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Published in:
Proceedings of ISCIS - the 23rd International Symposium on Computer and Information Sciences

DOI:
10.1109/ISCIS.2008.4717865

2008

Document Version:
Peer reviewed version (aka post-print)

Quality-of-Service-Aware Multicast Routing in Heterogeneous Networks with Ad Hoc Extensions

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***Abstract* – A growing number of users communicate on the move with each other utilising wireless network technologies. The heterogeneity level of networks is increasing with various wired and wireless parts as well as access technologies. Mobile ad hoc communications can fill the connectivity gaps in such networks. However, the increasing amount of multimedia content shared over the wireless medium makes quality of service (QoS) and resource efficiency essential requirements for mobile ad hoc networks. The growing number of group-oriented applications also requires efficient utilisation of network resources. The mesh-evolving ad hoc QoS multicast (MAQM) routing protocol proposes a solution to these problems. It achieves multicast efficiency by tracking resource availability in each node's neighbourhood and monitoring the QoS status continuously. Nodes decide on joining multicast sessions based on the sustainability of QoS. MAQM also evolves the initial multicast tree into a mesh to improve robustness. This article describes the modules of MAQM and presents its performance evaluation with regard to session- and packet-level QoS criteria. The results show that MAQM significantly improves multicast session efficiency.**

***Index Terms* – Mobile ad hoc networks, multicast routing, next generation networks, quality of service.**

1. Introduction

THE commercial success of portable computers shows that users want their information to go with them. They want to communicate with other users as well as a variety of information services. It is therefore reasonable to assume that people want the same communication capabilities on the move as in their homes or offices. The simultaneous popularity of portable computing and networking poses a paradox, since portable devices are not connected to the conventional wired networks. The paradox can be resolved by wireless data networks, through which the users retain the advantages of mobility and being connected at once.

The global heterogeneous multimedia network of the near future, as illustrated in Figure 1, will probably consist of a core with a wired backbone, infrastructure-based wireless networks with various access technologies and, at the periphery, ad hoc mobile extensions, which will be connected to the main internetwork via ad hoc gateways. The widespread use of mobile and handheld computers increases the popularity of mobile ad hoc networks, which are self-organising communication groups formed by wireless mobile hosts. They make their administrative decisions in a distributed manner without any centralised control. They are free from the boundaries of any pre-existing infrastructure and can be deployed anytime, anywhere [1]. The routing functionality possessed by the nodes enables them to communicate through multihop paths made of intermediate nodes that relay the packets from the source towards the destination, even if these reside beyond the transmission range of each other. Thus, mobile ad hoc networks are an effective means of extending the wireless communication capability beyond the physical limits of its infrastructure and fill the gaps of connectivity.

Due to their quick and economically less demanding deployment, mobile ad hoc networks are considered for many commercial applications [2]. In order to meet the qualitative expectations of users for these, mobile ad hoc networks need support for multimedia, which show real-time, variable bit-rate traffic characteristics. This makes quality of service (QoS) a fundamental requirement.

However, it is not an easy task to incorporate QoS to mobile ad hoc networks, since they possess various unique properties which make them very different from traditional wired and even wireless systems. Wireline QoS algorithms rely on the availability of precise state information, whereas in ad hoc networks this information is inherently imprecise.

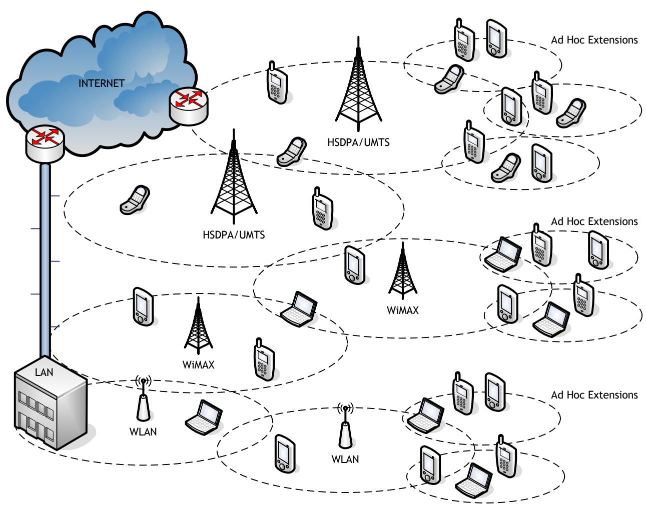

Figure 1. The global heterogeneous network of the near future.

