[MHSt07] *Parag Mogre, Matthias Hollick, Ralf Steinmetz;* **QoS in Wireless Mesh Networks: Challenges, Pitfalls, and Roadmap to its Realization**; Network and Operating System Support for Digital Audio and Video (NOSSDAV 2007), Urbana-Champaign, Juni 2007

QoS in Wireless Mesh Networks: Challenges, Pitfalls, and Roadmap to its Realization

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ABSTRACT

Wireless Mesh Networks (WMNs) have the potential to lead to a disruptive change in the landscape of wireless communications. The vision to support self-engineered wireless network infrastructures that allow for an organic growth of the network is to be realized by means of self-organizing mechanisms for network configuration, control and optimization. Supporting a Quality of Service (QoS) to enable a rich portfolio of applications and scenarios is foreseen to be vital for the success of next generation WMNs. Today's cutting edge standards supporting WMNs (e.g. IEEE 802.16's mesh mode and IEEE 802.11s) are not perfectly equipped to cater to this task. While providing the necessary flexibility as well as sophisticated protocol mechanisms, these standards come with an inherent complexity and suffer from innate problems with respect to QoS provisioning. As a result, care needs to be taken when developing algorithms for supporting QoS on top of the standard's mechanisms or when deploying such WMNs. We believe that a holistic approach is necessary to tackle the challenge for truly enabling QoS in WMNs. Failure to do so will result in inefficient performance and, in the worst case QoS violations. This paper reviews the critical aspects that need to be considered using the IEEE 802.16-2004 standard's mesh mode as a case-study. In addition to the research challenges, we highlight pitfalls and give pointers to realize QoS in WMNs.

1. INTRODUCTION

In the recent years the deployment of WMNs has been looked upon as an upcoming and promising step towards the goal of ubiquitous broadband wireless access. WMNs are interesting not only in the context of small community networks and neighbourhood networks, but also in the area of enterprise-wide networks or wireless backbone networks that can be established in an ad hoc manner, e.g. in disaster recovery scenarios. QoS is a critical issue especially in the latter two scenarios. Mission-critical applications depend on the provision of adequate QoS support when deployed in the WMN. Network providers who look at WMNs as a cheap alternative to expand their existing wireless network infrastructure without incurring exorbitant deployment costs also look at WMNs as a viable alternative. In such networks, the providers wish to support the integrated services they already offer on their traditional wireless platforms. These applications such as voice and video over IP need to be provided with carrier-grade QoS support.

The current modus operandi towards QoS provisioning in the Internet, namely that of over-provisioning of bandwidth and other resources, is not applicable to WMNs. In particular, due to the broadcast nature of the wireless medium, wireless networks need to deal with the fundamental issue of interference and noise, which is not an issue in wired networks. In contrast to traditional single-hop cellular networks, multi-hop networks such as ad hoc networks and WMNs introduce additional challenging issues, which emphasize the problem of interference, simply due to the fact that a multi-hop route needs more transmissions as compared to a single-hop connection.

Thus, bandwidth is a precious resource in wireless networks in general. WMNs are usually considered to have low (or no) node mobility, where individual nodes in the WMN are usually not considered to be energy constrained. These favourable characteristics of WMNs open up avenues for cross-layer optimization which are not found in ad hoc networks or wireless sensor networks, where the high mobility or the restricted energy available at nodes restricts the use of sophisticated optimization strategies.

In this paper we critically analyze the mechanisms provided by state-of-the-art WMNs to support QoS. We look into the practical aspects of deploying algorithms for providing QoS within these networks. Fundamental issues that need to be considered when optimizing the performance of the mesh network are reviewed. Without loss of generality, to present our arguments in realistic settings, we base our discussion on the MeSH[1] mode of the IEEE 802.16-2004 standard [11] for deploying a QoS-aware WMN.

