Dynamic Bandwidth Allocation Schemes for Multi-hop Wireless Mesh Networks

NURZAMAN AHMED
Department of Information Technology, North-Eastern Hill University, India-793022,
SATISH KUMAR DAS
Department of Computer Science & Engineering, Rajiv Gandhi University, India- 791112
and
MD. IFTEKHAR HUSSAIN
Department of Information Technology, North-Eastern Hill University, India-793022

The wireless mesh network is a promising low-cost technology in delivering broadband Internet access and wireless local area network connectivity for stationary and mobile hosts. The envisaged real-time applications over wireless mesh networks such as video-conferencing in rural telemedicine, e-learning, and voice-over-IP are required to operate while meeting the user expectations. Provisioning quality of service for different real-time applications over unreliable multi-hop wireless networks is a challenging task. Highly unpredictable link quality in WMN creates a very dynamic environment to control. Moreover, the multi-hop nature of wireless networks greatly affects the end-to-end network performance due to intra-flow and inter-flow interference created within the nodes. Dynamic bandwidth allocation schemes allocate the unused bandwidth of a network to the needy nodes and provide some level of quality of service to the real-time applications. This paper presents a comprehensive survey of the requirements, technical challenges, and existing works on dynamic bandwidth allocation schemes for supporting the quality of service in wireless mesh networks. We highlight the prospects and problems of related protocols and identify the factors for further improvement.

Keywords: Dynamic Bandwidth Allocation, Wireless Mesh Network (WMN), Medium Access Control (MAC), Time Division Multiple Access (TDMA).

1. INTRODUCTION

In multi-hop wireless mesh networks, unregulated transmissions by various nodes cause congestion around the gateway node. In provisioning end-to-end Quality of Service (QoS), congestion in such networks is considered to be an important issue. Voice and video based real-time applications such as video-conferencing, and voice-over-IP are required to operate maintaining service quality. Such services become more important while provisioning support for e-learning, telemedicine, etc., in the rural regions. For example, video conferencing requires voice and video frames to be transmitted within a certain delay limit. The video traffic also needs a minimum level of throughput for ensuring expected QoS. The lossy and limited bandwidth of the wireless network is another challenge.

QoS challenges in multi-hop wireless networks are a bit different from traditional wired networks. The unreliability of wireless links creates a very dynamic environment in a multi-hop scenario [Mogre et al. 2007]. End-to-end throughput and delay of already admitted traffic get greatly affected due to intra-flow and inter-flow interference created among the hops. Different parameters like Contention Window (CW) and back-off are tuned in contention-based MAC protocols like CSMA/CA to provide priority to some flows over the others. Schedule-based protocols like TDMA are proven to be a better solution for provisioning guaranteed bandwidth in wireless networks [Patra et al. 2007; Raman et al. 2005; Gabale et al. 2012]. In typical TDMA schemes, scheduling of transmission aims at increasing the overall network performance. In dynamic and heterogeneous network scenarios, the TDMA scheme may fail to provide the same. An adaptive and hybrid solution is required to solve the channel access mechanism considering actual traffic demands.

Typically a multi-hop wireless mesh network is a combination of infrastructure and client mesh network as shown in Figure 1. For uplink traffic, all the links forward their traffic towards the gateway node which is in turn connected to the Internet. However, if all the links send traffic at the same time, the congestion near the gateway/root node is obvious to occur. So, to solve this congestion issue, traffic should be restricted through proper network planning. However, such a situation creates a problem for achieving end-to-end QoS. Some of the MAC protocols such as Song et al. [2009], Rhee et al. [2008], and Ahn et al. [2006] are proposed to reduce this type of congestion and achieve high end-to-end data rate. Most of these protocols are based on hybrid MAC combining CSMA and TDMA. CSMA-based protocols are suitable in low-load whereas TDMA is more suitable in the high-load situations. Furthermore, to provide relative transmission opportunity, network metrics such as distance from the sink to the node, nodes slots use history, the queue length of children nodes, etc., can be used.

