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QoS Provisioning in Wireless Mesh Networks: A Survey

Md. Iftekhar Hussain[1] · Nurzaman Ahmed[1] · Md. Zaved Iqubal Ahmed[1] · Nityananda Sarma[2]

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Abstract

With the recent developments in Wireless Mesh Networks (WMN), provisioning of Quality of Service (QoS) for real time applications is considered as an important but challenging area of research. QoS support for various real time applications are implemented in different layers of the protocol stack. The diversity of such research efforts has contributed to many protocols/schemes. This paper presents a comprehensive survey on various QoS enhancement schemes reported in the literature covering various angles of research domains. Diversified QoS challenges in WMNs and their reported solutions proposed in the literature are discussed using a layered approach. While presenting the state of the art research findings in MAC and routing, a classification framework for each of the layers is proposed first. The classification frameworks provide unified approaches for categorizing different protocols based on their distinctive features and sketch their correlations. However, the proposals for leveraging TCP performance in WMN have been discussed straightaway. Further, this paper provides an insight into the pros and cons of the surveyed protocols and points out the open research challenges for the future generation networking.

Keywords MAC Protocol · Wireless Mesh Networks · Quality of Service (QoS) · Routing · TDMA

✉ Nurzaman Ahmed
nur.zaman@live.com

Md. Iftekhar Hussain
ihussain@nehu.ac.in

Md. Zaved Iqubal Ahmed
zaved.iqubal@gmail.com

Nityananda Sarma
nitya@tezu.ernet.in

1 Department of Information Technology, North-Eastern Hill University, Shilling 793 022, India

2 Department of Computer Science & Engineering, Tezpur University, Assam 784 028, India

1 Introduction

Wireless Mesh Network (WMN) has recently emerged as a new paradigm in wireless communication. A WMN facilitates traffic forwarding over any available wireless medium in single as well as multi-hop environments. Mesh networks may furnish wireless connections either to access points serving different WLANs or simply to devices supporting peer-to-peer wireless communication. The key advantages of such networks are their self-organization, self-configuration, and self-healing abilities [1]. They also work in low transmission power and are rapidly deployable in odd geographic terrains [2]. In addition to viewing WMN as a promising alternative to other wireless competitors, it turns out to be a much cheaper network technology for covering rural regions with the use of commodity hardware.

One of the major challenges in WMN is to ensure QoS over unreliable wireless networks in the presence of heterogeneous traffic types with stringent delay and bandwidth demands. Since bandwidth is considered to be the most scarce resource in wireless networks, proportionate allocation of bandwidth among different applications is obligatory as QoS requirements vary from application to application. Unreliable lossy links in wireless networks not only hinders the maximum achievable throughput of a network but also affects its energy consumption due to re-transmission and broadcasting [3]. The multi-hop traffic forwarding in WMN are often accompanied by scheduling delay which greatly impacts the QoS parameters such as latency and jitter. QoS-aware routing protocols are used to establish a path from source to destination which meets the QoS needs of traffic. The routing protocol's path computation, path selection, path recovery, and path optimization algorithms need to be stable and robust against heterogeneous network environments and traffic variations. Further, high packet loss rate leads to unnecessary congestion control in WMN which degrades the overall network performance. Thus, the congestion control mechanism of TCP needs to adapt to the network behavior of WMN.

As Medium Access Control (MAC) protocol is responsible for actual scheduling of traffic on the air, modification of the existing MAC protocols is inevitable in order to make them suitable for the changing scenario. While the existing IEEE 802.11a/b/g/n standards do not have any QoS support, different alternatives such as 802.11e, 802.16, and 802.11s have addressed the QoS requirements of different real time applications to some extent. Further researches are being conducted to address various issues born due to the architectural considerations of WMNs. Empowering the MAC layer with provisions for QoS does not alone placate the scenario of QoS in WMN. QoS support also need to be enforced in the network layer in terms of network load balancing, admission control, and topology aware routing. To this, cross-layer design has been extensively used to provision QoS in WMNs. This is due to the advancement of wireless transmission technology such as adaptable transmission rate, smart antenna use, multi-channel multi-radio technology, etc. Reporting of information like channel state, packet loss rate, scheduling decision taken by the lower layer protocols help the upper layers in taking appropriate decisions while providing QoS support to the network traffic.

The future of WMN is shown to be suitable for different real time applications. Therefore, strict packet delay and high bandwidth requirements are to be supported for real time applications such as such as Voice-over-IP (VoIP), interactive video, and neighborhood gaming. Various research works are being conducted to overcome the drawbacks of the existing standard of WMNs. Research works in developing optimal channel access mechanisms as well as routing solutions addressing QoS requirements in WMNs has received prime focus. Various aspects like interference, scheduling, channel assignment, time synchronization, and slot sizing have been considered while providing MAC solutions. In forwarding traffic over multiple hops in WMN, routing solutions considering various domains such as multi-casting, multi-path, multi-radio and multi-channel, considered routing metrics, topology-awareness and admission control have been explored by many researchers. Network layer solutions are observed to be mainly focusing on multi-constrained QoS routing algorithms. Also, for dealing with the unreliable characteristics of wireless links, adaptive and better responsive transport layer protocols have been proposed in literature.

This paper provides a survey on the reported MAC, Routing, and Transport layer protocols in the context of QoS provisioning in WMNs. In this process, the state-of-the-art proposals available in the literature have been considered based on their relevance in addressing various issues. The MAC and routing protocols proposed towards the end of QoS provisioning are classified into different categories based on two proposed classification frameworks. Transport layer protocols are studied in a straight forward manner. As the amount of work in the literature is very huge, this paper focuses on pointing out the issues/problems addressed/solved by different protocols rather than providing an in-depth survey on each one of them. Open research issues or advancement that can further be incorporated in each category have been put forward. This survey on different MAC and network layer solutions provides an issue based classification of different protocols and reports the issues addressed by each one of them. This study further reports the transport layer modifications for enhancing reliability and optimizing overall network performance. This survey creates scope for further analysis and advancement in the field of WMN. The key contributions of this paper are as follows:

- This paper starts by highlighting the importance of provisioning QoS and specifying the challenges thereof in Physical, MAC, Routing, and Transport layer communication.
- The state-of-the-art MAC and Routing protocols proposed for achieving QoS are classified into different categories based on their distinctive features and their correlations are sketched.
- This paper provides an insight into the pros and cons of the surveyed protocols in each of the categories and points out their open research challenges.

In the light of QoS provisioning in WMN, there is no survey work found that can be compared with our work. However, a few related works on WMN are available in the literature. In [4], authors reviewed the critical aspects that need to be considered using the IEEE 802.16-2004 standard's mesh mode as a case-study. The research challenges and pitfalls are highlighted and provided a roadmap towards realization. However, the volume of literature surveyed is very less in comparison to our survey. Further, it simply highlighted the work to be done in the field of QoS provisioning in WMN without any details of the mechanism used for the purpose. The QoS provisioning issues in MWN is studied in three different approaches in [5]: the routing layer approach, link layer approach and physical layer approach. When compared with our work, this classification framework lacks diverse aspects of QoS. There are various other surveys on WMN such as [6–8], etc., which do not consider QoS provisioning as criteria for their survey.

Rest of the paper is organized into four sections. Section 2 presents an overview of WMN architecture. Section 3 elaborates some major QoS challenges in WMN. In Section 4, the advances and research challenges in MAC, network and transport layers with respect to their QoS support in WMN are discussed. Different MAC and network layer protocols have been first classified using a classification framework and then a detail survey is presented. Open research issues have also been pointed out in each category exploring the possibility of further research. Finally, Section 5 gives the conclusion to the paper.

2 Wireless Mesh Network Architecture

Wireless Mesh Network has recently evolved as a strong alternative in providing seamless connectivity using wireless open standards. With backhaul access to the wired Internet, WMNs can be used to provide access to the Internet in regions where wired connectivity is otherwise difficult. The growing popularity of WMNs impacts the traditional aspects of networking and is expected to gradually substitute a part of the wired infrastructure by being able to provide quick and efficient deployment of wireless networks in urban, sub-urban and rural environments. The architecture of WMN is quite different from other wireless networks with lesser degree of node mobility involved in the networks. Based on the functionality, nodes in WMN are classified into—wireless mesh router and wireless mesh client. The wireless mesh routers forward traffic over multiple hops and one or more among them act as gateway in extending connectivity from some fixed points. The wireless mesh routers form the multi-hop backbone for extending Internet connectivity to the wireless mesh clients. On the other hand, the wireless mesh clients are the end-points in the network which are entrusted with functionality for end user connectivity. In spite of all the architectural differences, mesh routers or mesh clients are usually built using the conventional hardware platforms. As WMNs are multi-hop in nature, the MAC protocols in mesh routers are enhanced with better scalability in such environment. The use of directional antenna has also been common in creating wireless point-to-point links.

The architecture of WMN has been broadly classified into three categories by Akyildiz et al. [1]—Infrastructure/Backbone WMNs, Client WMNs, and Hybrid WMNs. Infrastructure WMN consists of wireless mesh routers and provides a backbone for the conventional clients and enable integration of WMN with existing networks, through gateway and bridge functionality in mesh routers. Client WMNs are peer-to-peer networks formed among wireless mesh clients which are featured with routing functionality and do not require any infrastructure. This architecture is similar to the traditional ad-hoc networks. Lastly, a hybrid WMN is a combination of both infrastructure and client WMNs. It combines the power of both types of WMN to provide an architecture where mesh clients can access the network through mesh routers as well as directly through other mesh clients. Figure 1 depicts a typical Hybrid WMN as a combination of infrastructure and client WMN.

Recently, the growing adaptation of the Internet of Things (IoT) [9] and Fog computing [10] created different localized deployment of client mesh networks such as IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) [11], WiFi, Mobiles, and Laptops. In such networks, gateways take the most important role by providing support for networking within and outside the network. On the other hand, for extending the Internet connectivity, backbone/infrastructure mesh networks are used. It is obvious that infrastructure mesh covers larger areas than a client mesh network. For example, for supporting remote applications—smart agriculture, smart home, e-learning, and e-health need Internet connectivity from district headquarter to the remote places. A combination of these two networks helps for connecting the remote devices to the Internet. The combined network is called a hybrid mesh network. In case of rural connectivity, due to the increasing number of hops and long-distance sectorized links in backbone and resource-constraint client mesh network, developing QoS-aware solutions are essential.

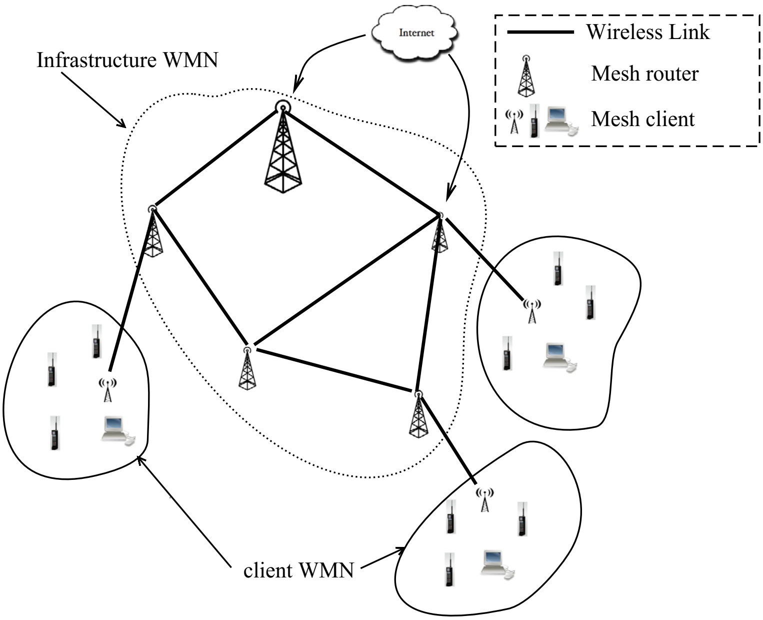

Fig. 1 A typical hybrid Wireless Mesh Network Architecture as a combination of Infrastructure and Client WMN

3 QoS Challenges in WMN

QoS in a network is defined by a set of quality parameters such as throughput, latency, jitter, and packet loss, which are needed to be met during a service processing [12]. The key network services—transmission, scheduling, delivery, routing, etc. A few number of QoS models are already available for networking in the literature. For example, IETF developed two of the main QoS provisioning models on the Internet—Integrated Services (IntServ) and Differentiated Services(DiffServ). With the aim of greater per-flow accuracy and a finer level of granularity, IntServ reserves state at QoS network entities. In the case of DiffServ, it relies on differential treatment and aggregation of traffic classes resulting in much better-scaling properties [2].

QoS provisioning in WMN has many challenges due to architectural changes in paradigm. The existing QoS models in general fail to address the QoS requirements of different applications in WMNs. The probable reason might be their adherence to a single layer in the protocol stack while provisioning QoS. Moreoever, WMN envisions running applications like e-learning, e-governance, tele-medicine, disaster relief and emergency response systems. As these real time applications demand a certain level of quality for their successful operation, QoS provisioning in WMNs has become a growing need. However, provisioning of QoS for real time communications like voice and video over wireless networks is highly challenging because of unstable wireless links, lack of any central coordination authority (for QoS and channel assignment), node mobility, limited battery power, multi-hop communication and contention for accessing the wireless channel [2]. QoS provisioning in routing layer of WMNs is relatively new compared to IP networks and MANETs. Compared to MANETs, WMNs seem to be a better candidate for provisioning QoS, as they have the advantage of having a relatively static and reliable network architecture [2]. The challenges lie in different layers of the protocol stack mainly in the physical, medium access, routing, and transport.