This work was supported in part by the State Planning Organisation of Turkey, under grant numbers DPT98K120890 – DPT03K120250 and the university research program of OPNET Technologies Inc, Bethesda, USA.

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The nodes of a mobile ad hoc network move arbitrarily. The network topology changes frequently and unpredictably. Nodes join, leave and rejoin the network at any place. Links appear or disappear any time. The actual throughput of wireless systems is often much less than the maximum radio transmission rate, due to the effects of multiple access, fading, noise and interference [3]. These effects result in time-varying channel capacity, making it difficult to determine the aggregate bandwidth between two endpoints. Finally, resources such as energy, bandwidth, processing power and memory, which are relatively abundant in wired environments, are limited and have to be preserved in mobile ad hoc networks [4]. Thus, protocols designed for wired networks are not appropriate for ad hoc networks due to their excessive overhead and lack of adaptation to the unpredictable network topology [2].

The ad hoc QoS multicast (AQM) routing protocol [5] incorporates a QoS-based approach into multicast routing in mobile ad hoc networks. As a tree-based protocol, the initial version of AQM is resource-efficient but less robust to changes in the network topology [6]. Thus, we integrated new procedures into AQM such that in its new version multicast trees evolve into meshes during sessions. In this article, we summarise the functional structure of the new version, the mesh-evolving ad hoc QoS multicast (MAQM) protocol, and evaluate its performance.

2. Multicast in Mobile Ad Hoc Networks

In the literature, multicast routing protocols developed for mobile ad hoc networks are classified into various categories [2]. They are grouped by how the multicast connectivity is established and maintained. In a source-initiated approach like the on-demand multicast routing protocol (ODMRP) [7], a multicast group is constructed per sender, where the formation of the group is initiated by the source. The source polls the network periodically with join request packets. Receivers wishing to join the multicast group respond with join reply packets when the propagated request reaches them. In a receiver-initiated approach like the multicast ad hoc on-demand distance vector (MAODV) routing protocol [8], a single multicast connection is shared by all senders of the same group. A receiver floods a join request packet to search for a path to a multicast group.

Another classification is based on the operation type of the ad hoc multicast protocols. Proactive protocols, such as the multicast core-extraction distributed ad hoc routing (MCEDAR) protocol [9], require table-driven preparation activities, whereas in reactive protocols, such as ODMRP and MAODV, the process is on-demand. It is shown by previous research that generally reactive approaches are better-suited to mobile ad hoc networks than proactive ones due to the dynamic nature of the network topology. However, both types of schemes actually have their advantages and limitations under certain conditions. Thus, there are also hybrid approaches such as the optimized polymorphic hybrid multicast routing protocol (OPHMR), which aims to combine the positive aspects of both approaches [10]. OPHMR defines four modes of operation depending on thresholds for power and mobility levels and node density. A polymorphic algorithm decides on the current mode and applies existing protocols as proactive and reactive behaviours accordingly.