The rest of the paper is organized as follows. Related work is introduced throughout the entire work. In Section 2 we discuss selected application scenarios that demonstrate the need for QoS in WMNs. In Section 3, we review the QoS-

[1]Throughout this document the notation "MeSH" refers to the optional mesh mode of the IEEE 802.16-2004 standard.

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capabilities of the MeSH mode and look at the critical issues and trade-offs that arise when deploying QoS. We discuss important challenges as well as selected pitfalls in enabling QoS in WMNs in Section 4. There, we also sketch possible solutions to some pertinent questions. This is followed by a conclusion and pointers to further research in Section 5.

2. SELECTED APPLICATION SCENARIOS FOR WIRELESS MESH NETWORKS

Applications for WMNs can be manifold. We first introduce a (non-exhaustive) list of applications for WMNs. To structure the presentation, we distinguish between (1) applications for closed user-groups such as enterprise users or users in emergency response operations, (2) semi-closed user-groups served by network providers/operators, and (3) open groups of end-users as experienced in community networks or a wireless Internet:

- Carrier-grade voice and video conferencing, online gaming, video streaming.
- Community networks, neighbourhood services, Internet connection sharing, localized P2P applications.
- High-bandwidth data (file transfer), interactive data (e.g. web browsing).
- P2P applications: communications, distributed computing, distributed file backup, gaming.
- Wireless backbone for campus networks or emergency response networks.
- Wireless sensing, monitoring and control for critical infrastructures.

Mechanisms to support QoS in WMNs should be designed and deployed keeping in mind these applications. Next we discuss selected applications in the context of the aforementioned scenarios for the deployment of WMNs; we highlight the QoS requirements for those scenarios.

Enterprise Perspective. This category of WMNs is deployed by an enterprise or an organization to serve as a broadband wireless backbone providing backhaul services. Examples for such networks are wireless backbone networks for a campus area, or for an organization. Additionally, such a broadband wireless backbone WMN may be deployed in order to respond to disasters or emergencies. Here, the WMN provides the backbone for communication between the different rescue teams, which communicate using wireless hand-held devices. The WMN is then responsible for supporting QoS to enable several services and collaboration among the responders and the command and control centre. It may be used for simple P2P communication, timely event notification, data transfer as well as to remotely control actuators such as robots that are deployed in hazardous zones. QoS support in such application scenarios is critical with most applications having strict delay bounds as well as bandwidth requirements.

Operator/Provider Perspective. WMNs are an interesting alternative for network providers who wish to expand the coverage of their existing network infrastructure incrementally, and without incurring exorbitant planning and deployment costs. Rural areas without network connectivity can be quickly provided with a broadband wireless network coverage using WMNs. Subscribers are increasingly demanding triple-play services over a wireless network and in addition seek support for subscriber mobility. WMNs deployed to meet the above goal need to feature mechanisms which allow the support of carrier-grade Voice over IP (VoIP), and other interactive and equally demanding applications such as video conferencing, video streaming and online multiplayer gaming. In addition, subscribers expect and require high-bandwidth connections to enable Peer-to-Peer (P2P) applications. Thus, the provider is interested in QoS mechanisms which enable the differentiation of multiple services in the WMN, while providing hard QoS guarantees for critical services.

End-user Perspective. Community wide WMNs are built usually using customer-operated equipment; they grow in an unplanned and organic manner. There may or may not be a central managing entity for the WMN. Individual nodes may join and leave the WMN at will. Community mesh networks are a cheaper alternative to traditional wired networks for the users. In areas lacking extensive network infrastructure this may be vital to provide Internet access to entire communities, despite the fact that only one or a few nodes have direct access to the Internet. Such networks may be used to support P2P data exchange among neighbours, for community-wide information services, neighbourhood patrol, etc. Most of the applications in this scenario do not have strict end-to-end delay bounds but profit when high bandwidth is available. QoS issues in such networks are therefore optimization of the capacity usage and supporting delay sensitive network applications such as conversational traffic. Additionally, QoS support in such networks has to consider security and trust issues. QoS support, thus, involves finding reliable and dependable routes from the source to destination. Also, because of the extensive use of P2P services and applications, QoS support needs to consider the challenges for P2P systems in traditional networks.