- *Physical layer challenges* Different PHY layer approaches are proposed for achieving QoS. Existing works such as increasing physical capacity using directional antenna [13], minimization of latency considering the time variability of wireless channels [14], and better compression and modulation scheme for increasing efficiency of network [15] are some of the important directions. Due to the undesirable effects of fading and interference, PHY layer reliability is still challenging. Spread spectrum solutions such as Frequency Hopping Spread Spectrum (FHSS), Code Division Multiple Access (CDMA), Orthogonal Frequency Division Multiplexing (OFDM), and Ultra-Wide Band (UWB) provide reliability up to a certain extent. However, a number of PHY layer issues still exists—(i) for mobile mesh nodes, a shift in frequency and therefore adaptation to the fast fading conditions is necessary, (ii) in case of a directional and sectorized antenna, alignment is an open problem, (iii) assignment of multiple channels for multi-interface or single interface, (iv) variation in the transmission power, (v) high Signal to Noise and Interference Ratio (SNIR), and (vi) capacity constraint.
- *Medium access control layer challenges* The key MAC layer approaches- CSMA, TDMA, and Hybrid (a combination of CSMA and TDMA) are used for scalable network performance in different circumstances. The existing CSMA-based protocols [16–19], TDMA-based protocols [20–26], and hybrid protocols [27–29] solve many issues. However, link scheduling, node synchronization, multi-radio operation, channel-assignment, interference, collision, multi-hop topology, unpredictable channel access delay, and lack of centralized QoS control need researchers' attention. Further, based on the current literature, different solutions to these issues are discussed in Section 4.1.
- *Network layer challenges* Provisioning QoS in the network layer is a well established solutions with various directions. The existing approaches such as routing metric [30–34], multicast [35–38], multipath [29, 39–41], flow-based [42], topology-aware [43–45], and admission control [46–50] are proposed for QoS in WMN. However, further works required in traffic differentiation (address varied QoS requirement), end-to-end QoS requirements, QoS route selection, multi-hop traffic forwarding, and admission control problem in stateless QoS model. Section 4.2 discusses the existing works related to the above mentioned challenges. The future works of this area of research are also highlighted.
- *Transport layer challenges* Although the existing protocols such as [51–54], and [55] solve many of problems in transport protocol. However, more works are required in congestion control, handling transmission errors, packet reordering due to multi-path routing, and multi-hop connection. Considering these issues, this paper provides a detail survey in Section 4.3.

A large number of schemes are proposed to solve many QoS challenges in WMNs. Most of the schemes are developed for provisioning QoS at MAC, Routing, and Transport layers. This paper discusses the state-of-the-art schemes, and based on open research issues are provided in the following section.

4 State-of-the-Art and Research Challenges for Provisioning QoS in WMN

The advances and research challenges towards QoS provisioning in WMN are layer wise discussed in this section. This work first presents two classification frameworks for categorizing the various protocols of MAC and Routing layers and then discusses the protocol's contributions.

4.1 QoS Provisioning at MAC Layer

As the amount of literature is very voluminous, in this subsection, this paper focuses on pointing out the issues addressed by the MAC protocols and put forward the open research issues.

4.1.1 Classification Framework

Wireless channel access mechanisms can broadly be categorized as contention-free, contention-based, 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 three categories are based on either Carrier Sense Multiple Access (CSMA) or Time Division Multiple Access (TDMA) or both. As depicted in Fig. 2, our classification framework considers these two major categories, i.e., *CSMA-based*, *TDMA-based* and hybrid MAC protocols.

Various researchers claim that *TDMA-based* MAC protocols make the best use of the WMN architecture in optimizing the overall network performance or provisioning some level of QoS guarantees for different real time traffic. In the endeavor of QoS provisioning in multi-hop WMN, TDMA-based MAC protocols have proved their efficiency and fairness in allocation of bandwidth among the traffic flows. In order to provide QoS, TDMA frames are generate in such a way that a single slot is used by multi non-interfering links for simultaneous transmission [20]. In order to have a clear understanding of the TDMA-based

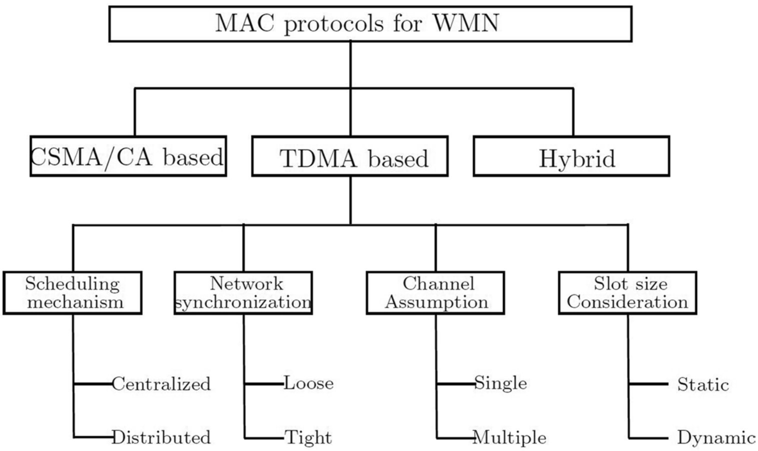

Fig. 2 Classification framework for MAC protocols of wireless mesh network

MAC protocols, we need to further classify them into more specific categories. Keen observation reveals that TDMA-based MAC protocols can broadly be classified based on the following considerations: scheduling mechanism employed, network synchronization method used, channel assumption, and slot size consideration. Figure 2 gives a pictorial representation of the categorization of *TDMA-based* MAC protocols.

Later in this section, this paper discusses the MAC protocols for WMN in light of this classification framework. The *CSMA-based* MAC protocols are discussed first, followed by the *TDMA-based* MAC protocols. Also, Table 1 depicts an overall comparison of the MAC protocols for QoS provisioning in WMN.

4.1.2 CSMA-based Protocols

CSMA/CA is the MAC protocol used in the standard IEEE 802.11, which a contention based protocol. However, this protocol has its limitation in provisioning QoS for delay sensitive traffic. Various research works have been conducted to provision QoS in WMN by enhancing the CSMA/CA MAC protocol [16–19]. An enhancement in CSMA/CA for smooth forwarding operation in WMN is proposed in [16], which is used to forward the data packet with a fewer signaling overhead. It is achieved by reducing RTS/CTS handshake operation for a packet going to the destination through some intermediate nodes. However, this approach does not provide prioritized access to the different delay sensitive traffic.

Authors in [17] proposes an augmented version of CSMA/CA termed as TCMA, in order to provide QoS to heterogeneous traffic types. The protocol combines admission control with prioritized access for different traffic. The hidden node problem and contention-based access over multi-hops in WMN pose serious challenges in meeting the QoS requirement of delay-sensitive traffic. Thus, prioritized access alone will not be sufficient for

Table 1 Comparison of the QoS provisioning techniques used in MAC protocols

Papers	Medium Access Method	Flow considered	Technique used for provisioning QoS
[16]	CSMA/CA	No	Reduce Signal (RTS/CTS) overhead
[17]	CSMA/CA	Yes	Combination of prioritize access and admission control
[18]	CSMA/CA	No	Wide contention window for backoff
[19]	CSMA/CA	Yes	Maintain carrier sense table
[20]	TDMA	Yes	Scheduling TDMA slots
[21]	TDMA	Yes	Scheduling
[22, 23]	TDMA	Yes	Scheduling and admission control
[24–26]	TDMA	No	Scheduling
[56, 58, 60]	TDMA	No	Network synchronization (loose)
[61–63]	TDMA	No	Network synchronization (tight)
[65–68]	TDMA	No	Multi-channel and Multi-radio used
[69]	TDMA	Yes	Multi-channel and Multi-radio used
[27]	Hybrid	No	Combination of DCF and PCF for channel access
[70]	Hybrid	No	Combination of TDMA and CSMA
[29]	Hybrid	No	Uses beacons to divide time into frames and frames into RAW. Also, performs traffic offloading

meeting the need of real time traffic. To this, a distributed QoS MAC protocol for WMN has been proposed in [18]. The repeated collisions due to hidden node problem has been eliminated by employing wide contention windows for backoff. By extending the duration field in a frame, the protocol achieves channel reservation in order to provide opportunity to the receiving node for forwarding the frame immediately. Also, it reduces collision probability on re-transmission by conducting immediate re-transmission as soon as the acknowledgement timer expires. Although, the end-to-end latency of the multi-hop flow has been greatly reduced but it compromises fairness. Further, it lacks bandwidth reservation for the overall period of communication.

Another MAC protocol for provisioning real time QoS in WMNs is sticky CSMA/CA [19]. This protocol provides TDMA-like performance to real time flows with implicit synchronization. After identifying the periodic flows, the protocol maintains carrier sense tables. The carrier sense table is looked up whenever a new real time flow arrives and a collision free transmission schedule is determined.

– *Comments and open research issues* The above enhancements to CSMA/CA do not fully address the issues pertaining to QoS provisioning in WMNs. The reason behind this is the conservative nature of CSMA/CA which combines the carrier sensing and collision avoidance mechanism that silence the communication of many other nodes in the network for a ongoing transmission. An open research issue is to fulfill QoS requirements of heterogeneous traffic by allowing the network resources to be used by many users simultaneously. Also, incorporating an efficient traffic based channel access priority mechanism in CSMA/CA still remains an open research issue.

4.1.3 TDMA-based Protocols

Recent researches indicate that TDMA-based MAC performs far better than CSMA/CA-based MAC protocol in WMNs [56–58]. This has stimulated the development of new TDMA-based MAC protocols such as 802.11s Mesh Deterministic Access (MDA) protocol [21]. Various other TDMA-based MAC protocols for WMNs have also been proposed in the literature addressing numerous challenges, such as supporting real time flows. At the end of this section, this paper discusses the TDMA-based MAC protocols based on the classification framework depicted in Fig. 2.

4.1.4 Scheduling Mechanism

The scheduling mechanism is the key for provisioning QoS in TDMA-based MAC protocols. Scheduling can be of two types: Distributed and Centralized. In centralized scheduling, a central coordinator node does the job of scheduling non-overlapping transmission slots for different links. In distributed scheduling, different nodes of the network locally take part in scheduling their transmissions. A variety of scheduling schemes are available in the literature [20, 21, 26].

Djukic et al. [20] proposes a centralized scheduling algorithm for QoS provisioning in terms of bandwidth and delay for VoIP flows. The algorithm assigns link bandwidth and guarantees a bound in the TDMA delay by formulating an optimization problem. for minimizing the number of TDMA slots. The scheduling process generates a transmission order with the Bellman-Ford algorithm by running it on a conflict graph.

Djukic et al. [21] further formulates an optimization mechanism, which uses the min-max delay across a set of multiple paths to finds the transmission order for a flow with minimum delay. Further, the Bellman-Ford algorithm has been modified to find minimum delay schedules in polynomial time.

Leoncini et al. [22] provides a Wired over Wireless (WoW) framework which used the Greedy Physical protocol proposed by Brar et al. [59] and exploits certain minimum bandwidth and maximum delay in WMNs. It uses a centralized spatial-TDMA scheduling and adapts to the change in traffic demands. The framework predicts the performance of the network by estimating the maximum delay and minimum bandwidth of each link in the network from the interference model. The framework also involves an admission control mechanism.

Koutsonikolas et al. [24] proposes a TDMA MAC protocol for multi-hop WMNs which overcomes challenges to calibrate and optimize the TDMA MAC protocol parameters in a wireless platform. It achieves network-wide synchronization with high accuracy, minimal overhead and bounded delay in the protocol. The protocol assumes global knowledge of the multi-hop network and carries out centralized scheduling to compute optimal transmission schedules.

Liu et al. [25] proposes a distributed multi-constrained scheduling algorithm on TDMA MAC for strict QoS provisioning in WMNs. In this algorithm, both network congestion and link quality are utilized to enhance the performance of the network. A unified approach is provided to calculate link QoS utility based on multiple QoS constraints. A near-optimal schedule is generated using the link QoS utility which captures the effect of QoS constraints, real time physical channel quality, and MAC queue status.

JaldiMAC [26] is a centralized ply-based packet scheduling algorithm proposed for WMNs. Initially, it categorized the traffic into—latency sensitive class and bandwidth greedy class for representing delay-sensitive and bandwidth requiring traffic respectively. The latency-sensitive traffic is given priority in the schedule generated by meeting their delay bounds. After that bandwidth-sensitive traffics are assigned in the unused slots in the schedule. The protocol guarantees loose QoS for delay sensitive traffic without hampering the fairness in each session. Error correction technique has been implemented to handle losses from overlaying TCP traffic.

Flow based packet scheduling and localized admission control has been combined to provide an integrated approach in [23]. Based on the delay and bandwidth requirements, real time traffic is categorized into three classes. A fine-tuned scheduling is performed provisioning the QoS requirements for the flows over a TDMA-based MAC protocol. Larger scope of transmission has been granted to delay and bandwidth sensitive real time traffic compared to other traffic in the scheduling algorithm. It also anticipates the arrival of periodic flows while preparing the schedule.

– *Comments and open research issues* Centralized TDMA scheduling schemes are known to perform better in provisioning QoS by centrally allocating links for transmission. However, distributed TDMA scheduling has a higher degree of scalability but at the cost complex scheduling mechanism. An open research issue is to design a distributed scheduling algorithm, which takes the unstable wireless path characteristics into consideration and optimizes the delay-throughput trade-off in terms of QoS. Most TDMA-based MAC protocols other than [26] and [23] do not handle scheduling of packets within a node. Providing a granular QoS for different prioritized traffic types with the stringent requirement, a fine-tuned QoS-aware packet scheduling algorithm avoiding congestion in intermediate hops still remains an open research issue.

4.1.5 Network Synchronization

All synchronous communications are based upon a certain degree of synchronization among the communicating systems. TDMA-based MAC protocols heavily rely on the time synchronization among the nodes which take part in scheduling decision. There are two levels of synchronization in TDMA-based MAC protocol: Loose synchronization and Tight synchronization. A global clock is referenced by all the nodes in the network by protocols employing tight synchronization. On the other hand, in loose synchronization, nodes in a network uses mechanism like token exchange to maintain their transmissions synchronized in lower degree compared to tight synchronization. Various TDMA-based MAC protocols employing both types of synchronization schemes, as found in the literature.

MAC protocols primarily rely on loose synchronization due to the lack of central coordinator in synchronizing time and the potential complexity in time synchronizing nodes over multiple hops. TDMA-based MAC protocols like 2P [58], WiLDNet [56], and JazzyMAC [60] maintain loose synchronization by using token exchange mechanism. All the nodes in the network, establish temporary synchronization with their neighboring nodes which facilitate effective localized communication.

Authors in [58] proposes a MAC protocol termed as 2P, which achieves simultaneous transmission and reception in bipartite topology. The protocol considers multi-radio at a single node and uses marker packet in order to perform synchronous operation such that a link is either transmitting or receiving. WiLDNet [56], an extension of 2P also relies on loose synchronization. Packet losses are recovered and throughput is enhance using Forward Error Correction (FEC) and bulk acknowledgements. JazzyMAC [60] which is later discussed in Subsection 4.1.3 also relies on loose network synchronization.