Based on the multicast topology, the protocols are grouped into two types: tree-based and mesh-based. While tree-based protocols are more efficient in terms of resource usage, mesh-based protocols are more robust to the changes in the network [6]. In a tree-based multicast routing protocol, a node accepts packets only when they come from another node which a tree branch has been established with. Thus, there is only a single path between a sender-receiver pair. Tree-based protocols are further categorised into shared-tree and source-tree topologies. In the former, all members of a multicast group are connected via a single shared tree, whereas in the latter, a group consists of multiple trees rooted at their respective sources. MAODV adopts the shared-tree approach, whereas MCEDAR is an example for the source-tree approach. A shared multicast routing tree spanning all the group members may not be optimal for the individual sources, but they are more scalable when the number of sources in a session or the number of multicast sessions increases. On the other hand, source-tree-based protocols perform better than shared-tree-based protocols under heavy traffic since they achieve more efficient load balancing. Since there is only a single path between senders and receivers in tree-based multicast routing protocols, they are vulnerable to the dynamics of the ad hoc network such as node mobility and link breaks. In contrast, mesh-based multicast protocols maintain a mesh consisting of a connected component of the network containing all the receivers of a group. They construct a mesh that allows data packets to be transmitted over more than one path from a sender to a receiver to increase robustness at the price of redundancy in data transmission. ODMRP is a well-known example for this approach.

Various protocols are developed to perform multicast routing in mobile ad hoc networks. However, they do not address multimedia QoS requirements of the sessions within the scope of ad hoc multicast routing sufficiently, which is becoming more important as the demand for mobile multimedia increases. Incremental changes on existing ad hoc schemes cannot efficiently solve the critical issues mentioned above. Thus, the AQM routing protocol is presented as a composite solution to this problem [5]. In comparison to the classification presented in this section, MAQM, the improved version of AQM, adapts several hybrid approaches: Connectivity is maintained by source-initiated session announcements as well as receiver-initiated join processes. Session management is table-driven, whereas the join mechanism is based on on-demand path verification. Finally, the initial multicast source-tree evolves into a mesh during the session to improve robustness in the current version of MAQM.

3. Mesh-Evolving Ad Hoc QoS Multicast

MAQM tracks the availability of resources within each node's neighbourhood based on the bandwidth reservations made by that node for ongoing sessions and requirements reported to it by its neighbours. The QoS status of the network in terms of bandwidth and delay is announced along with the QoS requirements of the session at the time

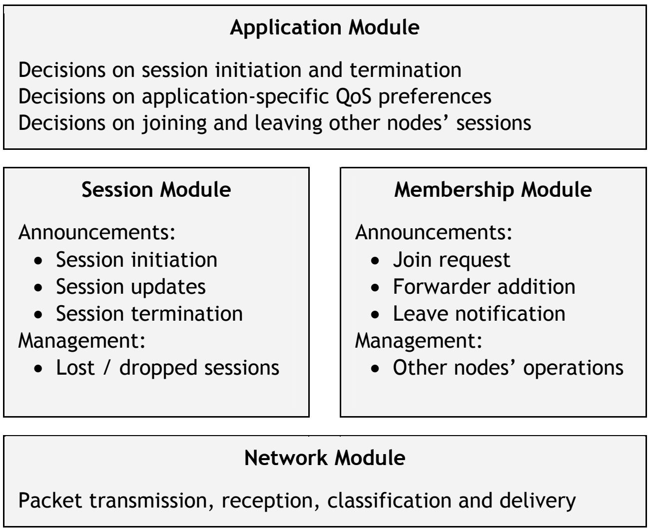


Figure 2. The modular structure of MAQM.

of session initiation and updated periodically to the extent of QoS provision. MAQM achieves delay restriction by limiting the number of hops allowed to join a session. Nodes are prevented from applying for membership if there is no feasible QoS path for the session at the time of their request. When a node requests to join a session, a three-phase process consisting of request, reply and reserve steps is utilised. Existing QoS information helps the routers select one of the appropriate paths meeting the service requirements of that session. The initial AQM protocol is described in [5]. In the following section, we summarise the algorithmic structure of an MAQM node consisting of application, session, membership and network modules. Figure 2 shows these modules according to their functions. Then, we introduce the additional procedure evolving a multicast tree into a mesh during the course of a session.