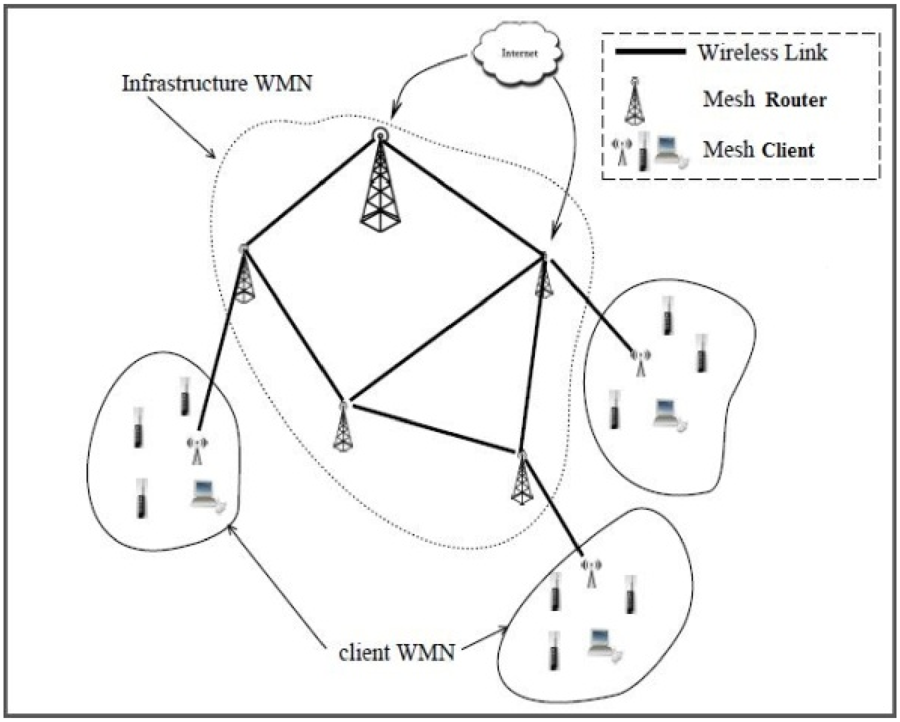
The critical challenges of Dynamic Bandwidth Allocation (DBA) schemes in resource constraint multi-hop Wireless Mesh Network (WMN) lie in the utilization of unused bandwidth and provisioning guaranteed services to the real-time traffic. In this paper, we provide a survey on DBA schemes in the context of QoS provisioning. In this process, the state-of-art proposals available in the literature have been considered based on their relevance in addressing various issues.

Rest of the paper is organized into three sections. Section 2 presents a background of dynamic bandwidth allocation. Existing DBA schemes are discussed in detail along with a classification framework in Section 3. Open research issues and future directions are discussed in Section 4. Finally, Section 5 provides a conclusion to this paper.

2. BANDWIDTH ALLOCATION IN WMN

MAC protocol plays a key role in the scheduling of link transmission. Hence, provisioning of QoS guarantees through MAC layer design has huge potential and a prolific field of research. While the existing IEEE 802.11a/b/g/n and 802.15.4 standards do not provide any inherent QoS support, different alternatives such as 802.11e, 802.16, and 802.11s address this issue to some extent. Contention-based MAC protocols usually support real-time applications by tuning some of the parameters of CSMA/CA such as the initial back-off and contention window. Due to the randomized back-off approach, CSMA/CA protocol is not suitable for real-time applications which require some level of guaranteed performance. Contention-free TDMA protocols are better candidates for providing predictable performance guarantees as they allocate certain transmission opportunities to the nodes [Gabale et al. 2012; Gabale et al. 2011; Ghosh et al. 2008]. QoS provisioning schemes for multi-hop WMN must address the issues born due to the architectural considerations of WMN. In interference-prone WMN, scheduling of channel bandwidth keeping the QoS requirements of the applications in mind can facilitate some level of QoS guarantees. Packets belonging to certain priority classes can also be provided with some priority while scheduling them for transmission.