TDMA-based MAC protocols provide better service with the use of tight time synchronization. A TDMA-based MAC protocolis proposed by Dhekne et al. [61] for rural mesh networks which incorporates tight time synchronization. The protocol takes the multi-hop scenario of WMNs into consideration and carries out time synchronization among nodes in the network. A central coordinator uses a centralized scheduling algorithm to allocate static slots to different flows over multiple hops. Achieving tight time synchronization among nodes over multiple hops reduces overhead in the system and improves the overall network performance.

Soft-TDMAC [62] is an overlay TDMA MAC protocol featured with microsecond level time synchronization. It uses Phase-Locked Loops (PLLs) for pairwise synchronization and builds a synchronization tree, which minimizes worst-case synchronization error. [62] compares the use of two scheduling strategies with Soft-TDMAC. One is even-odd scheduling which alternates equal transmission time between pairs of nodes. Another strategy is minimum delay scheduling used to generate schedule which minimizes end-to-end delay and maximizes throughput.

LiT MAC [63] maintains tight time synchronization (in microsecond level) in the network over multiple hops. It also incorporates spatial reuse and dynamic routing to improve network performance. A centralized scheduling in LitMAC is employed which is responsible for allocating slots to a flow meeting the end-to-end delay bound for real time traffic.

– *Comments and open research issues* Both loose and tight synchronization mechanisms have advantages over each other. Tightly synchronized TDMA MAC protocols like [61–63] are observed to provide strict time slot transition over the token-based mechanisms used by [56, 58], and [60]. As a result, tightly synchronized TDMA-based MAC protocols are expected to minimize end-to-end delay and maximize throughput. Conversely, tight time synchronization is often accompanied by larger overheads of synchronizing the entire network with respect to other token-based mechanisms. Thus finding a time synchronization mechanism having a trade-off between the degree of synchronization and overhead still remains as an open research issue.

4.1.6 Channel Assumption

In wireless communication, the available frequency spectrum is usually subdivided into a number of channels which are normally equal-sized. Each channel provides dedicated bandwidth for communication. Wireless channels are critical resources for WMNs and need to be optimally used by the MAC protocols. Different MAC protocols apply different channel assignment mechanisms ranging from simple to complex. An efficient channel assignment scheme greatly relieves the effect of interference in close-by transmissions. There are two different paradigms for channel assumption in WMNs. They are- (i) single-channel assumption and (ii) multiple channel assumption. Single-channel assumption use only a single channel for communication and employs a very simple and static channel assignment approach. Whereas, in multiple channel assumptions, the network uses multiple numbers of channels for communication and employs either static or dynamic channel assignment mechanisms. Various TDMA-based MAC protocols with single and multiple channel assumptions are available in the literature

Various protocols like 2P [58], WiLDNet [56], JazzyMAC [60, 61], and [21] assume single-channel operation. A single channel is used in all the links and the channel statically assigned for communication irrespective of their locality. The links are scheduled for transmission avoiding interference among them. Raman et al. [58] avoids the use of multi-channel and emphasizes on the use of a single channel empowered with SynOp [64] as there is a limited number of usable channels in 802.11.

Many researchers, on the other hand, suggest the optimal use of the available channels. MAC protocols such as [65–68], and [69] proposes in literature have multi-channel assumption.

Alicherry et al. [65] views that with the use of multi-radio and multi-channel configuration at a node in WMN, the capacity of WMN can be further improved by simultaneous transmission over multiple radios. The author keeps the notion that channel assignment and routing are inter-dependent as channel assignment has an impact on link bandwidths. In order to optimize overall network throughput, the protocol formulates a joint channel assignment, routing, and scheduling taking the interference and fairness constraints into account. The protocol achieve optimal load balancing and less congestion assuming that traffic takes multiple path.

Dutta et al. [68] develops a new channel allocation mechanism for WMNs characterized by long-distance point-to-point links. Inheriting the concept of SynOp from 2P [58], this scheme uses multiple channels for full-duplex communication. To achieve full-duplex communication, the protocol first considers any link in the network to be made up of two edges. Then, every outgoing and incoming link at a node performs synchronous transmission and synchronous reception operations at the same time. An orthogonally disjoint channel allocation method is used to avoid interference. Thus, use of multiple channel in it reduces cross-link interference, thus does not require tight synchronization among the nodes. Since the protocol assigns channels in a dedicated manner; the channel assignment process is static in nature and does not vary.

The work of Ramachandran et al. [66] presents a dynamic, interference-aware channel assignment scheme that minimizes interference between the WMNs and the co-located wireless networks. The channel assignment process is a centralized one where the central node assigns channels in such a way that each radio operates on channels that experience the least interference from the external radios. This is done by taking the estimation of interference from individual mesh routers periodically. As a result, the channel assignment process becomes dynamic. During the channel assignment process, a higher priority is given to the nodes closer to the central node and is assigned channels earlier than the other nodes.

Trung et al. [69] introduces a Multichannel Time-division Multiple Access Control (McTMAC) protocol which can handle delay over multiple hops in WMN using multiple channels. The objective of reducing end-to-end delay over multiple hops is achieved by using the Longest Flow First Channel Assignment (LFF-CA) and Time-slot Allocation (LFF-TA) algorithms in multi-channel TDMA based WMN. In this protocol, the channel assignment and time-slot allocation process are based on the length of the flow as delay and throughput performance in WMNs degrades significantly with the increase in the number of hops.

- *Comments and open research issues* One of the major limitations of a single-channel assumption is that it constraints the end-to-end delay and throughput in a multi-hop network depending on the link scheduling mechanism employed. An open research issue with the use of multiple channels is to incorporate dynamic QoS constraints during channel assignment and slot allocation. Also, an interference aware channel assignment for forwarding traffic over multiple hops could assist in QoS provisioning.

4.1.7 Slot Size Consideration

In TDMA-based MAC protocols, time slots are allocated either statically or dynamically as the time is shared among the nodes. In static time allocation a constant amount of time is allocated to each node for transmission. When a node joins or leaves the network, the slot layout changes in static TDMA. Although most of the cases considers fixed-ratio for uplink and downlink traffic. In the case of dynamic slot sizing, the size of the time slot is assigned dynamically as per the traffic requirements in the nodes.

Static slot sizing is adopted by protocols like 2P [58], WiLDNet [56, 61, 63, 20], and [25]. Time slots are assigned to nodes/links requiring transmission opportunities based on the scheduling algorithm used. Although the protocols like 2P [58] and WiLDNet [56] seem to employ variable slot sizing but maintain a fixed ratio between upstream and downstream traffic. In such situations, every alternate node gets equal opportunity for transmission using SynOp [64]. On the other hand, protocols like JazzyMAC [60] allocate slot sizes dynamically. Each node in JazzyMAC can have variable length link transmission slots based on the changing traffic demands. Enhanced throughput is achieved in this protocol by allowing parallel independent transmission for neighboring nodes.

With the use of different channels for up and downlinks, [68] transforms the WMN architecture into a full-duplex wire-like environment. These protocols do not require any kind of slot sizing and can seamlessly transmit in both directions without any restriction.

– *Comments and open research issues* The TDMA-based MAC protocols using static size slot consideration do not provide significant performance improvement, whereas protocols with the dynamic slot size consideration provide service to traffic with asymmetric demands. An open research issue is to incorporate dynamic slot size in TDMA-based MAC protocols fulfilling the QoS demands of different real time traffic irrespective of their symmetry or asymmetry. However, using variable transmission slots with SynOp, end-to-end performance optimization in multi-hop WMN may be an interesting problem.

4.1.8 Hybrid of TDMA and CSMA Protocol

Hybrid protocols function by switching between scheduled access and random access. To avoid throughput degradation due to increased collision in high load scenario, scheduled access mechanism is operated. And during low loads, access to the medium is random like that in CSMA. Consequently, hybrid MAC protocols are a promising approach for designing scalability for communications. In the literature, various protocols have been proposed which blends the features of ALOHA and CSMA with FDMA, TDMA and CDMA. Hybrid MAC protocols are further divided based on the distribution in the network and the use of the channel. The MAC protocols can be centralized and distributed or single-channel and multiple channels.

4.1.9 Centralized Hybrid MAC Protocol

Distributed Point Coordination Function-M (DPCF-M) is a MAC protocol proposed for IoT communication [27]. It amalgamates the DCF and PCF medium access mechanisms of IEEE 802.11. Further, the protocol considers two types of devices (i) Gateway-capable nodes and (ii) Local M2M nodes. Gateway capable nodes have two interfaces- one for local and other for the cellular network, whereas in M2M nodes only low-power short range radios are used. CSMA/CA's non-beacon mode is used for local communication.

Authors in [70] proposes a hybrid of CSMA and TDMA based protocol in order to enhance energy efficiency and scalability. Time is segmented into frames and frames are further sub-divided into four fields. The first field NP corresponds to Notification Period, second field COP corresponds to Contention only period, third field is announcement period (AP) and the last field is transmission only period (TOP). During NP, a base station informs to all the nodes about the COP. In the COP, the nodes that have data to be transmitted uses p-persistent to content for the channel by sending transmission requests to the base station. After that in AP the base station announces, the allocated slots for data transmission to the nodes that contended successfully. Finally in TOP the nodes transmit data on the allocated slots. The slot allocation is achieved by solving an optimization problem. Work reported in [70] has been further explored by [28] and has been added with features like QoS provisioning and fairness. This is implemented by taking into consideration a node's priority and observed throughput in deciding a node's contention probability.

4.1.10 Distributed Hybrid MAC Protocols

WMN and IoT are very cohesive in terms of the problems addressed. The IEEE 802.11ah protocol [29] has proven its potential in IoT communication [71]. In 802.11ah, time is divided into frames and each frame has two parts: RAW (Restricted

Access Window) and OT (Offload Traffic). Each RAW is further sub-divided into small transmission slots which are assigned to a device by the AP or randomly selected by a device for transmission. In order to contend for the channel access, binary exponential backoff is implemented by a device which sends a polling frame. Authors in [72] sub-divided the RAW into two parts: RAW-UL and RAW-DL. RAW-Uplink (RAW-UL) is allocated to transmit data from node to base station and RAW-Down Link (RAW-DL) is used to transmit data from station to nodes. For efficient channel access, the length of RAW needs to be estimated. This is done by calculating the size of RAW-UL and RAW-DL. With focus on the uplink, the station needs to find the appropriate length of RAW-UL. The size of RAW-UL is affected by the number of devices requiring transmission. Further, the probability of successful transmission in the last frame is also use to estimate RAW-UL. With this modification, the protocol achieves higher transmission rate. Wang et al. [73] proposes an adaptive RAW mechanism which takes into account energy constraints. Hamzi et al. [74] estimates the RAW size from the station's backoff stage. Based on the requirements calculated at the beginning of a RAW, authors in [75] propose a RAW grouping approach. Authors in [76] propose an alarm reporting mechanism for dynamically tuning the RAW size based on the reported activity in a cell. However, such a mechanism will not provide expected results in heterogeneous traffic and dynamic networking scenarios, as a station may require transmitting at any time.

QoS provisioning critical applications such as healthcare are essential. Li et al. [77] proposes a joint packet size analysis scheme for a hybrid of body sensor and WiFi networks. Both CSMA and TDMA MAC protocols are applied in the hybrid network and formulate a optimization model on communication energy by imposing throughput and delay constraint. The optimized packet size shows better performance as compared to the fixed-size packet network. Zhou et al. [78] presents a QoS-aware body sensor network. It proposes criticality-aware data stream, admission control, radio agnostic, and bandwidth allocation schemes for achieving QoS in body sensor networks. The evaluation and implementation over real testbed show significant improvement for critical body-related traffic.

– *Comments and open research issues* One issue with the centralized hybrid protocols is that while communicating with an external server, an M2M mode has to take help from one of the gateway capable node. As the M2M nodes are only equipped with low powered short-range radio, it creates a potential challenge in frequent such communication. The protocols in [28, 70] involve contention mechanism as well as schedule time slots; therefore, there always remains a trade-off between the two. A station's transmission rate is not constant and also it may join or leave the network at any moment. Such dynamic networking and traffic heterogeneity impose serious challenges on distributed hybrid MAC protocols.

Figure 3 highlights some of the future directions for designing MAC layer protocols. Channel access over relay nodes, multi-channel operations among different links, distributed channel access, and adaptive hybrid MAC protocol are some of the areas that need the researcher's attention. Upper layer solution, identifying heterogeneous requirements of traffic, and applying Machine Learning (ML) based technique are required to efficiently schedule limited channel bandwidth in a WMN.

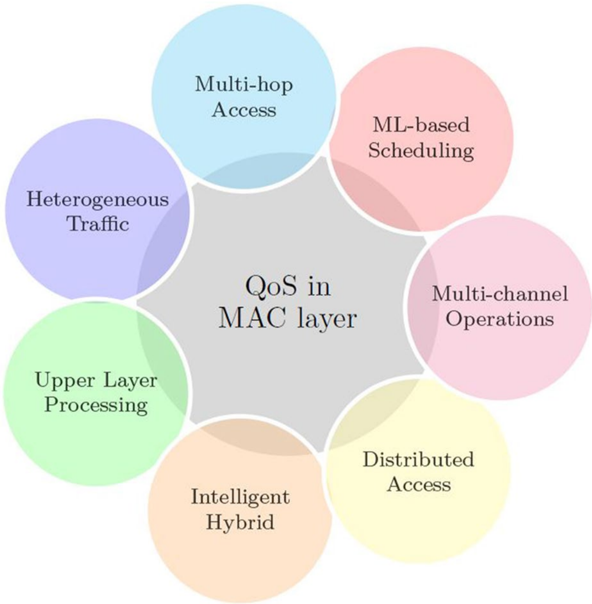

Fig. 3 Different domains of possible future directions for provisioning QoS in MAC layer

4.2 QoS Provisioning at Network Layer

In the literature, ample routing solutions which are specifically designed for WMNs can be found. But still many challenges in improving the end-to-end performance of WMNs. Different issues such as scalability, reliability, security, and end-to-end QoS provisioning are yet remaining open questions for WMN. So, the WMN protocols should address these issues either by modification of the existing protocols or by designing those afresh. The major limitation of the existing routing protocols such as AODV, DSR, DSDV, etc., in the absence of QoS support. Many routing protocols have been proposed to meet QoS challenges which focus on bandwidth, end-to-end delay, packet error, and jitter.

4.2.1 Classification Framework

In order to have a clear understanding of the QoS-based routing protocols, this work classifies them into different categories based on their characteristics and working principles. To classify the routing protocols for WMNs, non-QoS based and QoS based approaches are considered as shown in Fig. 4. This survey focuses on the routing protocols which primarily provide QoS in WMN and are mostly included in the QoS based approach in the classification framework.