Other classifications of WMNs are possible. Next generation WMNs are expected to comprise heterogeneous devices with differing capabilities, and, thus, require support for multiple services with differing QoS requirements. In all the above scenarios, QoS support is crucial for the success of the applications. Currently, we witness a trend towards P2P communication and services. Hence, traditional centrally managed QoS provisioning is not sufficient in the long run, but distributed provisioning of QoS should be part of the research agenda.

Ref. [1] gives a comprehensive overview of WMNs and also highlights some important research challenges in deploying WMNs. There exists today a plethora of proprietary wireless mesh networking solutions. However, proprietary solutions tend to involve high costs and hence are limited to small scale deployments. Most of these WMNs use the basic IEEE 802.11 [10] standard which suffers from various shortcoming if used for WMNs (see [21]). In addition, the basic 802.11 standard [10] does not provide means to provide delay and bandwidth guarantees effectively. The current state-of-the-art standards for deploying WMNs [11, 9] enable explicit reservation of bandwidth for individual links in the WMN. As a result, if sufficient bandwidth is available and is reserved on all links along the path, end-to-end QoS guarantees can be given. The IEEE 802.16 standard provides sophisticated mechanisms to support QoS provisioning and also foresees the support of different scheduling services catering to the demands of different application classes. The 802.11s proposal currently uses a handshake mechanism similar to the distributed scheduling mechanism outlined for the IEEE 802.16-2004 standard to support bandwidth reservation.

Standardized solutions are also expected to help further reduce the deployment costs for WMNs. In this paper we will look at the IEEE 802.16-2004 as a prototype state-of-the-art standard providing mechanisms to support QoS. Hence, we will present the challenges for deploying a QoS-aware WMN in the context of the 802.16 standard. We first provide a short review of the 802.16 standard's QoS and bandwidth allocation mechanisms in the MeSH mode. This is followed by a discussion of the QoS challenges and a presentation of the roadmap to facing these challenges.

3. QOS IN THE IEEE 802.16 MESH MODE REVIEWED

QoS in the IEEE 802.16 MeSH mode is supported on packet-by-packet basis using parts of the mesh connection identifier (MeSH CID) present in each MAC Protocol Data Unit (PDU) to decide the per-hop handling for the packet. The fields enable the specification of parameters like the the priority, drop precedence and the type of the data. In addition the MeSH CID is used to specify if a packet needs to be retransmitted if lost. Thus, the mechanism is sufficient to deploy Diffserv [2] like per-hop forwarding behaviour in the mesh network. However, such a mechanism is useless if no means are available to guarantee availability of sufficient bandwidth for individual links in the WMN. To enable this, the standard uses Time Division Multiple Access/Time Division Duplex (TDMA/TDD) with spatial reuse to allocate bandwidth to individual links and to share the available bandwidth between different nodes.

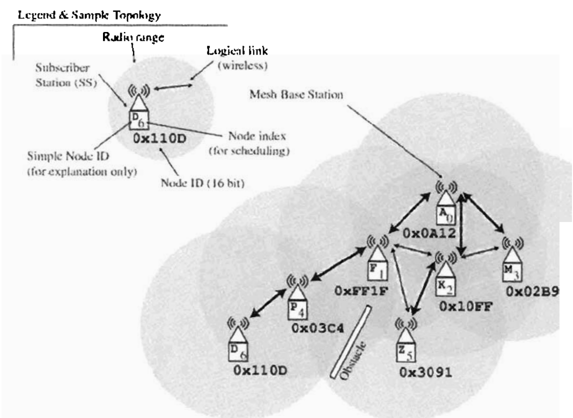

Figure 1: Sample MeSH topology

The time axis is divided into frames where each frame is composed of a control subframe and a data subframe. The control subframe is used to transmit management messages required for network maintenance and bandwidth management. Data is transmitted only in the data subframe. To allow shared access to the medium in the control subframe, it is divided into a number of transmission opportunities. A data subframe is on the other hand split into a number of minislots (a minislot is the smallest unit of bandwidth allocation). The control messages are used to request and allocate bandwidth to individual links. The standard provides a range of mechanisms to allocate bandwidth as well as to manage the request and granting of bandwidth. We next briefly outline these mechanisms using the sample WMN topology shown in Fig. 1.