A WMN is a network topology in which nodes are also responsible for relaying data for the network. Figure 1 shows a hybrid WMN structure (includes both infrastructure WMN and client WMN) where each node either has a point-to-point or point-to-multipoint connectivity with other nodes, (thereby forming a mesh). The mesh routers are static nodes equipped with high processing and memory capabilities, while mesh clients have limited memory, and computational power [Hossain et al. 2007]. Although 802.11 offers a few non-overlapping channels, most of the WMN set up uses a single channel for creating a backhaul network. Single channel assumption allows the other channels to be used for local access networks restricting the radio frequency pollution problem to occur. Internet connectivity reaches the rural end-user nodes via multi-hop WMN. In supporting multi-hop communication for rural WMN, multiple radios may be employed at various non-terminal nodes. Use of more than one radio in a node, and all of them using the



A typical hybrid Wireless Mesh Network architecture as a combination of Infrastructure and Client WMN

same channel does not allow independent transmission and reception at different radios.

MAC protocol solves the main sources of energy waste problems such as collision, idle listening, overhearing, and control packet overhead. It should optimally utilize the shared transmission medium which directly impacts on overall network performance. The wireless channel access mechanisms can broadly be classified as contention-based, contention-free, and hybrid. The first two types are the dominant channel access mechanisms in the literature of WMN. Most of the reported protocols found in these two categories are based on either CSMA or TDMA.

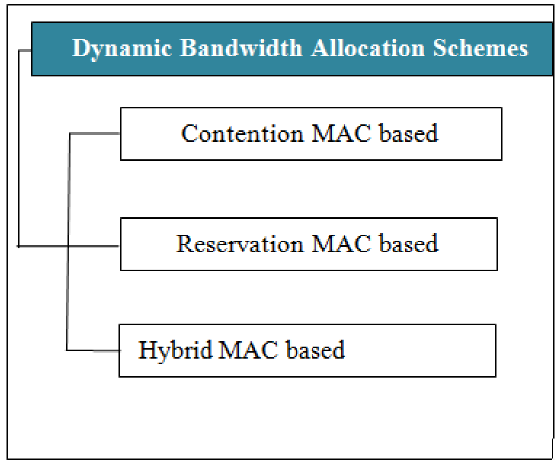
2.1 CSMA/CA-based MAC Protocols for WMN

The CSMA/CA follows DCF scheme for channel access delegation. In this, the nodes need to contend initially for a duration of time before it can practically transmit data. After waiting DIFS and a random backoff time, if the channel is finally found to be free then only a node can transmit. Otherwise, it defers the current transmission. This scheme helps correctly identify the total number of stations are going to transmit. However, with the increasing number of nodes, changes of simultaneous contention and as a result collision also increase.

The expected performance of such networks in supporting various real-time applications such as e-learning and telemedicine cannot be delivered efficiently by the existing MAC protocols. The key reasons for this detrimental performance are (i) high probability of packet loss due to multi-hop wireless transmissions, (ii) inefficient acknowledgment mechanism, and (iii) possible interference. Since the signal propagation time increases in long-distance communication, the probability of packet loss due to collision also proportionally increases [Seth et al. 2007]. This acknowledgment mechanism decreases the channel utilization significantly.

2.2 TDMA-based MAC Protocols for WMN

The TDMA-based access mechanism allows communication among the same frequency by sharing the time frame into different time slots. The coordinator node maintains the time frame which is designed based on the number of stations and scheduling scheme used. The slots are separated



Classification Framework for DBA Schemes

by a relatively smaller but not greater than synchronization time, a guard time is used to ensure non-overlapping transmission among nodes a single domain. Time synchronization among the nodes in the primary issues here. As a node knows its slot number, it can keep its radio off for the remaining to save energy.

On the contrary to CSMA/CA, TDMA saves the unnecessary overhead in terms of contention and control packets for getting access to the common channel. Using the designed TDMA scheduling, each node gets a particular share of non-overlapping time to transmit and hence TDMA-based MAC protocols are collision-free.