3.1. The Modules of MAQM

The *application module* initiates, terminates, joins and leaves sessions. Shortly after being activated, all MAQM nodes become aware of the existing sessions they can join. Alternatively, users can initiate their own sessions, whereby they set the QoS preferences of their application, become a session server and wait for other users to join their session. Session servers are also responsible for streaming the multimedia contents in form of data packets they prepare.

The main function of the *session module* is the management of the multicast sessions. Triggered by the application module, the session module generates and distributes session initiation and termination messages. It also handles similar messages received from other MAQM nodes. Finally, it is the responsibility of the session module to maintain session integrity throughout the network by utilising periodic session update and reactive session loss announcements. To maintain connectivity and support QoS with maximum possible accuracy and minimum overhead under mobility, nodes perform periodic cleanup operations on their session information. Thus, a node informs its successors when it loses its connection to a session.

Initiated by the application module, a join request is broadcast by the *membership module* to find a path between the requesting node and the existing multicast graph satisfying the QoS requirements of the session being joined in terms of bandwidth and delay. When it is time to leave a session, the application module of the member triggers the membership module to send a notification-of-leave upstream towards the predecessors of the node. In order to increase the robustness of the multicast graph, the membership module adds new links to the existing tree and evolves it into a mesh, which is explained in more detail in the next section. The membership module takes also part in similar operations of other nodes in the process of joining or leaving a session.

The *network module* of MAQM is the interface between the multicast protocol and the wireless medium access control (MAC) layer. The basic service provided by this module is to transmit and receive packets, to classify the packets it receives from other nodes and deliver them to either the session or the membership module. The network module also maintains the list of a node's neighbours, which contains their bandwidth allocation information that they exchange with each other. This information is used by the session and membership modules of the node to calculate the total bandwidth reservation within the neighbourhood. This is how the free bandwidth available for future routing requests is found, which is essential for the finding of a suitable QoS path in terms of bandwidth.

3.2. The Evolution of the Multicast Tree into a Mesh

One of the major concerns with mobile ad hoc networks is that they operate under continuous topological changes. The mobility and limited transmission range of nodes cause their wireless links to break very frequently, leading to disconnections. Thus, robustness is particularly important for protocols like MAQM. This can be done if extra wireless links can be added to the initial multicast tree, evolving it to a multicast mesh during the course of data streaming such that member connectivity is strengthened without compromising efficiency in resource usage. Figure 3 shows an example for this evolution.

MAQM utilises the inherent broadcast capability of the ad hoc network to achieve this goal. Due to this capability, members can start receiving multicast data from a node that is originally not their forwarder. If a receiver starts overhearing multicast data packets from a node that is a predecessor or a previously unknown node according to its

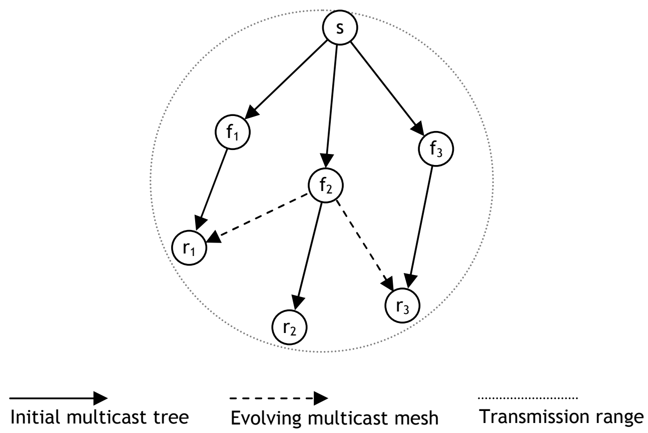


Figure 3. The evolution of the initial multicast tree into a mesh, where receivers r_1 and r_3 discover a new forwarder f_2 (other than their parents) that can deliver them data packets from the server *s*.

Table 1. QoS classes and requirements.