The non-QoS based approach is based on the routing information update mechanism, which alone does not suffice the study of the majority of the routing protocols for WMNs. Keen observation reveals that the routing protocols for WMN deal with different properties like multicasting, multipath routing, various performance metrics, load balancing, admission control, etc. Hence, a QoS based approach has been proposed to classify different routing protocols. Different considerations of the QoS based approach are casting mechanisms, multiple path information, radios and channels used, network

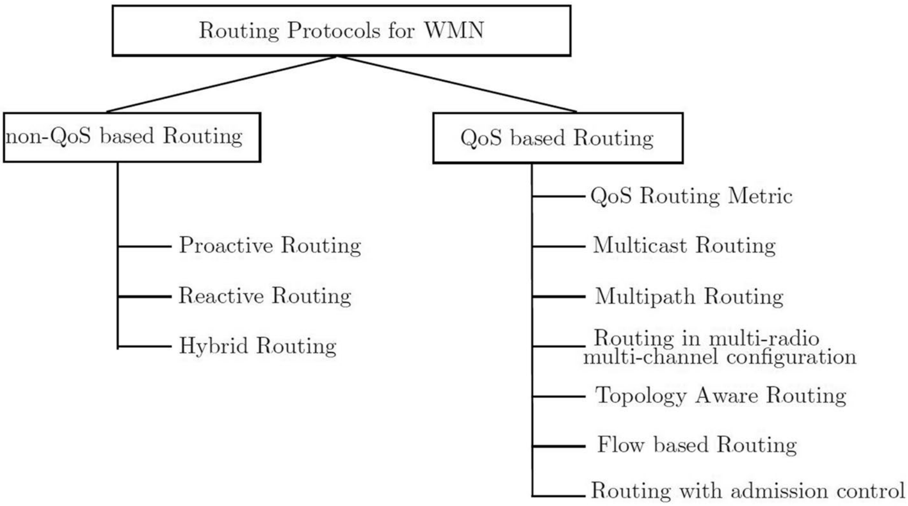

Fig. 4 Classification framework for routing protocols of wireless mesh networks

topology, performance metric considered, traffic flow, and admission control. A pictorial representation of the classification of routing protocols for WMNs has been presented in Fig.4.

Later in this section, we discuss the routing protocols based on the non-QoS based approach followed by the routing protocols based on the QoS based approach. Also, open research issues have been put forward for both approaches.

4.2.2 Non-QoS Based Approach

The non-QoS based approach basically looks into the type of communication that a router undergoes within the network for finding new paths maintaining the existing ones through route updates. Based on this approach, the routing protocols for WMNs are divided into three sub-categories- reactive, proactive, and hybrid routing.

4.2.3 Reactive Routing

Reactive or on-demand routing, the source node discovers a route to the destination node at the time of requirement. This type of routing protocol was originally designed for ad-hoc networks. Examples of such routing protocols are AODV [79], DSR [80], MCR [81], LBAR [82], etc. Flooding technique is usually used to discover routes as and when they are needed.

As compared to proactive routing protocols, ad-hoc network routing protocols faces issues like frequent line breaks ad node’s mobility. Flooding-based route discovery provide high network connectivity and relatively high message overhead. As WMNs are relatively static in nature, link failure, huge overhead, etc., are obvious. Therefore, it is not recommended to use reactive routing in mesh networks [83].

4.2.4 Proactive Routing

In proactive routing protocols, the nodes maintain a routing table with relevant fields. A table contains information of all nodes in the network. However, it periodically updates the information for maintaining consistency. Any changes in the topology gets updated in the tables as well. After receiving the routing update information, the nodes modify their routing table contents. These routing protocols differ in the method by which packets are forwarded along routes. Examples of such routing protocol are DSDV [84], WAR [85], OLSR [86], etc. There are two types of proactive routing protocols viz., source routing and hop-by-hop routing.

In the case of source routing, the sending node finds the path till the destination, and the complete path is written to its packet header. The intermediate nodes check the header and forward the packet accordingly. Initially, the sending packet carries the destination address, and intermediate nodes forward the packet along its path based on the destination address only.

4.2.5 Hybrid Routing

Hybrid routing protocols use the features of both proactive and reactive routing techniques. In hybrid routing, the first phase of the routing protocol starts with a proactive approach and then serves the demands from additionally activated nodes through reactive flooding. The reactive approach reduces the control overhead and a proactive approach decreases the latency during the route discovery process. Routing protocols such as LSRP [87], and ZRP [88], are some of the hybrid type routing protocols.

- *Comments and open research issues*
  The above non-QoS based routing protocols do not concentrate on finding a path based on QoS demands of the corresponding traffic. In a reactive routing protocol, a significant amount of delay occurs due to route discovery and route reply process. Designing a new route discovery mechanism with minimum delay is a challenging issue. On the other hand, proactive routing protocols require disseminating and processing additional control packets in order to maintain up-to-date topology information which incurs high overhead. Intelligent processing of control packets is a challenging issue for this type of routing protocol. In a hybrid routing protocol, applying the reactive or proactive routing protocols in a proper place of the WMNs is also considered to be challenging. Identification of location and taking advantage of both reactive and proactive routing protocols for a specific place, a protocol may provide better performance.

4.2.6 QoS Based Approach

The QoS based approach is based on various routing information such as bandwidth conservation techniques, multiple paths available between a pair of source and destination, routing topology, multiple radios using multiple channels with adjacent nodes, different routing metrics used for better performance, providing QoS, etc. Based on the routing information used, we classify the protocols into QoS metric, multicast, multipath,

Table 2 Comparison of the QoS provisioning techniques used in Routing protocols

Papers	Routing metric used	Technique used for provisioning QoS	Type of traffic
[30]	Traffic admission ratio, end-to-end delivery ratio, end-to-end delay	Admission control	Bandwidth and Delay sensitive
[31]	cross layer metric derived from physical layer	Find path based on the cross layer metric	Bandwidth sensitive
[44]	Link quality	Intelligent routing	Bandwidth sensitive
[32]	one-hop delay, throughput and PER	Route discovery for QoS flows	delay sensitive
[33, 89]	Bandwidth metric	Maximize bandwidth	Bandwidth sensitive
[90]	PDR, jitter, average end-to-end delay, throughput	Route discovery based on the metrics	Bandwidth and delay Sensitive
[91]	WCETT	Minimize interference and load balancing	Bandwidth and delay sensitive
[36, 37, 97]	–	Multi-casting	Bandwidth sensitive
[35]	–	GA based multi constrain multi-casting	Bandwidth and delay sensitive
[38]	–	Hybrid QoS multicast framework for load balancing and minimize traffic oscillation	Bandwidth sensitive
[100]	Bandwidth in multicast tree	Multicast routing	Bandwidth and delay sensitive
[115]	–	Gateway cluster based load balance multicast routing	–
[101]	Cross-layer metric	Multicast ring routing	–
[39]	ETT	multipath routing	Bandwidth and delay sensitive
[40]	Cross layer metric	Interference aware multipath selection	–
[41]	Distance	Hybrid multipath routing	–
[102]	Link delay	Link state based multipath routing	Delay sensitive
[104]	Interference	Topology control and routing in multi-channel	Bandwidth sensitive
[105]	Loss probability and channel bandwidth	Dynamic channel assignment	Bandwidth sensitive
[106]	WEED	Path selection with minimum end-to-end delay	Delay sensitive
[107]	MIND	Passive monitoring to reduce network overhead	Bandwidth sensitive
[108]	Metric based on topology and bandwidth	Cross-layer routing by exploiting multi-radio and multi-channel configuration	Bandwidth and delay sensitive
[43]	–	Routing in overlay network	Bandwidth sensitive
[45]	–	Topology aware routing	Delay sensitive

Table 2 (continued)

Papers	Routing metric used	Technique used for provisioning QoS	Type of traffic
[110]	–	ANN based hybrid routing	–
[42]	Link capacity	Constraint on the maximum aggregated flow that can be routed over a link	Bandwidth sensitive
[46]	–	Token bucket based admission control	Bandwidth and delay sensitive
[47]	Metric based on interference and traffic load	Select route based on the maximum bandwidth that can be granted	Bandwidth sensitive
[48]	–	MARIA	Bandwidth sensitive
[99]	–	Prioritize admission control	Bandwidth sensitive
[111]	–	Joint channel allocation and admission control	Bandwidth and delay sensitive
[112]	–	DCSPT for bandwidth estimation and admission control	Bandwidth
[49]	–	Intelligent route selection and admission control	Bandwidth and delay sensitive
[113]	–	Bandwidth estimation and admission control	Bandwidth sensitive
[50]		Bandwidth reservation and admission control	Bandwidth sensitive

multi-channel and multi-radio, topology-aware, admission control, and flow-based routing. Table 2 depicts an overall comparison of the QoS-based routing protocol.

4.2.7 QoS Routing Metric

In WMNs, when the number of nodes or hops is large, several issues like interference, channel errors, etc., crop up. Depending on such dynamic network characteristics, the routing protocols can focus on optimizing one or more performance metrics for network performance enhancement. Various considered metrics include hop count, expected transmission count, the effective number of transmissions, expected transmission time, etc.

Xue et al. [30] considers multiple performance metrics—traffic admission ratio, end-to-end delivery ratio, average end-to-end delay, a ratio of the late packet, and normalized routing overhead for proving QoS in WMN. A deadline-based routing decision maintaining the mentioned performance metrics. With the deadline and multiple QoS metric-based approach assured better services for needy applications. A cross-layer based routing metric is presented in [31]. The level of interference generated at each neighbor is calculated by adding the power perceived by each one. Packet Success Rate (PSR) is derived from the Packet Error Rate (PER), which takes into account the burst structure of errors. To maximize data rate, a power optimization technique (each node) with respect to PSR and Interference is also presented.

Another important routing protocol QUORUM [44] assumes a robustness metric for link quality and demonstrated its utility in route selection. The introduced metric provided intelligent routing using gray, fluctuating neighbors, and free-riding behavior. Moreover, link quality is measured using the number of HELLO packets during a time window. Measurement of the recent window is combined with historical value (Q) as an Exponentially Weighted Moving Average (EWMA) to compute the updated estimation. Based on the value of Q, a robustness metric is calculated by measuring the percentage of HELLO packets received. Each node maintains the robustness metric for the links to the neighbor. Thus, QUORUM avoids unreliable routes having lower robustness. Liu et al. [32] proposes a novel integrated QoS performance metric, considering various QoS constraints of the network. The route discovery procedure is initialized when new traffic flows are accepted by certain nodes. The scheme uses a route request packet with QoS flow constraints and maintains a timer during sending the REQ through the allocated time slot in the control channel to its one-hop neighbors. A dissatisfaction ratio, which is measured as the ratio between expected QoS metric value and the value provided by the QoS requirement of the applications. The expected QoS metric value is calculated through multiple QoS constraints such as end-to-end delay and throughput. The proposed scheme maintains a end-to-end throughput and delay dissatisfaction ratio for deciding the best path in a mesh network scenario. Hou et al. [89] develops a mechanism for computing the available bandwidth of a path in a distributed manner. To provide QoS in terms of bandwidth, it proposes a bandwidth metric using isotonic parameter so that packets can traverse the maximum bandwidth path consistently according to the routing tables constructed in the nodes along the path. The proposed solution calculates end-to-end packet.

Attempting to provide QoS using different performance metrics, [90] uses multiple routing metrics in the traditional AODV routing protocol. The QoS performance was improved with the use of metrics– packet delivery ratio, jitter, average end-to-end delay, and throughput. Enhancing AODV, Liu et al. [33] proposes a routing protocol called QoS- AODV with metrics such as delay and available bandwidth meeting the application's demands. The

RREQ includes delay and bandwidth requirements with current send time and path load rate. The intermediate nodes check whether the required bandwidth is greater than available bandwidth and also whether delay bound is less than accumulative delay. The load in the node reflects its congestion situation. The load rate used to find a relatively free path and has a stronger capability to accept more new load.

A routing metric to measure the link bandwidth is proposed in [91]. Here, a probing-based technique is used. The receiver computes received time difference between two packets and sends it to the sender. The authors in [34] proposes a routing metric named Weighted Cumulative Expected Transmission Time (WCETT). The WCETT metric combines the individual link weights. Enhancing these, a cluster-based routing metric is used in [92] considering an interference and load balancing in a network that focuses on minimizing the existing issues of networks for QoS. For routing in IoT, the IPv6 routing protocol for low power and lossy networks (RPL) is widely used. At the networking layer, the IPv6 routing protocol for low power and lossy networks (RPL) represents the reference standard proposed by the IETF for IPv6-compatible large-scale IoT applications [93]. The RPL provides mesh network support in low power WPAN. The default RPL considers only ETX as a routing metric. After this, there are a list of enhancements (such as [94–96], etc.) on RPL protocol can be found. This protocol enhances routing performance by considering different parameters such as energy, packet-loss, latency, etc.

– *Comments and open research issues* How accurate a routing metric is? The accuracy of a routing metric is a very important factor. Most routing metric leads to sub-optimal performance due to their adherence to empirical results. Can probabilistic/statistical determination of the routing metric lead to better performance? Based on the survey, a combined performance metrics can be designed from two or more existing routing metrics so that the selected path is optimized with good signal strength, satisfy bandwidth and delay requirements, experience low congestion, and low packet loss ratio. To support traffic using integrated-service classes, some new support in the network may need to deploy. Any changes in the metric may increase in the overall network overhead and thereby consuming network bandwidth and router CPU cycles.

4.2.8 Multicast Routing

Multicast routing is an effective way to communicate with multiple nodes in a network. The primary responsibility of this type of routing is to find a multicast tree, which is rooted in the source node and connects to all the destination nodes [35]. This mechanism helps in reducing bandwidth in the network by delivering information among the needy group of nodes. Any node wants to join the multicast group can put its requirements to the local router. Thereafter, the local router informs the other routers.

Ruiz et al. [36] proposes an integrated solution for efficient multicast routing in WMNs. The proposed scheme tries to construct a tree in order to reduce data overhead by taking full advantage of the broadcast nature of the wireless medium. This is done by connecting the subnetwork with the Internet. In the case of multiple gateway networks, multiple prefixes become available. All wireless routers using the same Internet gateway are configured with addresses on the same prefix.

Yuan et al. in [97] proposes a cross-layer framework to maximize the throughput in a wireless mesh network through multicast routing. This framework consists of two subproblems viz., data routing at the network layer and power control at the physical layer.