3. DBA SCHEMES FOR WMN

In multi-hop WMN architecture, the bandwidth of a link towards the gateway node is shared by the children links of the node. However, if all the nodes are allowed to transmit in their full capacity, congestion is bound to occur at the intermediate nodes. To avoid congestion, children nodes cannot be allowed to transmit in their full capacity even if they can do so. As a result, with the increase in the number of levels of the tree topology, the nodes available towards the bottom of the tree are restricted with very limited transmission bandwidth. In dynamic traffic situation, a node with sufficient real-time traffic in hand may not get adequate transmission opportunity whereas some others may not have any data to transmit or continue transmitting best- effort traffic.

Schemes providing static transmission opportunity to all the nodes do not map well in dynamic traffic conditions. Therefore, the transmission slots need to be dynamically allocated based on the QoS demands of the nodes. The architecture of multi-hop WMN resembles with Wireless Sensor Networks (WSN). Gateway-based multi-hop WMN is used as a backbone network and hence traffic is expected to keep the links saturated most of the time. On the other hand, conventional WSN carries sensory information to the sink node in a periodic fashion. Moreover, the traffic flow is mostly unidirectional in WSN whereas multi-hop WMN carry traffic in both the directions. Due to the close similarity between WSN and WMN, DBA schemes of one can easily be applied to the other. Few relevant DBA schemes available in the literature are discussed in the following subsections.

3.1 Contention-based DBA Scheme

Contention-based schemes are found to have some control mechanisms like persistence probabilities, wait (frame spacing) and back-off timers to allocate resources dynamically. A node having a packet for transmission attempts to transmit with a probability called the persistence probability.

Table I: Comparison of DBA Schemes

	Funneling-MAC Ahn et al. [2006]	Queue-MAC Zhuo et al. [2012]	Tree-MAC Song et al. [2009]	I-MAC Slama et al. [2008]	UBS Kas et al. [2010]	i-Queue-MAC Zhuo et al. [2013]	PSIFT Nguyen et al. [2006]	PR-MAC Firoze et al. [2007]	ICALO Karunaratne et al. [2018]	QDBA Hussain et al. [2015]
Type	Hybrid (CSMA/CA and TDMA)	Hybrid (CSMA/CA and TDMA)	Reservation (TDMA)	Hybrid (CSMA/CA and TDMA)	Reservation (S-TDMA)	Hybrid (CSMA/CA and TDMA	Contention (CSMA/CA)	Contention (CSMA/CA)	Contention (CSMA/CA)	Reservation (TDMA)
Multi-hop	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
QoS Support	No	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Topology	Tree	Tree	Tree	Tree	Mesh	Tree	Tree	Tree	Tree	Tree
Channel	Single-channel	Multi-channel	Single-channel	Single-channel	Single-channel	Multi-channel	Single-channel	Single-channel	Single-channel	Single-channel
System Initialization	Sink start beaconing	Parent nodes broadcast beacon to divide time	Runs CSMA to discover its neighbors	Nodes run neighbor discovery operation	Node's state detection	Nodes transmit beacon	——	——	——	Static slot allocation
Adaptive Traffic Handling	Sink assign slots to path from traffic rate	Allocating TDMA slots dynamically	Parent allocates children's frame on demand	Nodes are assigned priority according to their roles	Dynamic slot size based on nodes slot uses history and packet queue occupancy	Variable TDMA period	Dynamic CW size and IFS time	Dynamic CW size and IFS time	Adaptive and Learning based parameters	Dynamic slot allocation based on demands
Traffic Demand Notification	Sink monitors incoming data packet	Queue indicator for node's load	Piggybacks in upstream packets	According to the role of the node, contention window is varied	Weight information in HELLO message	Queue length	——	——	Location, Bandwidth utilization, end-to-end throughput	Traffic Indication Map (TIM)

Should a collision occur (another node attempts to transmit a packet at the same time), each node involved in the collision will wait for a certain random amount of time, called the back-off time, before attempting retransmission [Su et al. 2010]). Some of the well-known DBA schemes based on contention-based MAC protocol (CSMA) designed to provide QoS are discussed below.

