . That is to say, word space and block space do not refer to different spaces, but the space on the same storage body, but their division and usage methods are different. Among them, word space is randomly accessed by word or byte, so it is called word space; block space is accessed by block, so it is called block space. Based on the theory of dual-space storage, we propose a new computer architecture, see another article. Based on the theory of dual-space storage, we designed a large-capacity dual-space storage architecture, as shown in the Fig. 5.1. In this structure, 4 DDR3 DIMM slots are used, and 4 DDR3s are inserted to simulate large-capacity dual-space storage. The capacity of the memory space that the CPU needs to randomly access suddenly increases to the capacity of the external storage space, and the address bus of the CPU itself cannot be increased to the number required for random access to the external storage space. We use the memory space shift technology to solve this problem. The core is to construct a shift latch group to automatically map the memory space that can be directly accessed by the CPU itself to any section of 4 times the dual-space storage word space. The memory data buses from the CPU are directly connected to the corresponding data buses of the dual-space storage; A0∼A9 and A11 of the memory address buses from CPU are directly connected to the corresponding address buses of the dual-space storage, because these address buses are used to transfer column addresses in DDR3. The address buses A0∼A13 are connected to the shift latch group SSRAM (synchronous static random access memory), because these address buses are used to transfer row addresses. Data stored in SSRAM is the row address of the dual-space storage, which can be adjusted in actual operation as needed to carry out the memory shift, thereby realizing random access to the entire dual-space storage. The D0∼D13 output of SSRAM is connected to the row address bus of the dual space storage. D14 and D15 are outputted as nCE0∼nCE3 through the decoder. They are ORed with nCS0 and nCS1 respectively to obtain nCSx_0 and nCSx_1 (x is 0, 1, 2, 3). Among them, nCS0 and nCS1 are chip select signals of a single DDR3. The nCS04 in the figure represents 4 nCS0 signals respectively ORed with nCE0∼nCE3, and the same is true for nCS14. So, nCSx_0 and nCSx_1 are chip select signals of one dual-space storage body.

The application of large-capacity dual-space storage will historically change the computer architecture and will also change people's traditional concept of computer storage. On the other hand, the current artificial intelligence, big data and cloud computing, etc., all of them require high-performance computing. Large-capacity dual-space storage will lay a solid foundation for high-speed storage. In summary, large-capacity dual-space storage will become the final trend of memory development.

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