Challenges and Recent Advances in QoS Provisioning in Wireless Mesh Networks

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Abstract

Wireless mesh networks (WMNs) comprising of mobile and static nodes connected wirelessly are emerging as a key technology for future generation of wireless networks. WMNs self-organize, self-configure and self-heal themselves and can increase the coverage of conventional infrastructure-based wireless LANs and MANs without significant additional infrastructure deployments. Due to these unique features, WMNs are being used in many applications ranging from emergency response situations to wireless metropolitan area networks. Quality of Service (QoS) provisioning in WMNs is of utmost importance in order to support real-time audio and video communications. However, QoS provisioning in highly mobile wireless networks such as WMNs is a very challenging problem compared to provisioning of QoS in wired IP networks. The main reasons for this are unpredictable node mobility, wireless multi-hop communication, contention for wireless channel access, limited battery power and wireless range of mobile devices, as well as the absence of a central coordination authority in WMNs. This paper describes the challenges and the state of the art in provisioning of QoS over WMNs.

1. Introduction

Wireless Mesh Networks (WMNs) [1, 2 and 3] are comprised of a combination of mostly static "mesh routers" and mobile "mesh clients" as illustrated in figure 1.

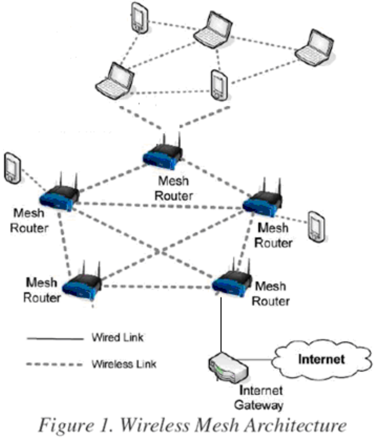

Figure 1. Wireless Mesh Architecture

Mesh routers generally have multiple wireless interfaces and provide access to a wired network in addition to forming a wireless multi-hop backbone for the mesh clients. The key advantages offered by WMNs are as follow:

a) *Rapidly deployable* – Mesh Routers can be deployed very rapidly in a WMN, without any need for backhaul wiring and infrastructure support. This makes the deployment and operation of WMNs relatively easy and less expensive compared to infrastructure based wireless networks.
b) *Self-organizing and self-configuring* – WMNs can survive in highly dynamic and mobile environments, and allow the addition of new mesh routers and clients into the network. Configuration and maintenance are relatively easy due to WMNs auto-configuration and self-organizing features.
c) *Self-healing* – WMNs do not have the problems of bottleneck links and communication disruption due to single points of failure as they have multiple redundant paths making the WMN more robust compared to traditional networks and generating the self-healing property of WMNs.
d) *Coverage Extension and scalability* – The range of wireless mesh routers and clients can be significantly extended using multi-hop routing of data in a mesh network. In comparison, conventional infrastructure-based networks such as WLANs have scalability problems which require significant infrastructure investments, to cover the same area mainly to install more access points and base stations. WMNs with the use of multi-hop connectivity can easily extend the range of conventional wireless networks with relatively low infrastructure investment.
e) *Low transmission power* – As the wireless signal only needs to reach the next hop in a WMN, the transmission power for nodes in a WMN is less per transmission hop compared to one longer hop.

Due to the above advantages, WMNs have found various applications [4, 5, 6, 7, 8, 9 and 10]. Such deployments cover a variety of applications such as disaster relief and emergency response, intelligent transportation systems, metropolitan area networks, and building automation etc.

QoS provisioning in WMNs is very important in order to support real-time communications such as audio and video. However, provisioning of communication QoS over wireless networks is far more challenging than for wired networks because of variability of wireless links, the lack of any central coordination authority (for QoS and channel assignment), node mobility, limited battery power, multihop communication and contention for accessing the wireless channel.