3.1.1 *PSHIFT.* A QoS-aware MAC protocol called PSIFT [Nguyen et al. 2006] is designed for event-driven applications which exploits the spatial correlation property of WSNs. Using CSMA-based MAC protocol, it provides traffic differentiation by varying the Inter Frame Space (IFS) and CW size for each traffic class. Further, it proposed two methods Explicit ACK and Implicit ACK for suppressing the unnecessary redundant reports of a detected event in an event-driven application by the sensor nodes. Some of the initial reports are sufficient for the sink node to accurately identify the event and elimination of redundancy decreases the probability of collision and latency. Although PSIFT helps in utilizing the bandwidth by reducing redundancy, it may not be applicable to all types of application in detecting events.

3.1.2 *PR-MAC.* PR-MAC [Firoze et al. 2007] prioritizes the sensor nodes according to the event generation and provides service differentiation among these events by varying both CW size and IFS for each of them. The transmitting node transmits a short pulse to reserve the medium rather than using RTS-CTS exchange. Collisions can only occur during the transmission of the burst pulse among nodes of equal priority. This protocol reduces the control overhead by removing RTS/CTS, but it may face some problems to support variable size packet delivery since RTS packets include the medium reservation duration.

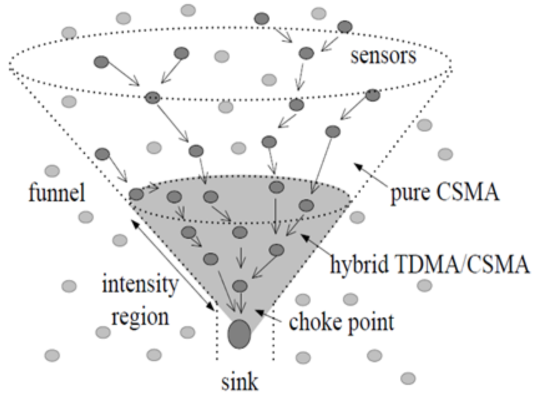
3.1.3 *ICALO.* ICALO [Karunaratne et al. 2018], an artificial intelligence based channel assignment and location optimization scheme for WMN. The proposed channel access scheme analyses the network and allocates channels efficiently. Modules like sensing, perception, and reinforcement-learning (RL) is used in different phases of the scheme. Parameters like RSSI for distance, channel utilization, and end-end-throughput are considered in the phases. The scheme runs the machine learning algorithm to dynamically utilize available bandwidth.

3.2 Reservation-based DBA Scheme

In reservation-based DBA schemes, the time slots are allocated among the contending nodes according to their traffic requirements, i.e., a node may get a time slot whenever it has some data to send.

3.2.1 *Tree-MAC.* In supporting high data rate real-time applications in WSN, Tree-MAC [Song et al. 2009] proposes a localized TDMA MAC protocol. Here, each node gets a number of time slots which is proportional to its bandwidth demand. At the time of network initialization, each node runs the CSMA algorithm to discover its neighbors. After neighbor discovery, a TDMA based approach is adopted to schedule nodes transmission. Tree-MAC divides each TDMA cycle into frames and each frame into three slots. Once the children of the sink node are discovered, it assigns slots to them. Using the parent-child relationship of the tree topology, the frame and slot assignment decision between a parent and its children nodes is taken by themselves. Keeping its own required slots, each parent node distributes the remaining slots among its children. This frame assignment is carried out based on the relative bandwidth demands of its children. Each node individually calculates slot assignment according to its hop distance to the sink node.

3.2.2 *Utilization Based Scheduling (UBS).* UBS [Kas et al. 2010] is utilization-based distributed dynamic scheduling scheme proposed for WMN. It assigns a weight to each node which is dynamically adjusted according to the slot uses history and packet queue occupancy of the nodes. The protocol works in a distributed manner where each node adjusts its own weight and makes pseudo-random transmission attempts using only the locally available information. UBS divides the time into several equal intervals called frames. Each node periodically runs the dynamic weight adjustment algorithm. Based on the current weight of a node which reflects



An illustration of Funneling-MAC

its demand for transmission slots in the next frame, the dynamic weight adjustment algorithm assigns a dynamic weight value to it. The number of time slots assigned to a node in a single frame is proportional to its weight.