Again, the data routing technique works in two different ways- multicasting based on tree packing and multicasting with network coding. To determine the power levels at all the transmitters, a SINR based link capacity function is used. Ke et al. [35] proposes a QoS multicast routing algorithm for WMN which creates a multicast tree from a WMN using edge-set [98] spanning-tree coding scheme. It creates an optimal route such that the bandwidth and delay requirement is satisfied. A Genetic Algorithm (GA) is used to design an efficient heuristic algorithm for the multi-constrained multicast routing in wireless mesh networks. It finds a set of random multicast trees using a random walk algorithm where a walk starts from the source node and moves over a randomly chosen adjacent edge to one of its neighbors. The process continues until all the destination nodes are visited. Using edge-set, each multi-cast tree is encoded into chromosomes. The mesh routers collect the network states. If a mobile node has a multicast requirement, it sends the requirement to its nearby mesh router. The mesh router then searches an optimal route and sends it to the source node.

A QoS-aware multicast routing for WMN is proposed by Rong et al. in [99], which provides a network graph pre-processing approach to enable traffic processing and QoS multicast routing algorithms. The pre-processing phase runs prioritized admission control to achieve traffic service. Some special links are chosen for conducting admission control. Such a link may be removed from the graph if the connection request does not pass the admission control test. Zhao et al. [37] proposes and efficient multicast scheme by taking care of all the traffic in the WMN and maintains the optimal load balancing. A client sends Multicast Sender Request (MSR) to its gateway. Then, the gateway broadcasts the HELLO message periodically with its routing detail such as sequence numbers to all the gateway nodes. The broadcasted HELLO message recived by another gateway records the reverse route to the sending node in its multicast routing table keeping only the fresh entries. Pourfakhar *et al.* [38] proposes a hybrid QoS multicast framework-based protocol for WMNs which addresses the problems of load balancing and traffic engineering in gateways to achieve QoS in WMNs. In [38], all nodes of the network proactively maintain their routes towards the gateway or to each of the multiple gateways. It performs the route discovery process in a hybrid (reactive-proactive) manner. Mesh routers dynamically choose an Access Point (AP) not used before and currently has the lowest workload. Zhen et al. [100] presents an effective heuristic algorithm for calculating bandwidth of a multicast tree and proposes a DSR-based multicast routing algorithm in TDMA-based WMN. It also proposes a new bandwidth calculation algorithm and a route request algorithm. The bandwidth calculation algorithm assigns time slots for multicast trees such that the least link bandwidth can decide the bandwidth of the tree. For a new flow, a control packet is broadcasted to determine the bandwidth-satisfied path. Destination nodes collect route details from the source node and send it back to the source node. The source host determines the construction of a multicast tree according to the path information from destination hosts. A ring-based multicast routing with QoS support in WMNs has been proposed in [101] which benefits from the information about the physical network connections. This solution finds a suitable group for multicasting with QoS. Moreover, the ring-based technique reduces the cost of group communication. For QoS, the protocol computes the optimum number of members of cluster heads and an optimum number of members in the per-cluster and it uses a color-based algorithm to ensure QoS.

- *Comments and open research issues* The major issues in multicast routing are load balancing, resource management, and control overhead. Many existing protocols focus on gateway load balancing. Although load balancing helps in bandwidth management but to ensure QoS in terms of all its parameters, it is not sufficient. As in this type of routing, packets are sent through a group of routers to a group of receivers, reducing the control overhead is a challenging issue. Therefore, an efficient QoS resource management scheme is needed to guarantee bandwidth, delay, and packet loss. In the literature, most focus is seen on bandwidth utilization through multicast tree formation and load balancing, however, less effort has been devoted towards end-to-end delay and reliability for an established connection. The present scenario also lacks an integrated approach to load balancing based on the multicast tree formation and flow connections.

4.2.9 Multipath Routing

In the multipath routing technique, the data transmission is facilitated over multiple paths. It is an effective strategy in achieving reliability in WMNs. However, multi-path routing does not guarantee deterministic transmission. This is because of the availability of more than one path for transmitting data between a pair of source and destination node.

Nandiraju et al. in [39] proposes a multipath hybrid protocol called MMESH, which discovers multiple paths to the gateway. The proposed scheme find multiple paths to the destination and distributed load by sending packets among the paths. It also considers route maintenance based on the new information receives. The route discovery process considers Expected Transmission Time (ETT) or delays for QoS. After the route discovery phase, every router continuously monitors the status of the active paths. In the case of node/link failure, the node detecting failure immediately revises its routing table. The traffic is shared among all the possible paths from every router. A routing protocol for WMN is proposed in [40], which defines two constraints—an interference-free link schedule constraint and an interference-free node schedule constraint in multipath discovery. Later, it applies AODV protocol to finds out multiple candidate paths concerning the constrains. The algorithm dynamically distributes traffic over multiple paths in order to reduce end-to-end delay. A convex optimization model is developed to formulate the multipath problem.

Zuo et al. in [41] proposes a hybrid multipath routing algorithm called DAWMNet. The proposed scheme uses distance as the routing metric. In the initial phase of the routing, it use Dijkstra's algorithm to discover the best path. Thereafter, Ant Colony Optimization (ACO) algorithm is used for multiple path discovery by diffusing pheromone packets. An ehnaced link-state routing protocol for provisioning QoS in proposed in [102]. The proposed protocol ensures a delay for real time multimedia traffic. With the use of HELLO and Topology Control (TC) messages, the protocol initially calculates the link delay among all the nodes. A delay bound property is set for each node which is the estimated delay. If the delay of a link goes beyond the estimated link delay, it is not given any chance to take part in the path selection in order to guarantee QoS. Finally, through a route computation scheme, it finds some link-disjoint paths from source to destination nodes. MESHEMERIZE [103] is an opportunistic multipath routing protocol that is designed and optimized for drone communication. The scheme considers the mobility of the nodes while making a decision. For reliability in the 5G network, a remaining bandwidth based multipath routing (RBMR) protocol is proposed. It considers the interaction of the remaining bandwidth information between adjacent nodes. The source route discovery that meets the data backhaul bandwidth requirements and the effective maintenance of the routing decision.

- *Comments and open research issues* The above protocols propose to find multiple alternative paths to gateway nodes. An alternative path is activated in the case of sub-optimal performance by the selected optimal path. Further, many algorithms propose a load balancing approach by distributing traffic evenly in order to avoid congestion. Different QoS factors have been used in calculating the routing metric. In an unreliable wireless network, exploring the best path based on the type of traffic flowing can help in providing QoS guarantees to real time traffic. Traffic splitting over multiple paths is also an open research issue where traffic from a single flow has more than one path maintained and used. This might result in throughput enhancement as well as provide tolerance over packet losses, as a failure in one path will be suppressed by the other available paths.

4.2.10 Routing in Multi-radio and Multi-channel Configuration

In multi-radio and multi-channel consideration, a node or router in the WMNs is assumed to have several radio interfaces which operate on different non-overlapping channels in order to achieve better utilization of radio spectrum. This method proves its ability to increase network capacity, scalability, and reduce interference and contention with the neighboring nodes. Tang et al. [104] proposes an interference-aware topology control and QoS routing in multi-channel WMNs. It defines the co-channel interference which can capture the impact of interference precisely. Based on it, a minimum INterference Survivable Topology Control (INSTC) problem is calculated to assign an interference-minimum channel of the network. Considering the inter-flow and intra-flow contention, it proposed an influence model for multihop QoS routing. It tries to solve the to solve the formulated Bandwidth-Aware Routing (BAR) problem with an optimal LP-based polynomial-time QoS routing algorithm. Makrm et al. [105] proposes a protocol using neighborhood nodes collaboration to support QoS routing in WMNs. In [105], a dynamic channel assignment scheme is proposed for the neighborhood node collaboration problem which is adaptive to the load in wireless mesh networks and supports QoS routing. It works in two phases—monitoring and channel switching. In the first phase, the proposed scheme checks for probability of loss and channel bandwidth of the links. If a router experiences loss on a link currently being used and a channel is allocated with higher capacity if the requested throughput is higher. The channel assignment problem is kept as local problem to minimize the loss rate.

Utilizing the multi-radios and multi-channels, different routing metrics are proposed for enhancing WMN's performance in [106]. Multi-Radio Achievable Bandwidth (MRAB) for a path considering the impacts of inter/intra-flow interference and space/channel diversity and Weighted end-to-end delay (WEED). In [107], a new metric is designed, called INterference and channel Diversity (MIND) for measuring the network interference and load. It uses a passive monitoring to avoid the overhead of active network state information gathering. The MIND metric includes two components, one for inter-flow Interference and LOAD awareness (INTERLOAD and other for capturing intra-flow interference, called Channel Switching Cost (CSC). For bandwidth greedy application such as multimedia transmission, a OLSR based QoS routing is proposed in [108]. It uses HELLO and Topology Control (TC) messages. With the idea of a multi-radio multi-channel technique as the background, [108] proposes the CLQ-OLSR protocol to provide QoS for real time applications.

– *Comments and open research issues* Does channel assignment based on traffic load on nodes provide optimal results? Very less focus is seen on how to utilize multi-radio and multi-channel to increase throughput in the network, which leaves scope for further research in throughput optimization in multi-radio and multi-channel operation. Protocols such as [108] considers the best effort and real time traffic separately and finds the best channel for routing real time traffic. Finding the best channel for a particular radio and allowing different real time traffic priority classes to a different situation is a challenging issue.

4.2.11 Topology-aware Routing

Topology-aware routing protocols are designed based on the network topology. For example, a network topology can be of type tree or graph. These types of topologies can further be divided into many subcategories like hop based, link-based, stability based, zone-based, cluster-based, etc. [109]. The routing protocols are specific to the topology of the WMN.

Li et al. [43] proposes a QoS-aware Routing in Overlay Network (QRON). Over the physical nodes, an overlay network is formed with Autonomous Systems (AS) and Overlay Brokers (OBs). More number of OBs can be added incrementally for scalability and fault tolerance. Overlay topology refers to the topology that connects all the OBs on the Internet. After discovering the topology using Dijkstra's shortest-path algorithm, a QoS requirement in terms of traffic bandwidth is guaranteed for different traffic. Kone et al. in [44] proposes a routing protocol for limiting the flooding of control messages using explicit knowledge of the hierarchical mesh network. For Video-on-Demand (VoD) application, local caching approach is used. Similarly, to ensure delay, in the route discovery phase it chooses the route on which the first in time reply arrives at the source.

A QoS routing in terms of delay is proposed by Demmer et al. in [45]. It is a routing protocol that is based on Delay Tolerant Network (DTN). The proposed scheme considers the issues of network connectivity in the rural mesh network and proposes a Link State Announcement (LSA) messages for conveying the network connectivity for a node in the system are flooded throughout the network. As DTN is comparatively stable, very few LSA messages are required. For DTN, normal LSA is expanded to include additional information like buffer occupancy, and the shortest path computations are weighted based on both link availability and buffer occupancy. Kojic et al. [110] proposes a neural network-based hybrid routing protocol for WMNs. Artificial Neural Networks (ANN) are formed to solve various problems related to network resources and network stability. A ring-based topology with the support of infrastructure nodes for group communications is formed in [101]. The proposed solution achieves QoS by finding the maximum group size concerning end-to-end delay and energy consumption.

– *Comments and open research issues* In order to find better route meeting QoS requirements for different traffic, an intelligent routing protocol which can take routing decision based on the topology infrastructure is desirable. For such a method, topology discovery is important. The discovery procedure should maintain neighborhood information for each node by local information exchange. This procedure can also provide each node the distance to the infrastructure, which facilitates the route discovery for external traffic.

4.2.12 Flow-based Routing

The flow-based routing checks all the current flows of a router and decides an outgoing flow-line as per the requirement. This approach relies on the amount of traffic flows in the network. For all the connection, using flow-capacity, average flow, and queuing theory, the mean packet delay is calculated. Therefore, provisioning QoS in such routing is easier if the flow characteristics are known.

Capone et al. [42] proposes a new model for the QoS routing problem in multi-hop wireless networks considering the bandwidth requirements of the network. It uses the well known multi-commodity flow where link capacity constraint is replaced with interference constraint of the radio links. The protocol finds all the links within two hops and it is possible to associate capacity with these links. The capacity depends on the transmission rate, overhead, and maximum aggregate flows of the link set. As the transmission cannot occur simultaneously and flows in the links share the same resources.

– *Comments and open research issues* The flow-based routing protocols are suitable candidates in providing QoS, as it considers not only the subnet topology but also the traffic load. Analyzing different traffic to find different factors like link capacity matrix, traffic matrix, mean packet size, etc., is a difficult problem in a flow-based routing protocol.

4.2.13 Routing with Admission Control

In supporting real time multimedia traffic services such as voice and video applications in WMNs, some sort of QoS guarantees are inevitable. This type of service requires a pre-specified bandwidth, delay, etc., between any two given endpoints. In such a case, the network must be equipped with a protocol to decide whether to accept a new request or not and to find a route with sufficient bandwidth or minimum for an admitted flow. Also, admission control focus on providing ongoing flows with higher priority.

Tsai et al. [46] proposes a protocol based on Token bucket-based Admission Control (TAC) for IEEE 802.16 distributed networks. Initially, a method is developed to estimate the bandwidth of a link. Second, the estimated bandwidth is used for implementing the admission control algorithm. Later, it checks the available bandwidth, then the station determines whether to downgrade the flow or not otherwise it grants the time slots. The station checks for current usage exceeds the minimum usage of the traffic class. If yes, the flow is rejected. Hong et al. [47] proposes a routing algorithm that selects routes and calculates the maximal bandwidth that could be granted to the mesh routers along the selected routes. It considers interference and load in the path for QoS. A router requests the gateway with the required bandwidth for approval. The gateway can update the uplink and downlink scheduling and distributes the time slots to all routers. In [48], authors propose a Mesh Admission control and QoS Routing with Interference Awareness (MARIA) for enhancing QoS support for multimedia in WMNs. It introduces the interference scenario in wireless networks using a conflict graph model. An admission decision is made based on the residual bandwidth at each node.

Rong et al. [99] proposes a prioritized admission control, for accepting or rejecting flow requests based on their bandwidth requirements and the state of the special link. For different priority classes, the bandwidth requirements vector is used. A cross-layer routing for

VoD service is proposed in [111]. The proposed scheme introduces joint channel allocation and admission control with the help of MAC protocol's parameters. A routing protocol proposed in [112] is a Dual-Carrier Sense with Parallel Transmission-awareness (DCSPT) method for available bandwidth estimation. It introduces a packet probing-based available bandwidth estimation method and calculate maximum attainable rate (MAR) of traffic for admission control, and consequently, supporting QoS on wireless mesh networks.