The 802.16 standard supports the following bandwidth allocation mechanisms in the MeSH mode, which are introduced below.

1. Coordinated centralized scheduling
2. Coordinated distributed scheduling
3. Uncoordinated distributed scheduling

Coordinated centralized scheduling. Here bandwidth allocations are centrally managed by the Mesh Base Station (MeSH BS). The MeSH BS specifies a scheduling tree (shown by the thicker arrows in Fig. 1) rooted at the MeSH BS. Nodes in the scheduling tree forward their bandwidth requests to the MeSH BS which in turn allocates bandwidth for the uplinks and the downlinks in the scheduling tree. Coordinated centralized scheduling cannot be used to allocate bandwidth for links not included in the scheduling tree (e.g. here link between nodes $F, 1$ and $K, 2$ is not included in the scheduling tree). Besides, the performance of coordinated centralized scheduling degrades with the growth of the scheduling tree (see Ref. [16] for a performance analysis considering real-time traffic constraints).

Coordinated distributed scheduling. Here nodes schedule (coordinate) their transmissions within their two-hop neighbourhood such that conflicting transmissions are not scheduled. The nodes use a three-way (request, grant, grant-confirmation) handshake protocol for reserving bandwidth for a link. To enable the computation of a conflict-free schedule each node locally maintains the status of individual minislots based on the information it has obtained from the neighbours about their schedules. Nodes obtain information about transmissions/receptions scheduled by their neighbours from the handshake messages. Thus, the correct reception of the transmitted handshake management messages is critical for the functioning of coordinated distributed scheduling. The IEEE 802.16 standard specifies a distributed mesh election algorithm for accessing the transmission opportunities in the control subframe such that when a node transmits no other node in its two-hop neighbourhood (at least) transmits simultaneously. This ensures that the neighbours of a node are able to correctly receive the transmitted control messages with a high probability. The coordinated distributed scheduling handshake messages are transmitted in the control subframe using the mesh election algorithm. Ref. [3] gives a performance analysis of the distributed scheduler in the MeSH mode.

Uncoordinated distributed scheduling. Here nodes use the same mechanisms as in coordinated distributed scheduling except for the mesh election algorithm. Handshake messages are not transmitted in the control subframe but in the data subframe. Transmission of messages takes place in minislots already reserved for the links in question (i.e. link from the data transmitting node to the data receiving node and vice-versa). Thus, the nodes do not have to wait to win a transmission opportunity using the mesh election algorithm. This type of scheduling is useful for the quick allocation of bandwidth. However, as nodes in the neighbourhood are not aware of the handshake (and hence the minislots allocated using the handshake) they may schedule conflicting transmissions.

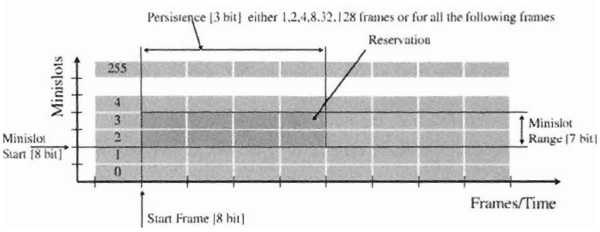

Figure 2: Bandwidth reservation (allocation) concept

Fig. 2 visualizes the concept of bandwidth allocation in the MeSH mode. Using the above scheduling schemes a range of minislots can be allocated to individual links for a contiguous range of frames, where the number of contiguous frames is chosen from the set allowed by the reservation persistence shown in Fig. 2.