3.2.3 *QoS-aware Dynamic Bandwidth Allocation (QDBA).* QDBA [Hussain et al. 2015] efficiently distributes the unused TDMA time slots among the needy nodes. To give guaranteed service to the real-time traffic, they are provided higher priority over best-effort traffic. During the network initialization, a static slot allocation process is carried out which equally distributes the time slots of a parent node among its children nodes of a given cluster. Subsequently, in the dynamic slot allocation, the bandwidth demands of children nodes are placed to the parent node through sending Traffic Indication Map (TIM). After receiving the TIMs from its children, a parent node tries to allocate time slots according to their demands. If a parent node is not able to allocate the required number of slots to its children nodes, it prepares a TIM specifying the requirement and sends to its immediate parent node.

3.3 Hybrid DBA Scheme

In this category of DBA schemes, contention and reservation based MAC protocols are used at low and high traffic load situations respectively.

3.3.1 *Queue-MAC.* Queue-MAC [Zhuo et al. 2012] is a hybrid CSMA/TDMA-based MAC protocol proposed for multi-hop WSN. This protocol addresses the issue of burst network traffic maintaining a limited duty cycle. It uses a customized superframe structure composed of the beacon frame, variable TDMA period, fixed CSMA period, an inactive period. The parent node acquires the load of each child node from the packets received from them. The packets carry the load information through a special field called queue indicators. In normal or low load, the transmission is carried out during the fixed CSMA period of the superframe. As the traffic load increases, the active period is accordingly extended by adding more TDMA slots to increase the bandwidth. This scheme combines the strengths of CSMA and TDMA while off-setting their weaknesses

3.3.2 *Funneling-MAC.* Funneling-MAC [Ahn et al. 2006] is a localized, sink-oriented hybrid MAC protocol. It recognizes that the traffic density towards the sink node is more and as a result of that overall network performance degrades. This fact is termed as funneling effect. To address this funneling effect problem, it proposes a hybrid of CSMA/CA and TDMA protocol. A localized TDMA is used in the funneling region and CSMA/CA protocol is implemented for the rest of the network. Figure 3 illustrates the working of Funneling-MAC. The gray colored region in the diagram is the high intensity area.

The local TDMA controlled by the sink node provides additional transmission opportunity to the nodes closer to it. The sink node monitors data traffic and keeps track of incoming traffic rate for each path. The traffic rate is calculated by monitoring the number of incoming packets in one super frame per path. To maintain the traffic rate information, the sink node uses a path table. Based on the rate of monitored traffic in the table, the sink node allocates time slots to each path. If the traffic rate of a path is k and the number of hops of the path is h, the sink allocates k*h slots to the path. But, if the traffic rate of a path is less than 1, the sink allocates 1*h slots to the path.

3.3.3 *I-MAC.* In Slama et al. [2008], a hybrid MAC scheme called I-MAC is proposed. I-MAC protocol assigns different levels of priority to different nodes thereby improving the channel utilization. To reduce energy consumption, shorter back-off periods are given to higher priority nodes. It reduces the amount of packet collision as only the nodes having the same priority compete to access the channel. I-MAC is composed of two phases - (i) set-up phase and (ii) transmission phase. During the set-up phase, activities like neighbour discovery, slot assignment, local framing, and global synchronization are done. The transmission phase uses three levels of priority and the priority of each node is set according to its role within the network and to its traffic load. All nodes are allowed to transmit during any slot. However, the owner of the slot gets the first priority. If the owner has no data to transmit, non-owners can compete to use the slot. The chances of getting a slot by a non-owner node depend on its priority level.