According to IETF RFC 2386 [11], QoS is a set of requirements (such as latency, jitter, and packet loss) to be met by the network while transporting a particular flow of data. A QoS model is a mechanism for provisioning of QoS resources to meet the QoS requirements. IETF has developed two of the main QoS provisioning models in the Internet: (i) Integrated services (IntServ) and (ii) Differentiated services (DiffServ). IntServ maintains per-flow reservation states at QoS network entities aims at a greater level of accuracy and a finer level of granularity. DiffServ on the other hand does not maintain any per-flow reservation states at QoS network entities and only relies on aggregation and differential treatment of traffic classes resulting in much better scaling properties compared to IntServ in the internet.

There are a number of proposals for QoS provisioning in MANETs [12, 13, and 14]. However, it is impossible to provide hard QoS guarantees in this kind of network due to the highly dynamic node behavior, i.e. all nodes are considered mobile. In contrast, WMNs typically consist of a combination of mobile nodes and a static infrastructure component. The availability of relatively static infrastructure nodes in WMNs renders the problem of QoS provisioning more tractable, compared to MANETs. This paper outlines the research challenges and evaluates the first approaches and early proposals for provisioning of QoS in WMNs.

2. Challenges for QoS Provisioning for Multi-hop Wireless Networks

QoS provisioning in highly mobile wireless multi-hop networks such as MANETs and WMNs is very challenging compared to wired networks because of various difficulties associated with these types of networks. Even though some of these problems have been addressed in the QoS models for MANETs and WMNs, many of the challenges remain unresolved.

a) *Capacity Constraints*: Wireless bandwidth is scarce and expensive [15]. Furthermore, clients in multi-hop wireless networks at present are generally equipped with a single radio interface only, limiting the communication capacity of these nodes.

b) *Unreliable Communication Medium*: The wireless medium used for communication in multi-hop wireless networks is prone to errors due to interference generated from transmissions of other wireless devices in the vicinity, as well as multi-path fading effects [16]. This makes it extremely challenging to provide any guarantees regarding reliable packet delivery.

c) *Unpredictable Channel Access Delay*: As there is no centralized controller in a multi-hop wireless network, media access control is based on a distributed algorithm. This leads to the difficulty of calculating and guaranteeing tight delay bounds generally required for real-time communication.

d) *Inaccurate Bandwidth Estimation*: Available wireless channel bandwidth at a mesh client or router is difficult to be accurately determined, as it is affected by a number of factors, including the traffic load in the wireless transmission and sensing range, node mobility, as well as the general variability of wireless links.

e) *Node Mobility and Dynamic Topology*: The client nodes in multi-hop wireless networks are generally mobile, resulting in routing information to become stale relatively quickly. Furthermore, battery powered wireless clients acting as relays could randomly turn off due to their battery exhaustion. These topological changes may require QoS path re-establishment. If the rate of topology changes is higher than the speed of QoS path re-establishment, it would be virtually impossible to provide QoS.

f) *Absence of Centralized QoS Control*: In a multi-hop wireless networks there is no centralized controller which keeps track of client node's location and the remaining QoS resources information of the network. Therefore, QoS provisioning has to be done in a distributed fashion, which is much more challenging than for a centralized network.

g) *Network Heterogeneity*: Another key challenge in QoS provisioning is the high level of heterogeneity present in multi-hop wireless networks. Mesh routers differ from mesh clients considerably in terms of level of mobility as well resource availability. For example, mesh routers are typically equipped with multiple radios, giving them a higher aggregate communication capacity than single radio mesh clients.

h) *QoS Route Selection and Querying Problem*: Control packets are used for the purpose of multi-hop route discovery and selection in wireless mesh networks. These control packets are different then actual data packets properties in terms of packet size, lead to inefficient route selection [24].

i) *Varied QoS Requirements*: Different application of wireless multi-hop networks have different set of QoS requirements making it difficult to develop one single standard for QoS provisioning to cover all the different QoS requirements. For example, a sensor network deployed to identify a chemical leak might require high reliability, while a disaster relief and response network may want less end-to-end communication delay and route discovery latency in order to quickly inform rescuers and paramedics [20].

j) *False Admission Control Problem in Stateless QoS Models*: Since in a multi-hop wireless network there is no centralized QoS controller or identity, multiple flows in a network may send probe messages to check current bandwidth availability at the same time. If the QoS model happens to be stateless, it may result in a situation where multiple flows (sharing a common path or one intermediate node) send probe messages simultaneously and observe that the network QoS resources are available, but in reality they are not [21].