QoS Class	Bandwidth Requirement	Average Duration	Delay Limit	Application Type
1	128 Kbps	300 s	10 ms	Voice conversation
2	256 Kbps	900 s	50 ms	Streaming music
3	512 Kbps	600 s	10 ms	Video conference
4	2 Mbps	1 200 s	50 ms	Streaming video

member table, this means that there is actually an active session member within its transmission range other than its selected data forwarder for the session. In this case, the receiver decides that it can use this node streaming multicast data actually to a third node as an extra forwarder in order to improve its chance of remaining connected to the session despite frequent topological changes. The receiver informs the additional forwarder of its existence by registering itself at this node for that session and ensures that the forwarder is also aware of its new receiver.

By adding extra links during data streaming, forwarders and receivers are connected to their session servers through multiple intermediate forwarders, which makes session losses a less frequent event and yields to less control overhead. In other words, by increasing redundancy in their graphs, multicast sessions become less prone to lost forwarders. Moreover, the registration at more forwarders does not generate extra data traffic since they are already forwarding data to their existing receivers.

4. Performance Evaluation

The evaluation of QoS multicast routing performance in ad hoc networks requires criteria that are both qualitative and measurable. The main concern of this section is to test the efficiency of MAQM in providing multicast users with QoS and satisfying the service requirements of multimedia applications. Therefore, it is necessary to define QoS-related performance metrics to measure multicast efficiency at member and session levels, whereas previous research mainly focuses on quantitative aspects of efficiency such as packet loss ratio, delivery delay and control overhead.

The simulations are conducted using OPNET Modeler 11.5 Educational Version and Wireless Module [11]. The results are aggregated for a multicasting scenario with four QoS classes, which are defined in Table 1 by different bandwidth and delay requirements to represent a sample set of multimedia applications. The effect of mobility is observed under the random waypoint mobility model. The parameters of the mobility model and the other simulation settings are given in Table 2. The usage scenarios consist of open-air occasions such as search and rescue efforts and visits to nature in an area with boundaries, where a network infrastructure is not available and nodes move around with walking or running speeds. In order to achieve more realistic performance results, several improvements have been made on the simulation environment presented in [5]. Background data traffic is added to the experiments. Multicast data traffic is given a bursty nature instead of being represented as an aggregated value. The IEEE 802.11b protocol is used as the MAC layer of MAQM.

Table 2. Simulation parameters.

Parameter Description	Value
Background traffic inactivity period	300 s (exponential)
Background traffic file size	2 MB (lognormal)
Greeting message interval	10 s
Maximum link bandwidth	10 Mbps
Mobility model	Random waypoint
Node pause time	10 – 40 s (uniform)
Node speed	1 – 4 m/s (uniform)
Multicast inactivity period	100 s (exponential)
Network population	100 nodes
Session update message interval	15 s
Simulation duration	1 h
Wireless transmission range	250 m

The non-QoS protocol developed for comparison purposes is basically a modified version of MAODV [8]. However, MAODV utilises the information collected during the unicast route discovery, which is not implemented in the non-QoS protocol developed for the simulations to achieve fair comparison conditions.