For further details about QoS support in the MeSH mode as well as details about the scheduling schemes readers are referred to [11, 15]. Ref. [15] gives a detailed overview of the above scheduling schemes in addition to further detail about the MeSH mode.

4. QOS CHALLENGES, PITFALLS, AND POSSIBLE SOLUTIONS

In this section, we present QoS solutions based on realistic assumptions, i.e. we use the requirements of the above scenarios and consider standardized WMN technologies as a framework for the QoS solutions. While a variety of academic research problems persist, we consider addressing real-life challenges (including implementation aspects) as the next step to make QoS-aware WMNs a reality. Our approach, thus, is to start with existing state-of-the-art standards and augment practically feasible extensions also ensuring compatibility. While it is a good idea to use a level of abstraction when designing algorithms and solutions, we recommended that the implementation aspects are kept in mind right from the start to lead to technologically sound solutions which can be realized in practice.

We maintain the above perspective when presenting the QoS challenges. We use the 802.16 MeSH mode as a prototype state-of-the-art WMN standard with built-in basic QoS support. Hence, without loss of generality, we outline the challenges, pitfalls, and a roadmap to solutions within the above context. In the following we present selected challenges and highlight the crucial aspects that need to be taken into account when designing solutions.

Differentiation of Service, Interworking. To enable various applications, the differentiation of service is crucial. The IEEE 802.16 standard identifies for the point-to-multipoint (PMP) mode of operation the following scheduling services: Unsolicited Grant Service (UGS), Real-time Polling Service (rtPS), Non real-time Polling Service (nrtPS) and Best Effort (BE) (for details about the scheduling services see [11]). The current MeSH mode specifications do not allow the realization of such scheduling services easily, however. Thus, a QoS architecture and mechansims need to be designed within the framework of the MeSH mode to support sophisticated scheduling services. Moreover, interworking of the QoS mechanisms with higher layers such as IP has to be addressed. The incompatibility between the PMP and MeSH QoS specifications needs to be bridged to allow seamless interoperability. This is especially of interest for network providers who may initially deploy a PMP network and may wish to later adapt it to a mesh when the coverage area needs to be extended. Ref. [14] presents a QoS architecture to enable the deployment of scheduling services compatible with the PMP. In addition, sound mechanisms to service the packet transmission queues have to be deployed to ensure that QoS requirements of applications are met (see Ref. [20] for example).

End-to-end QoS Provisioning. The MeSH defines per-link, per-hop QoS mechanisms. However, for carrier-grade QoS support it is necessary to address an end-to-end regime within the mesh. In addition to the per-link mechanisms, QoS-aware routing mechanisms have to be considered (see [4, 5, 18] for QoS routing issues). Most of the literature, however, investigates the performance of QoS routing protocols solely for the contemporary, contention-based MAC protocols such as IEEE 802.11. For the novel reservation-based MAC technologies such as IEEE 802.16, the bandwidth reservation schemes cannot be decoupled from the QoS routing protocols, but play a significant role in the obtained routing performance. A cross-layer ([17, 19]) approach is needed to make effective use of the MAC layer mechanisms when provisioning end-to-end QoS. We believe that further work in this area is required to analyze the dependencies across layers and to find an optimal solution jointly across all protocol layers.

Efficient and Adaptive Bandwidth Management. When different traffic classes are supported (corresponding to the different scheduling services) the bandwidth reservation has to adapt to the needs of the applications. We need optimal schemes to schedule the long-lived and QoS-critical flows, while balancing the load in the network such that dynamic traffic demand can be fulfilled adequately. Static bandwidth reservation schemes which do not consider the class of traffic will lead to inefficient bandwidth usage leading to additional problems like unfair bandwidth distribution among nodes as well as wastage of reserved bandwidth resources. Ref. [14] proposes one such class-aware bandwidth reservation scheme. The presented scheme makes effective usage of the various distributed scheduling options provided by the MeSH mode to enable effective bandwidth reservation and scheduling services similar to the PMP mode. Similar suggestions to support QoS can also be found for the PMP mode (see [13]). In addition novel concepts such as network-coding may be applied to WMNs to increase the traffic that can be supported by the WMN (see [12]). Further research in this area is needed.