3. QoS in Wireless Mesh Networks (WMNs)

QoS routing and provisioning in 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 the presence of relatively static mesh routers providing a relatively stable wireless backbone network [1]. QoS routing and provisioning schemes for WMNs can utilize this specific feature. To meet the QoS demands of applications, extensions have been proposed to improve the performance of the existing protocols. This section presents the main QoS extensions that have been developed specifically for WMNs [22, 23].

3.1 QUORUM

QUality Of service RoUting in wireless Mesh networks (QUORUM) [23] uses reactive route discovery and a reservation based QoS provisioning approach. Admission control is carried out in the reactive route discovery phase [17], aiming to provide QoS constrained routes from source to destination. The key features of QUORUM are as follows:

3.1.1 Admission Control*:* Admission control in QUORUM is carried out during the route discovery phase of the protocol, where each intermediate node on the path checks whether the new incoming flow could be accepted or not. If the intermediate node accepts a new incoming flow then that node creates a Flow Table entry for that particular flow.

3.1.2 Robust Link Selection: QUORUM estimates Route Robustness for route selection. Nodes in the network monitor the robustness of their links with their neighbors. This is done by counting the frequent "HELLO" packets that are received during a given time.

3.1.3 Limiting Flooding of Control Information: Topology information is used in QUORUM for the purpose of discovering routes [23]. If source and destination are being served by the same mesh router, then control information's flooding is limited only to nodes served by that mesh router. Alternatively, if the source and the destination happen to be served by two different mesh routers then the nodes in the two *mesh groups* and all mesh routers only receive the control traffic. This could reduce congestion in the remaining mesh groups [23]. This is achieved by assigning the mesh clients which are in the same mesh group the same unique subnet in QUORUM. QUORUM also makes use of the concept of nodes accepting flooding messages only from "robust" neighbors. Robust neighbors are those with whom a node has link quality above a specified threshold. This can eliminate selection of paths that have links with low quality and help in alleviating the communication gray zone [24] problem.

3.1.4 End-to-End Delay Calculation: QUORUM makes an estimation of End-to-End delay by first sending DUMMY-RREP packets. This is done in the route discovery phase after a source has received an RREP packet from the destination by sending stream of DUMMY data packets along the path which was taken by RREP packets for a particular route. DUMMY data packets are given the same size, priority and data rate as the actual data packets about to be sent by the source. This can help in emulating real data traffic on a data path. If the average delay of the DUMMY packets is within the acceptable bounds, the source selects this route and starts transmitting data traffic.

3.1.5 Managing Misbehaving Nodes: In QUORUM, a node can possibly misbehave by not broadcasting its HELLO packets while listening to its neighbors' broadcasts at the same time. Since the neighboring nodes of this misbehaving node do not have any information about the misbehaving node due to the absence of HELLO messages from this node, the neighbors select their routes via their other neighbors. At the same time this misbehaving node keeps utilizing its neighbors to route its packets. To overcome this problem in QUORUM, a node only forwards the packets of a neighboring node if the neighbor's link quality is higher than a threshold.

3.1.6 QoS Violation and Recovery: QUORUM maintains flow table entries and if a node in the network receives a data packet for which there does not exist a corresponding Flow Table entry for that flow, then QUORUM interprets this as some sort of reservation time-out and sends a Route Error (RERR) message to the source to rediscover the path. Also, when end-to-end delay for a particular data flow exceeds the maximum delays as detected by the destination, the destination node sends an RREP message back to the source. The source upon receiving the RREP packet sends packets on the path followed by the RREP.