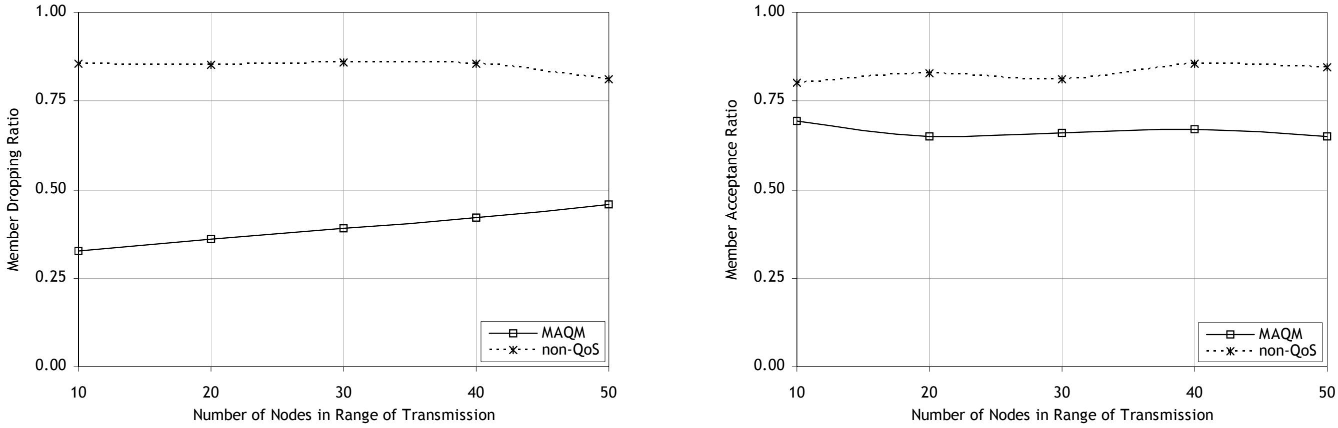
Two sets of simulations are conducted with these parameters. The first set examines the effect of network density on MAQM. In this set, the average number of neighbours within a node's transmission range is the variable. In the second set, the percentage of the sessions which belong to the heaviest service class, Class 4 in Table 1, is the variable, and the other classes share the remaining occurrence probability equally. The aim here is to test the effect of the changes in multicast traffic load on MAQM.

4.1. Session-Level QoS Criteria

The success of a QoS multicast routing system depends primarily on the quality of its sessions. In this regard, the most important criterion for the QoS-related multicast routing decisions made by MAQM is the improvement in the ratio of session members successfully served by their respective applications. It is one of MAQM's main concerns that network resources are not excessively utilised to avoid possible collisions, packet loss and delay due to overload and keep the QoS conditions at a satisfactory level. Once accepted to a session, the QoS level of individual nodes during the course of the session is vital. Therefore, it is necessary to observe the changes of the QoS conditions experienced by a session. The ratio of dropped session members is an important criterion for the evaluation of session-level QoS since it is a measure of the percentage of nodes experiencing severe delay and loss problems due to allocations exceeding the resource limits of the network.

On the other hand, it has to be taken into account that the session-level QoS achieved by the prevention of overload has an effect on the system observed by the lower percentage of users that are admitted to the multicast sessions. An efficient QoS multicast protocol should not allow its user admission rate to drop unacceptably as a result of the application of QoS restrictions. In other words, the majority of the users who wish to join a multicast session should still be admitted even with QoS limitations. Their ratio reflects the success rate of MAQM in accepting a node's request to join a session.

Figure 4 compares the session-level performance of MAQM to a non-QoS scheme in terms of the number of (a) dropped and (b) accepted session members as the network density increases. It should be noted that the non-QoS protocol does not actually drop members. Instead, the



(a) Member dropping ratio as a function of network density (b) Member acceptance ratio as a function of network density