Liu et al. [49] proposes a cross-layer framework that exploits the physical channel properties to perform intelligent route selection, admission control provides QoS to a variety of underlying applications. The QoS requirement for different connection is checked and concerning this, a connection admission control is employed to admit flow ensuring QoS of the flows which are already running. Liu et al. in [113] proposes a threshold-triggered approach which is used to estimate the bandwidth. Using this approach, each node estimates the residual bandwidth on each associated channel and calculates the sustainable sending rate of a path. Authors in [50] proposes a QoS routing and traffic scheduling for long-distance 802.11 WMNs. The bandwidth reservation and admission control are implemented during the route discovery process. If there are multiple paths, the path with maximum reserved bandwidth for high and normal priority traffic is selected. For the best-effort traffic, the path with maximum unreserved path bandwidth is selected. A new bandwidth estimation technique is introduced in [114] but applies to multi-channel or multi-radio environments and provides parameters to balance the tradeoff between control message overhead and estimation accuracy.

– *Comments and open research issues* Admission control is an important mechanism to provide QoS guarantees to the ongoing real time traffic flows. Avoiding congestion in WMN is a challenging issue, which can be solved by using a proper admission control policy. In such a situation, if the bandwidth estimate of the best path cannot admit the new request, the associated traffic can be forwarded through other available alternate paths, provided the route meets the QoS. Also, taking into account the delay and reliability of a path is challenging and still remains an open research issue. Does admission control based on bandwidth estimates suffice QoS for real time applications? Does bandwidth reservation put bottleneck in the network's achievable throughput? These are some of the questions which still remain answered.

In the future, Machine Learning (ML)-based approaches can be used to identify the traffic and accordingly to provide the QoS as per their requirements. The use of Multi-path caching and cross-layer metric in an existing scheme can improve the routing performance. Moreover, heterogeneous header processing, and flow management in Software-Defined Networking (SDN) are the areas that need researcher's attention. Figure 5 highlights some of the future works in this domain.

4.3 QoS Provisioning at Transport Layer

Among the transport layer protocols, TCP plays a crucial role on the Internet by providing reliable, connection-oriented, full-duplex communication. However, TCP is popularly known to suffer from end-to-end performance degradation in mobile wireless environments. This is due to the packet losses because of the high bit-error-rate and mobility induced disconnects. The packet losses unnecessarily trigger the congestion control mechanism which induces low throughput performance. Research works have been conducted to

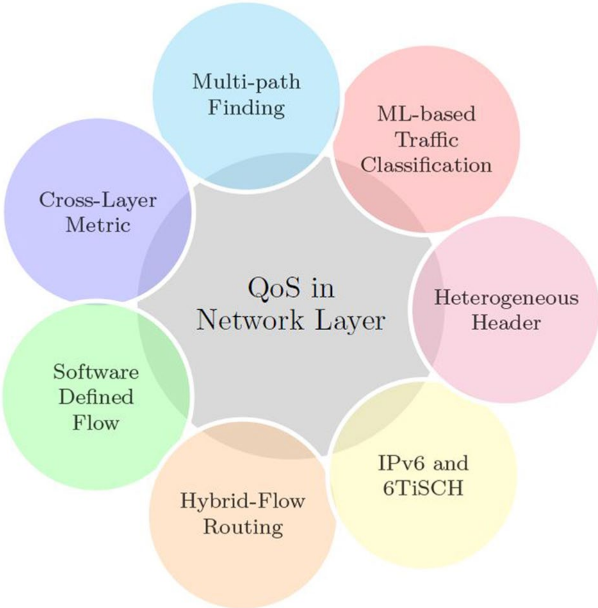

Fig. 5 Different domains of possible future directions for provisioning QoS in Network layer

overcome the existing limitations of TCP in WMNs and incorporate enhancements in the TCP/IP protocol stack. As the amount of literature is limited, this paper straight away discusses them without any classification.

4.3.1 An Adaptation to TCP (ATCP) [51]

ATCP indicates that packet loss due to the variability of wireless links leads to performance degradation. An approach eliminating the performance degradation effect on TCP for two-way data transfer termed as ATCP is proposed in [51]. ATCP is a cross-layering approach where the network layer gives feedback about the mobility status in terms of connection and disconnection events, which are further used in modifying the congestion control mechanism. Cross-layer signals are appropriately used to freeze/continue ongoing data transfers and change the action taken at Retransmission Time Out (RTO) event, leading to enhanced TCP throughput. However, in this approach, TCP cannot react disconnects that occur over multiple hops in the path from source to destination.

4.3.2 Loss Tolerant TCP (LT-TCP) [52]

It proposes a mechanism to improve TCP performance over networks comprising of lossy wireless links. The mechanism uses a dynamic and adaptive Forward Error Correction (FEC) scheme to hide packet losses which also includes an adaptation of the maximum segment size for TCP. Two FEC approaches have been introduced: Proactive FEC and Reactive FEC. Pro-active FEC is a function of the actual Packet Erasure Rate (PER). It provides FEC on an end-to-end basis for TCP. On the other hand, reactive FEC minimizes the effect of packet losses during the re-transmission phase. The overall scheme is called Loss Tolerant TCP (LT-TCP) which includes an adaptive maximum segment size (MSS) component to reduce the risk of timeouts with as effort to minimize the number of packets in the TCP window. The scheme balances the overhead added for FEC and the protection obtained for bit errors and the resultant packet erasures. Based on the PER value, FEC components are chosen dynamically to reduce overhead. Similarly, for a path with little or no erasures, there are negligible overhead.

4.3.3 TCP with Adaptive Pacing (TCP-AP) [53]

EIRakabawy et al. [53] proposes a new congestion control algorithm for TCP over multi-hop IEEE 802.11 network. It uses a rate-based control over the TCP congestion window. The 4-hop propagation delay describes the time taken by the first bit of a TCP packet from a TCP source to reach the TCP destination which is 4 hops apart. The RTT estimates are conducted with the most recent RTT observed and the coefficient of variation is calculated. It retains the semantics of TCP and does not depend on cross-layer information.

4.3.4 An Adaptive and Responsive Transport Protocol (AR-TP) [54]

The protocol proposed an adaptive and responsive transport protocol (AR-TP) which fairly allocates the network resources among multiple flows while minimizing the performance overhead. Authors in [54] criticizes the use of end-to-end congestion and rate control for WMN as wireless links suffer from variable RTT, high BER, radio interference, etc. As a solution to the problem, they propose AR-TP protocol which is based on hop-by-hop congestion control and coarse grain reliability mechanism. The hop-by-hop congestion control mechanism keeps track of dynamic multi-hop network characteristics in a responsive manner. On the other hand, the coarse-grained reliability algorithm provides packet-level reliability at the transport layer. AR-TP also incorporates a local rate adaptation scheme which involves two mechanisms: backpressure and forward threshold adaptation.

4.3.5 A Stateful Transport Protocol for Multi-channel Wireless Mesh Networks [116]

Authors in [116] argue that transport layer states can also be maintained in intermediate nodes along the path from source to destination, as long as it can maximize the utilization. To this, a stateful transport protocol named Link-aware Reliable Transport Protocol (LRTP) is proposed in [116]. The protocol maintains a state of flows in the intermediate nodes which can locally take part in congestion control and provide reliability through retransmission at the points where packet loss occurred. LRTP leverages link-layer ACK to determine each packet transmission status at each hop and eliminates packet wise transport layer ACK. The WMN nodes run the LRTP protocol and the nodes other than them continue to use original TCP. Using such a mechanism, LRTP provides a platform to enhance TCP throughput.

4.3.6 A Unified TCP Enhancement for Wireless Mesh Networks [55]

Liu et al. [55] points out that transmission errors, packet reordering due to multi-path routing, multi-hop connection and congestion are the challenges faced by TCP while deployed in WMN. In [55], a new TCP enhancement called Congestion Coherence (CC) which distinguishes between congestion losses due to transmission errors from that due to multipath reordering, and based on that invoke or suppress TCP congestion accordingly. CC uses a wireless side enhancement which is to modify the behavior of base station or mobile host in cooperation with the TCP algorithm at the source. The enhancement in the proposal uses Explicit Congestion Notification (ECN) for congestion control and local re-transmission at the link layer. CC exploits the notion that congestion neither happen nor disappears suddenly. Thus, the protocol introduces a nomenclature "Coherence context" which includes packets that come before or after the packet at a congestion point. For congestion problem, the receiver transmits duplicate ACK with ECN-Echo, which is an indication of congestion if there is a loss in the coherence context otherwise not. A timer is used to reduce the incorrectly held duplicate ACK or re-transmission of packets.

4.3.7 TCP Enhancement for WMN Without Modification in the Transport Layer

Various researchers viewed that the change in the lower layers other than the transport layer could eliminate the problems faced in TCP transmissions from air-born side-effects due to the lossy wireless environment.

Tung et al. [117] puts forward that the channel interference problems such as hidden terminal and exposed terminal have a larger impact on TCP transmissions over WMNs. To mitigate the impact of the interference problems, authors in [117] proposes a multi-channel assignment algorithm which uses the spatial channel reuse property of WMN and eliminates the hidden terminal problem. Authors in [118] proposes a new system design for multi-path forwarding in WMN based on backpressure. This system is termed as a horizon and is implemented in a slim layer between the data link and network layers. The backpressure approach to obtain a simple 802.11 compatible packet forwarding heuristics and a lightweight path estimator to maintain global optimal properties result in TCP performance enhancement without any change in the transport layer. Karlsson et al. in [119] propose that packet aggregation on TCP in WMN can not only improve the TCP performance in such networks but also improve fairness and reduce end-to-end delay. Based on simulation results, they claim that packet aggregation can improve TCP performance up to 73% using commodity 802.11 hardware for WMN.

A novel technique called Cooperative Neighborhood Airtime-limiting (CNA) is proposed in [120] which explicitly allocates the channel resources. CNA achieves efficient airtime allocation by equally distributing available airtime within a wireless neighborhood. It monitors the airtime utilization and dynamically allocates the underutilized airtime to underserved nodes in order to improve overall airtime utilization. The power of CNA lies in its ability to adapt to external interference thus leading to better airtime allocation. This airtime allocation technique results in improvised congestion control which functions effectively in WMN.

– *Comments and open research issues* Protocols other than [117–120] provide enhancement to the transport layer which requires modification in the transport layer. All most all the protocols aim at increasing reliability for the communicating flows thus optimizing network throughput. However, packets losses and duplicate transmissions due to multi-path forwarding of traffic have not been addressed to its totality. An integrated approach for handling packet losses due to multi-path routing, avoiding false congestion notification, forward error correction, and hop-by-hop re-transmission and congestion control to provide greater reliability in provisioning QoS for different applications still remains as open research issues. Further, in the recent network like IoT, due to the variety in communication patters, TCP is not suitable due to, constraint nature of devices, a

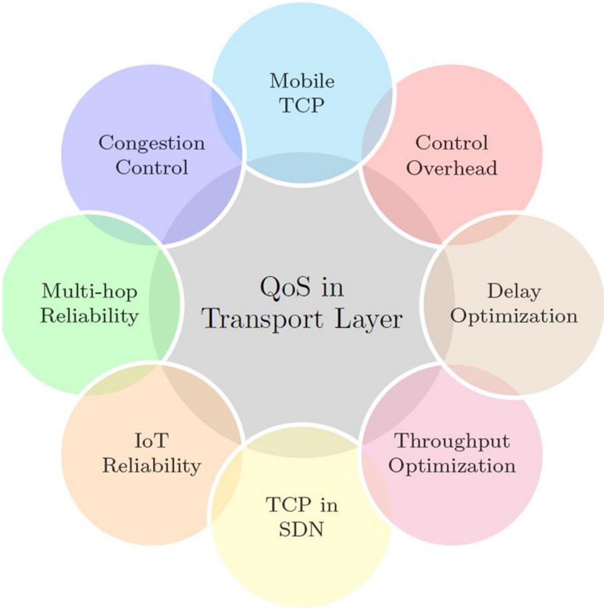

Fig. 6 Different domains of possible future directions in provisioning QoS at Transport layer

small amount of data, and high latency [121]. It may cause head-of-line blocking due to the lossy, in-order delivery and re-transmission [122].

Figure 6 shows the possible future directions in designing transport layer protocols. Performance of TCP over resource constraint IoT and M2M network is challenging. With the growing number of devices, there is a need for redefining the mobile TCP architecture considering next-generation mesh network architecture. Applying TCP in Software-Defined Networking (SDN) in another area for research. Multi-hop reliability, reliability over IoT, and congestion while applying TCP are challenging. More works are required to optimized the delay and throughput while achieving reliability.

5 Conclusion

QoS provisioning in WMN for supporting real time applications is a growing concern. In this survey, we focused on the variety of QoS schemes that are proposed in different layers of the protocol stack. The proposed classification frameworks provided a clear understanding of the features of various protocols and also provided an insight into their relationship among them. This survey presented an integrated approach in understanding the QoS architecture of WMN and finding the key aspects in provisioning QoS for heterogeneous traffic. Lastly, this paper provided a thought into the pros and cons of surveyed protocols and pointed out some open research issues in the domain of QoS provisioning in WMN which may be helpful for further research.