3.1.6 Delay estimation: DUMMY RREP packets, which are similar to actual data packets, are used in QUORUM to estimate the end-to-end delay on a path.

3.2 Wireless Mesh Routing (WMR) Protocol

Wireless Mesh Routing (WMR) [18] is similar to QUORUM [23] in that it uses a reactive route discovery approach and IntServ type of reservations and admission control scheme. WMR uses a novel bandwidth estimation algorithm and includes the following key features:

3.2.1 Topology discovery: WMN makes use of frequent HELLO messages for topology discovery. Nodes maintain a distance metric and embed it in the HELLO message, which is the number of hops that node is away from its mesh router.

3.2.2 Route exploration*:* Proactive routing is used in WMR. Required bandwidth and delay constraints are embedded in the route discovery message by the source. For destination nodes that are within the WMN a TTL constraint flooding algorithm is used. While for nodes that are outside of the WMN, the distance tag is used in such a way that only nodes with a distance tag smaller than the source receive the packet. Every time the packet is forwarded, the intermediate node stamps it with its own distance tag thereby selectively exploring routes with least number of hops to the mesh router.

3.2.3 Admission Control*:* Upon receiving a route request packet, a node adds a routing table entry and marks it "explored" if it can meet the QoS requirements before forwarding the request.

3.2.4 Route Registration (Reservation): Upon receiving a route reply packet (from the destination), the node (which has been explored earlier) checks again for the QoS requirement before accepting the flow and updating the status to "registered" and can now accept data packets for that flow.

3.2.5 Bandwidth control*:* WMR estimates the available wireless bandwidth of the shared channel available at a node from the bandwidth already in use by the node in question, and its neighboring nodes.

3.2.6 QoS Violation Detection: WMR detects route failures if the reservations time-out at the destination and initiates a new route discovery towards the source.

3.2.7 QoS violation recovery: If a destination observes QoS violation, it sends a route discovery message in the reverse direction towards the source which undergoes the same admission control procedure. However, this may lead to selection of routes which are unidirectional (routes which may transport data from destination to source only and not vice-versa), or have adequate QoS in the direction of Destination to the Source only (since the direction of route discovery is destination to source).

3.3 DARE Protocol

In the Distributed End-To-End Allocation of Time Slots for Real-Time Traffic (DARE) Protocol [25], no particular routing strategy (reactive or proactive) is proposed, unlike for QUORUM [23] and WMR [22]. DARE assumes that a route is set up by any routing protocol, and DARE then provides resource reservation along this path that avoids interference with the neighboring nodes and handles real-time data communication. Time-slots are reserved on the intermediate nodes as well as nodes in the interference range of the intermediate nodes of a path.

3.3.1 Resource Reservation: To reserve resources, source nodes send a message towards the destination (request-to-reserve (RTR) message) which includes the QoS requirements. When the intermediate node receives the RTR message, it checks whether it has enough resources to meet the resource requirement, it makes an initial entry in its reservation table and sets it to "preliminary" before forwarding the message further. If however, an intermediate node falls short of the required resources, it does not forward the RTR message and the "preliminary" reservation shall time-out. When the destination receives the RTR, it sends a clear-to-reserve (CTR) message back to the sender on the reverse path taken by the RTR message changing the status of the "preliminary" reservation to "fixed" in the node's reservation table. The source starts sending the data packets after receiving CTR. After forwarding a RTR message, the intermediate node starts a RTR Timer, and if it does not receive a corresponding CTR within that time the reservation shall time out. If in case the requested time slot is already reserved at a node, then the node sends back to the previous node alternate receiving time slot in a update-transmit-reservation (UTR) message and if the previous node can transmit in that time-slot a new RTR message is formed and forwarded and the previous preliminary reservations released.