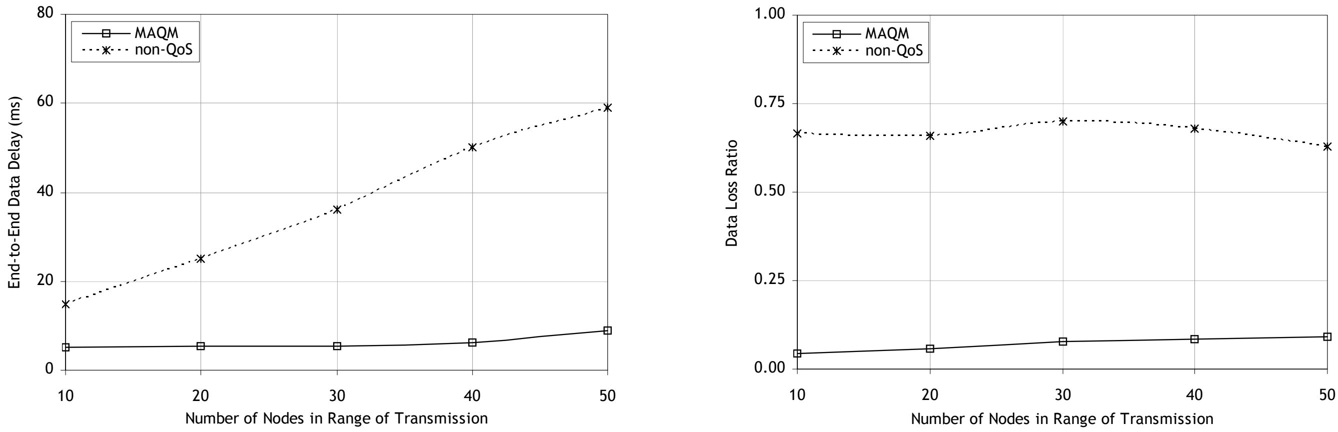
Figure 4. Comparison of MAQM to a non-QoS scheme with regard to session-level QoS criteria as the network population increases.

members are marked *"should be dropped"* as soon as their QoS cannot be sustained in order to calculate their ratio among all members. On the other hand, MAQM monitors its session members with regard to their QoS level such as their packet delay and loss rates. If a member experiences loss or delay beyond the limits of acceptable QoS, MAQM decides that the QoS of the membership cannot be sustained any more and drops the member off the session to prevent further waste of resources. Due to this efficient resource usage policy, MAQM is able to sustain the membership QoS for a significant portion of the members once it accepts them to a session, whereas the non-QoS protocol can only provide poor QoS conditions to its users, mainly due to the fact that it accepts all the join requests it receives without considering the resource limitations of the network. MAQM has a lower rate of member acceptance as a result of its stringent QoS restrictions and resource management precautions. However, it is still able to achieve an acceptance ratio close to its non-QoS competitor and preserve this ratio even as the network density increases, since it does not waste resources on unreachable members and recycles them for new admissions.

4.2. Packet-Level QoS Criteria

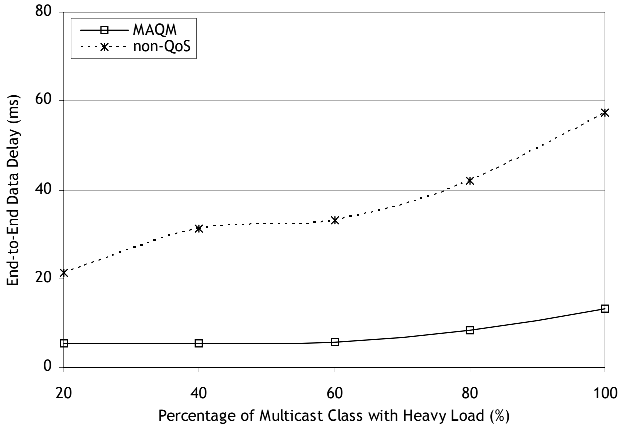
MAQM decides on the sustainability of a membership based on a combination of various QoS metrics such as the ratio of lost data packets and the average end-to-end delay. This is a necessary countermeasure in order to protect the rest of the network from performance degradation. Therefore, these two basic QoS metrics deserve a more thorough examination, which is provided in this section.

Figure 5 displays (a) the average end-to-end delay and (b) the loss rate of data packets experienced by MAQM and the non-QoS protocol as the network density increases. The main reason for end-to-end delay is contention, which happens much rarer in MAQM as a result of its ability to reserve resources and balance network load. There is only a slight increase in the end-to-end delay of MAQM as the network becomes denser. The delay averages of the non-QoS protocol are higher than acceptable and increase drastically with network density. The dropping of members with unacceptable data streaming quality enables MAQM to limit the network load in such a way that collisions are rare and data delivery rates are high for the remaining session members. Thus, the data loss rate increases only slightly with network density, which is an important achievement for a QoS-aware multicast routing protocol. The results show that MAQM is able to deliver data packets in a streaming fashion as required by multimedia applications under relatively stable QoS conditions.