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Declarations

Conflict of interest The authors declare that they have no competing interests

References

1. Akyildiz, I. F., Wang, X., & Wang, W. (2005). Wireless mesh networks: A survey. *Computer Networks, 47*(4), 445–487.
2. Marwaha, S., Indulska, J., & Portmann, M. (2008). Challenges and recent advances in QoS provisioning in wireless mesh networks. In *the*8^{th}*IEEE International Conference on Computer and Information Technology (CIT '08)*, pages 618–623. IEEE.
3. Li, Y., Harms, J., & Holte, R. (2005). Impact of lossy links on performance of multihop wireless networks. In *Proceedings of*14^{th}*International Conference on Computer Communications and Networks*, pages 303–308. IEEE
4. Mogre, P.S., Hollick, M., & Steinmetz, R,. (2007). QoS in wireless mesh networks: Challenges, pitfalls, and roadmap to itsrealization. In *International workshop on Network and Operating Systems Support for Digital Audio & Video (NOSSDAV)*.
5. Bemmoussat, C. eddine, Didi, F., & Feham, M., (2012). A survey on QoS in wireless mesh network. In: *The Fifth International Conference on Advances in Mesh Networks (MESH 2012)*.
6. Zhao, L., & Al-Dubai, Ahmed Y. (2012). Routing metrics for wireless mesh networks: A survey. *Recent Advances in Computer Science and Information Engineering* (pp. 311–316). Springer.
7. Saha, S., Acharjee, U. K., & Islam, T.-U. (2014). A survey on wireless mesh network and its challenges at the transport layer. *International Journal of Computer Engineering & Technology (IJCET), 5*(8), 169–177.
8. Karthika, K. C. (2016). Wireless mesh network: A survey. In *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, IEEE. pages 1966–1970.
9. Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, Michele. (2014). Internet of Things for smart cities. *IEEE Internet of Things Journal, 1*(1), 22–32.
10. Mutlag, Ammar Awad, Ghani, Abd, Khanapi, Mohd, Arunkumar, N., Mohammed, Mazin Abed, & Mohd, Othman. (2019). Enabling technologies for fog computing in healthcare IoT systems. *Future Generation Computer Systems, 90,* 62–78.
11. Krishner M., Yves L., Coronel, V.A., Fernandez, I. C., Ung, K., Miras, C., Densing, C. V., Ong, D., Austria, I., Talampas, M., Tiglao, N., (2019). Implementation of 6LoWPAN and controller area network for a smart hydroponics system. In *2019 Global IoT Summit (GIoTS)*, pages 1–4. IEEE.
12. Crawley, E., Nair, R., Rajagopalan, B., & Sandick, H. (1998) A framework for QoS-based routing in the Internet. RFC 2386 (Informational).
13. Jun, J., & Sichitiu, M. L. (2003). The nominal capacity of wireless mesh networks. *IEEE Wireless Communications, 10*(5), 8–14.
14. Lee, J., & Jindal, N. (2008). Energy-efficient scheduling of delay constrained traffic over fading channels. *IEEE Transactions on Wireless Communications, 8*(4), 1866–1875.
15. Stefan Aust, R., Prasad, V., & Niemegeers, I. G. M. M. (2015). Outdoor long-range WLANs: A lesson for IEEE 802.11ah. *IEEE Communications Surveys & Tutorials, 17*(3), 1761–1775.
16. Rao Gannapathy, V., Bin Haji Suaidi, M.K., Johal, B., Chuan, Lim Kim, Bin Ramli, N., & Mohamad, H. (2011). A smooth forwarding operation in wireless mesh network. In *IEEE*10^{th}*Malaysia International Conference on Communications (MICC)*, pages 83–87. IEEE.
17. Benveniste, M., (2002). Tiered Contention Multiple Access (TCMA), a QoS-based distributed MAC protocol. In *the*13^{th}*IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, volume 2, pages 598–604. IEEE.
18. Benveniste, M. (2008). A distributed QoS MAC protocol for wireless mesh. In *the*2^{nd}*International Conference on Sensor Technologies and Applications (SENSORCOMM '08)*, pages 788–795, Washington, DC, USA, 2008. IEEE, IEEE Computer Society.
19. Singh, S., Acharya, P. A. K., Madhow, U., & Belding-Royer, E. M. (2007). Sticky CSMA/CA: Implicit synchronization and real-time QoS in mesh networks. *Ad Hoc Networks, 5*(6), 744–768.
20. Djukic, P., & Valaee, S. (2007). Quality-of-service provisioning for multi-service TDMA mesh networks. Lecture Notes in Computer ScienceIn Lorne Mason, Tadeusz Drwiega, & James Yan (Eds.), *Managing Traffic Performance in Converged Networks* (Vol. 4516, pp. 841–852). Berlin Heidelberg: Springer.

21. Djukic, P., & Valaee, S. (2009). Delay aware link scheduling for multi-hop TDMA wireless networks. *IEEE/ACM Transactions on Networking (TON), 17*(3), 870–883.
22. Leoncini, M., Santi, P., & Valente, P. (2008). An STDMA-based framework for QoS provisioning in wireless mesh networks. In the 5*th* IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS '08), pages 223–232. IEEE.
23. Hussian, I., Saikia, D.K., Sarma, N., Ahmed, N. (2014). A fine-tuned packet scheduling for WiFi-based long distance networks. In the 1*st* International Conference on Applications and Innovations in Mobile Computing (AIMoC'2014), pages 97–103, Kolkata, India. IEEE.
24. Koutsonikolas, D., Salonidis, T., Lundgren, H., LeGuyadec, P., Charlie H., Y., & Sheriff, I. (2008). TDM MAC protocol design and implementation for wireless mesh networks. In the 2008 ACM CoNEXT Conference (CoNEXT '08), pages 28:1–28:12, New York, NY, USA. ACM.
25. Liu, Chi Harold, Gkelias, Athanasios, Hou, Yun, & Leung, Kin K. (2008). A Distributed Scheduling Algorithm with QoS Provisions in Multi-Hop Wireless Mesh Networks. In IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WIMOB '08), pages 253–258. IEEE.
26. Ben-David, Yahel, V.,, Matthias, F., Seth, Brewer, E. (2010). JaldiMAC: Taking the distance further. In the 4*th* ACM Workshop on Networked Systems for Developing Regions (NSDR '10), pages 2:1–2:6, New York, NY, USA. ACM.
27. Azquez-Gallego, F.V., Alonso-Zarate, J., Balboteo, I., & Alonso, L. (June 2013). DPCF-m: A medium access control protocol for dense machine-to-machine area networks with dynamic gateways. In 14th IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC). IEEE.
28. Liu, Y., Yuen, C., Cao, X., Hassan, N. U., & Chen, J. (2014). Design of a scalable hybrid MAC protocol for heterogeneous M2M networks. *IEEE Internet of Things Journal, 1*(1), 99–111.
29. Sun, W., Choi, M., & Choi, S. (2013). IEEE 802.11ah: A long range 802.11 WLAN at sub 1 GHz. *Journal of ICT Standardization, 1*(1), 83–108.
30. Xue, Q., & Ganz, A. (2002). QoS routing for mesh-based wireless LANs. *International Journal of Wireless Information Networks, 9*(3), 179–190.
31. Iannone, L., Khalili, R., Salamatian, K., Fdida, S. (2004). Cross-layer routing in wireless mesh networks. In *the1stInternational Symposium on Wireless Communication Systems*, pages 319–323. IEEE.
32. Liu, C. H., L., Kin K., & Gkelias, A. (2008). A novel cross-layer QoS routing algorithm for wireless mesh networks. In International Conference on Information Networking (ICOIN '08), pages 1–5. IEEE.
33. Liu, L., Zhu, L., Lin, L., & Qihui, W. (2012). Improvement of AODV routing protocol with QoS support in wireless mesh networks. *Physics Procedia, 25,* 1133–1140.
34. Li, J., Khan, M., Lee, B., & Han, K. (2019). Load balancing and interference delay aware routing in IoT aware wireless mesh networks. *Journal of Internet Technology, 20*(1), 293–300.
35. Ke, Z., Li, L., Sun, Q., & Chen, N. (2007). A QoS multicast routing algorithm for wireless mesh networks. In *the8thACIS International Conference on Software Engineering, Artificial Intelligence, Networking, and Parallel/Distributed Computing (SNPD '07)*, volume 1, pages 835–840. IEEE.
36. Ruiz, P. M., Galera, F. J., Jelger, C., Noel, T. (2006). Efficient multicast routing in wireless mesh networks connected to Internet. In *the1stInternational Conference on Integrated Internet Ad Hoc and Sensor Networks (InterSense '06)*, New York, NY, USA. ACM.
37. Zhao, L., Al-Dubai, A. Y., Min, G. (2009). A QoS aware multicast algorithm for wireless mesh networks. In *IEEE International Symposium on Parallel & Distributed Processing (IPDPS '09)*, pages 1–8. IEEE.
38. Pourfakhar, E., & Rahmani, A. M. (2010). A hybrid QoS multicast framework-based protocol for wireless mesh networks. *Computer Communications, 33*(17), 2079–2092.
39. Nandiraju, N. S., Nandiraju, D. S., Agrawal, D. P. (2006). Multipath routing in wireless mesh networks. In *the IEEE International conference on Mobile Adhoc and Sensor Systems (MASS '06)*, pages 741–746. IEEE.
40. Shu, Y., Shu, Z., & Luo, B. (2012). A multipath routing protocol in wireless mesh networks. *Chinese Journal of Electronics, 21,* 131–136.
41. Zuo, Y., Ling, Z., & Yuan, Y. (2013). A hybrid multi-path routing algorithm for industrial wireless mesh networks. *EURASIP Journal on Wireless Communications and Networking, 2013*(1), 1–12.
42. Capone, A., & Martignon, Fabio. (2007). A multi-commodity flow model for optimal routing in wireless MESH networks. *Journal of Networks, 2*(3), 1–5.
43. Li, Z., & Mohapatra, P. (2004). QRON: QoS-aware routing in overlay networks. *IEEE Journal on Selected Areas in Communications, 22*(1), 29–40.

44. Kone, V., Das, S., Zhao, Ben Y., & Zheng, H. (2007). QUORUM: Quality of Service routing in wireless mesh networks. In *The Fourth International Conference on Heterogeneous Networking for Quality, Reliability, Security and Robustness & Workshops*, page 18. ACM.
45. Demmer, M., & Fall, K. (2007). DTLSR: Delay tolerant routing for developing regions. In *the 2007 workshop on Networked Systems for Developing Regions*, page 5. ACM.
46. Tsai, T.-C., & Wang, C.-Y. (2007). Routing and admission control in IEEE 802.16 distributed mesh networks. In *the IFIP International Conference on Wireless and Optical Communications Networks (WOCN '07)*, pages 1–5. IEEE.
47. Hong, C.-Y., Pang, A.-C., Wu, J-LC. (2007). QoS routing and scheduling in TDMA based wireless mesh backhaul networks. In *Wireless Communications and Networking Conference (WCNC '07)*, pages 3232–3237. IEEE.
48. Cheng, X., Mohapatra, P., Lee, S.-J., Banerjee, S. (2008). MARIA: Interference-aware admission control and QoS routing in wireless mesh networks. In *IEEE International Conference on Communications (ICC '08)*, pages 2865–2870. IEEE.
49. Liu, C. H., Gkelias, A., Hou, Y., & Leung, K. K. (2009). Cross-layer design for QoS in wireless mesh networks. *Wireless Personal Communications, 51*(3), 593–613.
50. Zenghua, Z. H. A. O., Ming, H. E., Jie, Z. H. A. N. G., & Lianfang, Z. H. A. N. G. (2012). QoS routing and traffic scheduling in long-distance 802.11 wireless mesh networks. *Chinese Journal of Electronics,21*(2).
51. Singh, A.K., & Iyer, S. (2002). ATCP: Improving TCP performance over mobile wireless environments. In 4^{th}*International Workshop on Mobile and Wireless Communications Network*, pages 239–243.
52. Tickoo, O., Subramanian, V., Kalyanaraman, S., & Ramakrishnan, K.K. (2005). LT-TCP: End-to-end framework to improve TCP performance over networks with lossy channels. In *Quality of Service–IWQoS 2005*, Springer. pages 81–93.
53. ElRakabawy, Sherif M., Klemm, A., Lindemann, C. (2005). TCP with adaptive pacing for multihop wireless networks. In *the*6^{th}*ACM International Symposium on Mobile Ad Hoc Networking and Computing*, ACM. pages 288–299.
54. Gungor, V. C., Pace, P., Natalizio, E. (2007). AR-TP: An adaptive and responsive transport protocol for wireless mesh networks. *In IEEE International Conference on Communications (ICC '07)*, pages 3740–3745. IEEE.
55. Liu, C., Shen, F., & Sun, M.-T. (2007). A unified TCP enhancement for wireless mesh networks. In *International Conference on Parallel Processing Workshops (ICPPW '07)*, pages 71–71.
56. Patra, R., Nedevschi, S., Surana, S., Sheth, A., Subramanian, L., & Brewer, E. (2007). WiLDNet: Design and implementation of high performance Wifi based long distance networks. In *the*4^{th}*USENIX Conference on Networked Systems Design & Implementation (NSDI '07)*, Berkeley, CA, USA. USENIX Association.
57. Chebrolu, K., & Raman, B. (2007). FRACTEL: A fresh perspective on (Rural) mesh networks. In *ACM SIGCOMM Workshop on Networked Systems for Developing Regions*.
58. Raman, B., & Chebrolu, K. (2005). Design and evaluation of a new MAC protocol for long-distance 802.11 mesh networks. In *the*11^{th}*annual international conference on Mobile Computing and Networking (MobiCom '05)*, pages 156–169. ACM.
59. Brar, G., Blough, Douglas M., & Santi, P. (2006). Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks. In *the*12^{th} *annual international conference on Mobile computing and networking*, pages 2–13. ACM.
60. Nedevschi, S., Patra, Rabin K., Surana, S., Ratnasamy, S., Subramanian, L., & Brewer, E. (2008). An adaptive, high performance MAC for long-distance multihop wireless networks. In *the*14^{th}*ACM international conference on Mobile computing and networking*, pages 259–270. ACM.
61. Dhekne, A., Uchat, N., & Raman, B. (2009). Implementation and evaluation of a TDMA MAC for WiFi-based rural mesh networks. *NSDR '09*
62. Djukic, P., & Mohapatra, P. (2012). Soft-TDMAC: A software-based 802.11 overlay TDMA MAC with microsecond synchronization. *IEEE Transactions on Mobile Computing, 11*(3), 478–491.
63. Sevani, V., Raman, B., & Joshi, P. (2014). Implementation-based evaluation of a full-fledged multihop TDMA-MAC for WiFi mesh networks. *IEEE Transactions on Mobile Computing, 13*(2), 392–406.
64. Bhaskaran R., & Kameswari C. (2004). Revisiting MAC design for an 802.11-based mesh network. *HotNets-III*
65. Alicherry, M., Bhatia, R., & Li, L. E.. (2005). Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks. In *the*11^{th}*Annual International Conference on Mobile Computing and Networking (MobiCom '05)*, pages 58–72, New York, NY, USA. ACM.