3.3.2 Avoiding Inter-flow Interference: In DARE in order to avoid any inter-flow interference the nodes adjacent to a QoS reservation path also receive RTR and CTR messages and the information of the reserved time-slots. The neighboring nodes then do not transmit during those reserved time slots. Furthermore, to inform nodes which did not hear RTR and CTR, the reservation information is embedded in the header of each data packet and acknowledgement. To further minimize the risk of interference the intermediate nodes in a QoS data path, also avoid the reservation time slots made by nodes 2 hops away both upstream and downstream on the reserved path. For a neighboring node to overhear RTR and CTR messages not addressed to it but to another node it must operate in promiscuous mode; this comes at the price of higher battery power consumption [26].

3.3.3 Link Failure Detection*:* Data packets are acknowledged by listening (overhearing) to the re-broadcast in the downlink direction when the data packet is forwarded by a node to reduce the signaling overhead. However since there is no hop after the destination node, the destination node sends an explicit ACK back to the second last hop.

3.4 IEEE 802.11s Mesh Networking Standard

In the proposed IEEE 802.11s [27] standard to detect the peer nodes, two methods are employed. In the first message nodes transmit beacons (passive scanning) and in the second method the nodes transmit probe request frames (active scanning). An "airtime cost" metric is calculated for a Mesh Link (ML) as shown in equation (1).

$$c_a = \left[O_{ca} + O_p + \frac{B_t}{r}\right] * \frac{1}{1-e_f} \tag{1}$$

Where:

a) O*ca* is the Channel access overhead (depending on Modulation and Coding Scheme (MCS)),
b) O*p* is the Protocol overhead (depending on MCS),
c) B*t* is the Number of bits in a test frame (depending on MCS),
d) *r* is the MCS bit rate and;
e) e*f* is the Frame error rate for the test frame.

Other metrics may be defined that depend on additional properties. Path selection is done using a Hybrid Wireless Mesh Protocol (HWMP) protocol, which operates in the following modes: (a) A proactive scheme similar to Ad-hoc On-demand Distance Vector (AODV) [17] or (b) A tree based scheme, where a Mesh node in the Mesh network becomes the root Mesh node and frequently sends either (i) *PREQ messages* which are used to maintain paths between all Mesh nodes and the root, or (ii) *Root Announcement (RANN) messages* that enable Mesh nodes to build a path to the root on-demand.

The above modes (AODV and the tree-based) could be used at the same time. Upon receiving a PREQ message (broadcast by the mesh root) a mesh node checks whether it contains a more recent sequence number or a better metric to reach the root, if so it updates its path table. A mesh root may ask the mesh nodes to reply in the PREQ message with a PREP message to establish a bidirectional path. A mesh root node sends RANN messages to update each Mesh node on how to find the root node.

In IEEE 802.11s standard the QoS reservation is done at the MAC layer. All nodes constantly monitor the wireless channel and check the reservation information in the wireless frame's duration field.

4 Discussions

QoS models and mechanisms for WMN borrow some concepts from the QoS models for wired networks. QUORUM and WMR, the two main mechanisms for QoS provisioning in WMN both utilize on-demand reactive route discovery, although it is scoped so as to control the flooding. The network size of WMNs is comparatively smaller compared to wired IP networks which also make the IntServ type scalability problem less important. The only issue with IntServ type of QoS provisioning in wireless multi-hop networks is the need for state management at nodes which may have very little memory and computational power. Below is the comparison of the various characteristics and features of QUORUM, WMR and DARE in more detail:

a) *Stable Link Selection:* QUORUM uses HELLO messages to detect stable links and gives preference to use such links for route selection purposes. No such mechanism exists in WMR and DARE. IEEE 802.11s uses an airtime metric which makes use of bit-error rate.
b) *Limiting Route Discovery:* The routing messages in QUORUM are limited only to nodes served by the same mesh router of the source and the destination. WMR uses "distance constrained discovery" forwarding request packets closer to the mesh router for each hop traveled. This results in using the mesh router and/or using the backhaul link for communication. Although QoS routing using Mesh Routers and backhaul links (if available) may provide more robust routes, such routes may be longer in terms of hop-count (compared to direct source to destination multi-hop path) and get congested and form bottlenecks as most flows will prefer mesh routers over clients while selecting paths (as all nodes will implement the same routing algorithm, giving higher priority to mesh routers). This eventually may result not only in higher end-to-end delay but also higher buffer overflow at mesh routers and bottleneck links could be formed.
c) *QoS Misbehaving Node Detection:* QUORUM also has a mechanism to detect misbehaving nodes in the network that do not forward data packets for other nodes but use other nodes to forward their own data packets [23]. WMR and DARE do not provide any such mechanism for detection of misbehaving nodes.
d) *QoS Route Repair:* WMR and QUORUM, have a route repair mechanism whereby the Destination upon discovering QoS violation, sends a Route Reply packet to the source, which undergoes admission control as well. The source then uses this route for sending data packets. However, the routes may be unidirectional, that is from destination to source and not in the other direction (as the links are wireless). This may lead to route failures.
e) *Topology Awareness:* WMR and QUORUM require the nodes in the network to be topology aware. WMR requires mesh clients served by the same mesh router to reside in the same unique subnet, while QUORUM makes use of frequent HELLO message broadcasts by all nodes with a Distance Tag (to the nearest mesh router) embedded in the HELLO messages for this purpose. Using IEEE 802.11s when a Mesh Router exists, the network can use proactive routing to find and maintain routes.
f) *Admission Control:* WMR and QUORUM use bandwidth based admission control while DARE also provides some kind of physical layer admission control through the slot reservation process. HELLO beacon overhead: WMR and QUORUM both use HELLO broadcasts by all nodes for topology discovery and for robust link selection respectively. This leads to high control overhead.
g) *Per-Flow Reservation Maintenance:* DARE, WMR and QUORUM maintain per-flow reservation state information. This may incur high overhead in terms of memory and computation, to check for reservation timeouts and refresh messages and/or implicit refresh messages (data packets).
h) *Reservation Protection:* Nodes adjacent to the reservation path also receive the reservation messages in DARE, being thus informed about the reserved time slots. Reservation information is also contained in the header of data packets and acknowledgments in DARE, informing the nodes that did not overhear the reservation setup phase. In IEEE 802.11s also, the transmission time-slots are specified in the packet to inform neighboring nodes. Although time-slot reservations help in meeting QoS bounds, it can be time consuming to set-up reservations at the time-slot level, as it can involve negotiation between each set of transmitter and receiver pair to find available time-slots.

5. Conclusion

This paper presents the challenges in QoS provisioning for Wireless Mesh Networks (WMNs), which have little or no infrastructure support and the first approaches for QoS provisioning in WMNs. Provisioning of QoS in order to support an array of services and applications such as voice and video is crucial in WMNs, as multimedia communication is one of the key applications of WMN. However, QoS provisioning in wireless networks especially MANETs and WMNs is a very challenging problem due to various factors such as dynamically changing topology, capacity limitations and link variability, multi-hop communication etc.

Future research direction in QoS provisioning for WMNs should focus on utilizing the added benefit of the relatively static mesh routers in WMN which are absent in MANETs. Furthermore, QoS provisioning in wireless networks is heavily influenced by the resource management mechanism at the MAC layer, therefore the QoS routing protocol interaction with MAC layer in order to find available wireless resources per hop and be able to reserve them for the entire multi-hop paths should be explored. In addition to the resource reservation and maintenance features, the WMN QoS protocols must incorporate priority queuing for real-time packets to make sure they are transmitted ahead of non-real-time packets. With advances in these areas, WMNs will become a viable approach for QoS provisioning in dynamic wireless networks.

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