Thus, I-MAC allows sensor nodes that have higher load (higher priority) to get more chances to access the radio resources. Moreover, the lifetime of loaded sensors is prolonged since the prioritization mechanism reduces collision and shortens their listening period.

3.3.4 *i-Queue-MAC.* To deal with burst traffic in data collecting tree-based sensor networks, i-Queue-MAC proposes a hybrid MAC combining CSMA/CA and TDMA protocols. i-Queue-MAC runs CSMA in light load and TDMA in high load situation. In high load, it uses the senders queue length to dynamically allocate time slots to them for packet transmission. The nodes of a network are divided into two types- (i) Simple nodes and (ii) Routers. Each simple node is associated with a router. A router is responsible for collecting the packets of its simple nodes. i-Queue-MAC uses the queue length of each node and allocates suitable TDMA transmission slots accordingly. In light load situation, no TDMA slot is allocated. In high load traffic, i-Queue-MAC senses the build-up of packet queues and dynamically schedules adequate number of slots for packet transmission. A consolidated comparison of the dynamic bandwidth allocation schemes discussed in this section is presented in Table 1.

4. FUTURE RESEARCH DIRECTION

The bandwidth is the most important resource, especially in wireless network. The networks like Internet of Things connect a huge number of devices to the Internet. The available limited bandwidth needs to be efficiently utilized among all the nodes of such networks. Therefore, dynamic bandwidth allocation/management schemes play an important role in deciding the network performance. Smart and adaptive DBA schemes are important for such a large scale network. A few possible future directions are-

a) **Bandwidth estimation:** Different network metric such as- network capacity, available bandwidth and bulk transferring capacity can be helpful to decide the estimate required bandwidth in a node and remaining can be kept for others use. Estimating a regions bandwidth and importantly those bandwidths could be altered as of the current need of that region. This improves the scalability of the network.
b) **Efficient admission control:** For maximizing the user's sum capacity, maximize behavior of user capacity relates the worst case and minimizing accumulation of power consumption an efficient admission control scheme can be used.
c) **Resource sharing:** The unused bandwidth of nodes can be informed to the controller and accordingly the controller can allocate them to needy nodes.

d) **Quality of Service:** After observing the network or nodes, they can be classified into different categories according to their priority. Based on this, the remaining limited bandwidth can be allocated to some more important nodes of the network.

5. CONCLUSION

This paper presents a comprehensive survey on QoS schemes for multi-hop wireless mesh networks. The state-of-the-art DBA schemes have been presented with an emphasis on the issues addressed by them and pointing out the issues requiring further research attention. DBA schemes based on reservation and hybrid MAC protocols are found to be more efficient in providing QoS in WMNs. Designing an energy efficient DBA scheme to provide QoS for real-time traffic in hierarchical WMN covering larger area is left as future work.

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Mr. Nurzaman Ahmed was born in Dhupdhara, India. He received the B.Tech. and M.Tech. degrees in information technology from North-Eastern Hill University, Shillong, India, in 2013 and 2016, respectively, where he is currently pursuing the Ph.D. degree at the Department of Information Technology, School of Technology.
His current research interests include Machine-to-Machine networks, Internet of Things, and WiFi-based long distance networks.
Mr. Ahmed is a member of the Indian Science Congress Association.

Mr. Satish Kumar Das acquired the B.E. degree in computer science and engineering from Dibrugarh University, Dibrugarh, India, and the M.Tech. Degree in Information Technology from Tezpur University, Tezpur, India.
He is an Assistant Professor in the department of Computer Science & Engineering, Rajiv Gandhi University, Arunachal Pradesh-791 112.

Dr. Md. Iftekhar Hussain received the B.E. degree in computer science and engineering from Dibrugarh University, Dibrugarh, India, and the M.Tech. degree in information technology and the Ph.D. degree in computer science and engineering from Tezpur University, Tezpur, India.
He is an Associate Professor with North-Eastern Hill University, Shillong, India. His current research interests include wireless mesh networks and Internet of Things.
Dr. Hussain is a Life Member of the Indian Science Congress Association.