66. Ramachandran, Krishna N., Belding-Royer, Elizabeth M., Almeroth, Kevin C., & Buddhikot, Milind M. (2006). Interference-aware channel assignment in multi-radio wireless mesh networks. In *the25thIEEE International Conference on Computer Communications (INFOCOM '06)*, volume 6, pages 1–12.
67. Yu, H., Mohapatra, P., & Liu, X. (2007). Dynamic channel assignment and link scheduling in multi-radio multi-channel wireless mesh networks. In *the4thAnnual International Conference on Mobile and Ubiquitous Systems: Networking & Services (MobiQuitous '07)*, pages 1–8. IEEE.
68. Dutta, P., Jaiswal, S., Panigrahi, D., & Rastogi, R. (2008). A new channel assignment mechanism for rural wireless mesh networks. In *the27thConference on Computer Communications (INFOCOM '08)*, pages 2261–2269. IEEE.
69. Trung, T. M., & Mo, J. (2010). A multichannel TDMA MAC protocol to reduce end-to-end delay in wireless mesh networks. *ETRI Journal, 32*(5), 819–822.
70. Liu, Y., Yuen, C., Chen, J., & Cao, X. (2013). A scalable Hybrid MAC protocol for massive M2M networks. In *2013 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE.
71. Adame, T., Bel, A., Bellalta, B., Barcelo, J., & Oliver, M. (2014). IEEE 802.11ah: The WiFi approach for M2M communications. *Wireless Communications, IEEE, 21*(6), 144–152.
72. Park, C. W., Hwang, D., & Lee, T.-J. (2014). Enhancement of IEEE 802.11ah MAC for M2M communications. *IEEE Communications Letters, 18*(7), 1151–1154.
73. Wang, Y., Li, Y., Chai, K. K., Chen, Y., & Schormans, J. (2015). Energy-aware adaptive restricted access window for IEEE 802.11ah based Smart Grid networks. In *International Conference on Smart Grid Communications (SmartGridComm)*, pages 581–586. IEEE.
74. Hazmi, A., Badihi, B., Larmo, A., Torsner, J., Valkama, M., (2015). Performance analysis of IoT-enabling IEEE 802.11ah technology and its RAW mechanism with non-cross slot boundary holding schemes. In *International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, pages 1–6. IEEE.
75. Lei, X., & Rhee, S. H. (2017). Performance improvement of sub-1 GHz WLANs for future IoT environments. *Wireless Personal Communications, 93*(4), 933–947.
76. Madueño, G. C., Stefanović, Č., & Popovski, P. (2016). Reliable and efficient access for alarm-initiated and regular M2M traffic in IEEE 802.11ah systems. *IEEE Internet of Things Journal, 3*(5), 673–682.
77. Li, Y., Qi, X., Keally, M., Ren, Z., Zhou, G., Xiao, D., & Deng, S. (2012). Communication energy modeling and optimization through joint packet size analysis of BSN and WiFi networks. *IEEE Transactions on Parallel and Distributed Systems, 24*(9), 1741–1751.
78. Zhou, G., Lu, J., Wan, C-Y., Yarvis, Mark D., & Stankovic, John A. (2008). BodyQoS: Adaptive and radio-agnostic QoS for body sensor networks. In *27th Conference on Computer Communications*, pages 565–573. IEEE.
79. Chakeres, Ian D., Belding-Royer, Elizabeth M. (2004). AODV routing protocol implementation design. In *the24thInternational Conference on Distributed Computing Systems Workshops*, pages 698–703. IEEE.
80. Johnson, D. B., Maltz, D. A., Broch, J., et al. (2001). DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks. *Ad Hoc Networking, 5,* 139–172.
81. Kyasanur, P., & Vaidya, N. H. (2006). Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks. *ACM SIGMOBILE Mobile Computing and Communications Review, 10*(1), 31–43.
82. Zhou, A., Hassanein, H. (2001). Load-balanced wireless ad hoc routing. *In the Canadian Conference on Electrical and Computer Engineering*, volume 2, pages 1157–1161. IEEE.
83. Yang, Y., Wang, J., & Kravets, R. (2005). Designing routing metrics for mesh networks. *IEEE Workshop on Wireless Mesh Networks (WiMesh).*
84. Perkins, Charles E., & Bhagwat, P. (1994). Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers.*In ACM SIGCOMM Computer Communication Review*, volume 24, pages 234–244. ACM.
85. Aron, Ionuţ D., & Gupta, Sandeep K. S. (1999). A witness-aided routing protocol for mobile ad-hoc networks with unidirectional links. *Mobile Data Access* (pp. 24–33). Springer.
86. Jacquet, P., Muhlethaler, P., Clausen, T., Laouiti, A., Qayyum, A., & Viennot, L. (2001). Optimized link state routing protocol for ad hoc networks. In *IEEE Internationall Multi Topic Conference (IEEE INMIC '01)*, pages 62–68. IEEE.
87. Arora, A., & Zhang, H. (2006). LSRP: Local stabilization in shortest path routing. *IEEE/ACM Transactions on Networking, 14*(3), 520–531.
88. Pearlman, M. R., & Haas, Z. J. (1999). Determining the optimal configuration for the zone routing protocol. *IEEE Journal on Selected Areas in Communications, 17*(8), 1395–1414.

89. Hou, R., Lui, K. -S., Chiu, H. -S., Yeung, Kwan L., & Baker, F.. (2009). Routing in multi-hop wireless mesh networks with bandwidth guarantees. In *the*10*th* *ACM International symposium on Mobile ad hoc networking and computing*, pages 353–354. ACM.
90. Arafatur R., Md., Saiful A., Md., & Anwar, F.. (2009). Intergating multiple metrics to improve the performance of a routing protocol over wireless mesh networks. In *the 2009 International Conference on Signal Processing Systems*, pages 784–787. IEEE.
91. Hasan, M. Z., Al-Turjman, F., & Al-Rizzo, H. (2017). Optimized multi-constrained quality-of-service multipath routing approach for multimedia sensor networks. *IEEE Sensors Journal, 17*(7), 2298–2309.
92. Li, J., Silva, B. N., Diyan, M., Cao, Z., & Han, K. (2018). A clustering based routing algorithm in IoT aware wireless mesh networks. *Sustainable Cities and Society, 40,* 657–666.
93. Kim, H.-S., Kim, H., Paek, J., & Bahk, S. (2017). Load balancing under heavy traffic in RPL routing protocol for low power and lossy networks. *IEEE Transactions on Mobile Computing, 16*(4), 964–979.
94. Di Marco, P., Athanasiou, G., Mekikis, P.-V., & Fischione, C. (2016). MAC-aware routing metrics for the Internet of Things. *Computer Communications, 74,* 77–86.
95. Djedjig, N., Tandjaoui, D., Medjek, F., & Romdhani, I. (2017). New trust metric for the RPL routing protocol. In *the 8th International Conference on Information and Communication Systems (ICICS)*, IEEE, pages 328–335.
96. Khallef, W., Molnar, M., Benslimane, A., & Durand, S. (2017). Multiple constrained QoS routing with RPL. In *2017 IEEE International Conference on Communications (ICC)*, IEEE, pages 1–6.
97. Yuan, J., Li, Z., Wei, Yu., & Li, B. (2006). A Cross-layer optimization framework for multihop multicast in wireless mesh networks. *IEEE Journal on Selected Areas in Communications, 24*(11), 2092–2103.
98. Raidl, G. R., & Julstrom, B. A. (2003). Edge sets: An effective evolutionary coding of spanning trees. *IEEE Transactions on Evolutionary Computation, 7*(3), 225–239.
99. Rong, B., Qian, Y., Lu, K., & Hu, R. Q. (2008). Enhanced QoS multicast routing in wireless mesh networks. *IEEE Transactions on Wireless Communications, 7*(6), 2119–2130.
100. Zhen, X. (2010). A QoS multicast routing in wireless mesh networks. In *the*3*rd* *IEEE International Conference on Computer Science and Information Technology (ICCSIT)*, volume 9, pages 260–264. IEEE.
101. Alasaad, A., Nicanfar, H., Gopalakrishnan, S., & Leung, Victor C. M. (2013). A ring-based multicast routing topology with QoS support in wireless mesh networks. *Wireless Networks,* 1–25.
102. Sun, Y., Sun, J., Zhao, F., & Zhuoxian, H. (2014). Delay constraint multipath routing for wireless multimedia ad hoc networks. *International Journal of Communication Systems*.
103. Pandi, S, Gabriel, F., Zhdanenko, O., Wunderlich, S., Fitzek, Frank H. P. (2019). ESHMERIZE: An interactive demo of resilient mesh networks in drones. In *the 16th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, IEEE, pages 1–2.
104. Tang, J., Xue, G., & Zhang, W. (2005). Interference-aware topology control and QoS routing in multi-channel wireless mesh networks. In *the*6*th* *ACM international symposium on Mobile ad hoc networking and computing*, ACM, pages 68–77.
105. Makram, S. A., Samad, F., & Gunes, M. (2009). Neighborhood nodes collaboration to support QoS routing in wireless mesh networks. In *IEEE Symposium on Computers and Communications (ISCC '09)*, IEEE, pages 763–769.
106. Li, H., Cheng, Y., Zhou, C., & Zhuang, W. (2009). Minimizing end-to-end delay: A novel routing metric for multi-radio wireless mesh networks. In *INFOCOM*, pages 46–54. IEEE.
107. Borges, Vinicius C. M., Pereira, D., Curado, M., & Monteiro, E. (2009). Routing metric for interference and channel diversity in multi-radio wireless mesh networks. *Ad-Hoc, Mobile and Wireless Networks* (pp. 55–68). Springer.
108. Peng, Y., Guo, L., & Gai, Q. (2012). Cross-layer QoS-aware routing protocol for multi-radio multi-channel wireless mesh networks. In *the*14*th* *International Conference on Communication Technology (ICCT '12)*, IEEE, pages 197–201.
109. Mauve, M., Widmer, J., & Hartenstein, H. (2001). A survey on position-based routing in mobile ad hoc networks. *Network, 15*(6), 30–39.
110. Kojić, N., Reljin, I., & Reljin, B. (2012). A neural networks-based hybrid routing protocol for wireless mesh networks. *Sensors, 12*(6), 7548–7575.
111. Xie, F., Hua, K. A., & Jiang, N. (2008). A cross-layer framework for video-on-demand service in multi-hop WiMax mesh networks. *Computer Communications, 31*(8), 1615–1626.

112. Ergin, M. A., Gruteser, M., Luo, L., Raychaudhuri, D., & Liu, H. (2008). Available bandwidth estimation and admission control for QoS routing in wireless mesh networks. *Computer Communications, 31*(7), 1301–1317.
113. Liu, T., & Liao, W. (2009). Interference-aware QoS routing for multi-rate multi-radio multi-channel IEEE 802.11 wireless mesh networks. *IEEE Transactions on Wireless Communications, 8*(1), 166–175.
114. Yang, Y., & Kravets, R. (2005). Contention-aware admission control for ad hoc networks. *IEEE Transactions on Mobile Computing, 4*(4), 363–377.
115. Zhao, L., Al-Dubai, A. Y., & Geyong Min, G. L. B. M. (2010). A new QoS aware multicast scheme for wireless mesh networks. *Journal of Systems and Software, 83*(8), 1318–1326.
116. Raniwala, A., Sharma, S., De, Pradipta, Krishnan, R., & Chiueh, Tzicker. (2007). Evaluation of a stateful transport protocol for multi-channel wireless mesh networks. In *the*15th*IEEE International Workshop on Quality of Service*, IEEE, pages 74–82.
117. Tung, L.-P., Shih, W.-K., Cho, T.-C., Sun, Y. S., & Chen, M. C. (2007). TCP throughput enhancement over wireless mesh networks. *IEEE Communications Magazine, 45*(11), 64–70.
118. Radunović, B., Gkantsidis, C., Gunawardena, D., & Key, P. (2008). Horizon: Balancing TCP over multiple paths in wireless mesh network. In *the*14th*ACM International Conference on Mobile Computing and Networking*, ACM, pages 247–258.
119. Karlsson, J., Kassler, A., & Brunstrom, A. (2009). Impact of packet aggregation on TCP performance in wireless mesh networks. In *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks Workshops (WoWMoM '09)*, pages 1–7.
120. Jang, K.-Y., Psounis, K., Govindan, R. (2010). Simple yet efficient, transparent airtime allocation for TCP in wireless mesh networks. In *the*6th*International Conference (Co-NEXT '10)*, pages 28:1–28:12, New York, NY, USA. ACM.
121. Shang, W., Yingdi, Y., Droms, R., & Zhang, L. (2016). Challenges in IoT networking via TCP/IP architecture. *NDN, Technical Report NDN-0038*.
122. Asveren, T. (2018). Methods and apparatus for preventing head of line blocking for RTP over TCP, November 13. US Patent App. 10/129,163.

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Md. Iftekhar Hussain is an Associate Professor at North-Eastern Hill University (NEHU), India. He received his B.E in Computer Science and Engineering from Dibrugarh University, and M.Tech in Information Technology and Ph.D in Computer Science and Engineering from Tezpur University. He is a member of IEEE and a life member of the Indian Science Congress Association and Computer Society of India (CSI). His research interests include Wireless Networks and Internet of Things (IoT).

Nurzaman Ahmed is Senior Research Associate at Indian Institute of Technology, Kharagpur, 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 IEEE and Indian Science Congress Association.

Md. Zaved Iqubal Ahmed received his B.Tech. degree in Information Technology from the North-Eastern Hill University (NEHU), Shillong, India in 2013. He was involved in the research project titled “QoS Provisioning in WiFi-based Long Distance Wireless Networks for Hilly Terrain Rural Areas” as a Junior Research Fellow in Department of IT, NEHU, Shillong. He completed his M. Tech(IT) degree from Tezpur University, Assam in 2016. Currently, he is working as Assistant Professor in the Computer Science Department, Pandit Deendayal Upadhyaya Adarsha Mahavidyalaya, Dalgaon, Assam. His research interests are Wireless Mesh Networks, Cognitive Radio Networks, Low Cost Internet Solutions, and Machine Learning.

Nityananda Sarma received his B.E., M.Tech., and Ph.D. in Computer Science and Engineering from Dibrugarh University, Indian Institute of Technology Kharagpur, and Indian Institute of Technology Guwahati in 1992, 1999, and 2009, respectively. He is currently working as a Professor in the Department of Computer Science and Engineering, Tezpur University, India. Prior to Tezpur University, he worked in Jorhat Engineering College, Jorhat, India. He has published more than 120 papers in international journal/conference and co-authored a book. His research interests include QoS-aware Protocols, Cross-layer Design, Optical Networks, and Cognitive Radio Networks. He is a professional member of ACM, senior member of IEEE and fellow of IETE.