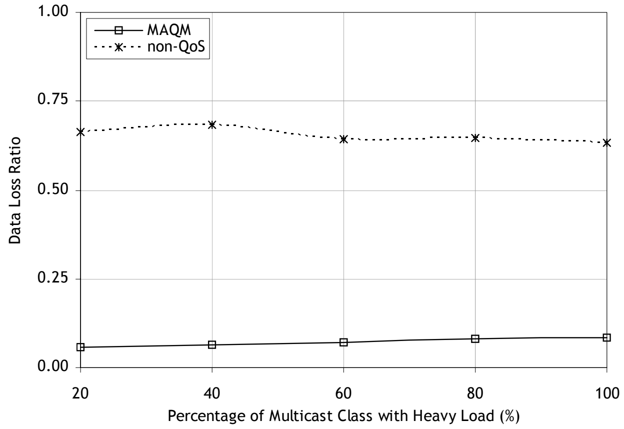


(a) End-to-end data delivery delay as a function of network density (b) Data loss ratio as a function of network density

Figure 5. Comparison of MAQM to a non-QoS scheme with regard to individual QoS criteria as the network population increases.



(a) End-to-end data delivery delay as a function of multicast traffic load



(b) Data loss ratio as a function of multicast traffic load

Figure 6. Comparison of MAQM to a non-QoS scheme with regard to individual QoS criteria as the multicast traffic load increases.

Figure 6 shows (a) the average end-to-end delay and (b) the loss rate of MAQM and its competitor as the multicast traffic load changes. For both protocols, there is an increase in delay as the ratio of heavy-class sessions grows. For MAQM, this increase is a result of the larger transmission delays incurred by the large-sized data packets. Since there are more heavy-class sessions in the network, more large-sized data packets are produced and more time is consumed to transmit them due to the fragmentation and reassembly operations at the MAC layer. However, the delay results are still within the QoS limits of the heavy-class application. On the other hand, the non-QoS protocol experiences additional delay due to contention at lower layers, which increases its end-to-end delay beyond acceptable limits.

Due to the larger data packets of the heavy class, the data loss ratio of MAQM also increases. MAQM experiences slightly more data losses with the growing ratio of heavy-class sessions. Nevertheless, MAQM is still able to keep these changes within allowed QoS limits by decreasing its member acceptance ratio as necessary. The non-QoS protocol has a data loss rate too high for multimedia applications. Its member acceptance ratio also decreases, but this is rather a result of lost control packets and therefore does not help it achieve lower loss rates.

5. Conclusion

The increasing amount of multimedia content shared over wireless communication networks makes QoS-related, resource-efficient routing strategies essential. Moreover, the growing number of group-oriented applications requires the efficient utilisation of network resources. Multicast is a promising communication technique, which can achieve this efficiency by facilitating the broadcast capability of the wireless medium. MAQM provides the mobile networks of the near future with QoS support and multicast routing features. It improves multicast quality through efficient resource management. MAQM checks bandwidth availability within each node's neighbourhood based on previous reservations and ensures that updated QoS information is used to select routes that can meet service requirements of a session. It evolves the initial multicast tree into a mesh in the course of the session to improve the node connectivity in the face of topological changes.

MAQM can be further extended so that it can serve the members of a multicast session across different networking domains, which is an important feature in the context of next generation networks. In this regard, some possible future research directions are the handling of various underlying data link layer technologies in a heterogeneous network and the mapping of the QoS parameters between these data link layers and the network layer, where MAQM takes charge. Another important issue is the design of dual-stack MAQM gateway nodes that make necessary protocol conversions at the boundaries of the network domains.

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