Optimal Values for the Standard's Parameters. In addition to the scheduling mechanisms, the MeSH mode involves several other protocol states and parameters, which need to be optimized. For example, the choice of parameters for the distributed mesh election algorithm highly influences the performance and delay of the three-way handshake used to set up per-link bandwidth using the coordinated distributed scheduling mechanisms [3]. Protocols for network entry and handover also need to be optimized. Non-optimal choice of parameters severely affects the time required for a new node to join the network, and in scenarios like an emergency-response will lead to an inacceptable delay for setting up the WMN. Ref. [8] investigates the performance of the network entry in the IEEE 802.16 standard and shows how critical the correct choice of values for the standard parameters is. Other mechanisms in the standard need to be critically analyzed and optimized. For operation in open and organically growing mesh networks, the self-adaptation of operational parameters needs further attention.

Security and Dependability Issues. The quest for security in wireless mesh networks is a challenging one. Especially in open and unplanned WMNs which grow organically, issues of dependability need to be addressed [7]. Self-stabilizing protocols in combination with trust and reputation management mechanisms for the individual nodes in the WMN play a critical role. Lack of security is a serious issue, and lays waste to all efforts expended in providing QoS. In closed mesh networks for critical infrastructures, guaranteeing QoS even under attack is of paramount interest. The IEEE 802.16 standard specifies a security sublayer which is responsible for enabling per-link encryption and security mechanisms. However, these mechanisms are not adequate to guarantee security from an end-to-end perspective.

Mobility and Physical Layer Issues. Features such as mobility support or elaborated PHY mechanisms such as concurrent usage of multiple wireless channels, directed antennas, etc. add to the complexity of the problem. E.g. the MeSH standard currently does not adequately support mobility. This again emphasizes the need for solutions that enable interworking and compatibility between standards that are feasible for a (static) MeSH backhaul network and technology to support user-mobility.

In addition to the above issues various further optimizations are possible (see [6] for example). We perceive that a holistic approach to QoS provisioning is needed for next-generation WMNs. Neglecting any of the above aspects when designing comprehensive QoS solutions will lead to severe problems. In addition to the above, features like self-configuration, self-healing and self-optimization of WMNs should be considered from the QoS perspective.

5. CONCLUSION

Wireless Mesh Networks are foreseen to lead to a disruptive change in wireless communications. However, to be successful, a set of criteria has to be fulfilled: a critical mass of subscribers/users need to be present, applications need to be adequately supported, secure and dependable operation has to be guaranteed. However, one crucial factor—possibly the tipping point—in making WMNs a success story is the support for QoS. In contrast to the wired Internet, bandwidth is scarce and over-provisioning cannot be applied to WMNs; thus, without adequate QoS mechanisms a lot of promising applications is likely to fail.

We propose the following roadmap for realization of QoS in WMNs. First, one has to derive the QoS requirements from application scenarios, and to analyze and state the assumptions that are induced by the employed wireless technologies/standards. The selection of an optimal combination of application and tool (i.e. state-of-the-art standard for WMNs) is the next step to reach the set goal. Second, we strongly believe that a holistic approach is needed to have enough flexibility to address the challenge of enabling QoS for WMNs. We opt for a cross-layer perspective, because optimization at one protocol layer needs to consider the trade-offs and influences at the other layers. Third, while designing the mechanisms, one should strive to keep the solution as simple and transparent as possible. This is particularly true, if we keep realistic implementation aspects in mind. The standard's mechanisms need to be optimally harnessed, as well. Such an approach is vital for QoS to successfully accomplish the transition from theory to practice in WMNs.

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