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QoS Support in TDMA-Based Mobile Ad Hoc Networks

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Abstract Mobile ad hoc networks (MANETs) are gaining a lot of attention in research lately due to their importance in enabling mobile wireless nodes to communicate without any existing wired or predetermined infrastructures. Furthermore, in order to support the growing need for multimedia and realtime applications, quality of service (QoS) support by the networking protocol is required. Several important QoS parameters that are needed by such applications can be identified. They include bandwidth, end-to-end delay, delay jitter, and bit error rate. A good amount of research has been developed in this area covering different issues and challenges such as developing routing protocols that support bandwidth reservation and delay management. In this paper, the current state of research for QoS support in TDMA-based MANETs at different layers of the networking model is presented and categorized. In addition, the current issues and future challenges involved in this exciting area of research are also included.

Keywords mobile ad hoc networks (MANETs), quality of service (QoS), routing, time division multiple access (TDMA)

1 Introduction

Mobile ad hoc networks (MANETs) have rapidly gained a considerable amount of attention in research lately. As more and more smart, small, portable, and powerful computing devices are introduced into everyday life, the need for such devices to communicate on the fly in a seamless manner and without any preexisting network wiring or infrastructure is growing. It is also natural to expect such devices to support multimedia and real time applications, which are becoming increasingly feasible due to the significant advances in CPU power, memory, speed, storage, and communication capacity of mobile devices. Such applications require the underlying network to provide certain guarantees that are manifested in the support of several important Quality of Service (QoS) parameters such as bandwidth, delay, and bit error rate. Maintaining these QoS commitments in MANETs is not an easy task. This is due to the unpredictability and variability of many factors such as bit error rates, mobility, and continuous change in the connectivity of different nodes in the network.

Providing QoS support in MANETs encompasses all of the layers of the OSI model starting with the application layer at the top of the stack, down to the physical layer at the bottom. This paper focuses on QoS provisioning in the network and medium access control (MAC) layers. Furthermore, it presents a graph-theoretical foundation that is directly related to providing interference-free operation in the wireless environment.

Due to the dynamic nature of MANETs, designing communications and networking protocols for these networks is a challenging process. One of the most important aspects of the communications process is the design of the routing protocols used to establish and maintain multi-hop routes to allow the communication of data between nodes. A considerable amount of research has been done in this area, and multi-hop routing protocols have been developed. Most of these protocols such as the Dynamic Source Routing protocol (DSR)[1], Ad hoc On-Demand Distance Vector (AODV) protocol[2], Temporally Ordered Routing Algorithm (TORA)[3], and others establish and maintain routes on a best-effort basis. While this might be sufficient for a certain class of MANET applications, it is not adequate for the support of more demanding applications such as multimedia audio and video. Such applications require the network to provide certain QoS guarantees.

The research has been active in recent years in the area of QoS support in MANETs. Numerous QoS routing protocols have been proposed for this environment. Most of these protocols provide QoS support in the form of bandwidth reservation for multi-hop paths between source and destination nodes. This is because bandwidth is the most critical parameter in most MANET applications due to the scarcity of this resource in wireless networks. The protocols discussed in this paper support QoS to varying degrees, using different methods and communication models.

There exist several surveys that discuss QoS support in MANETs[4−7]. Although the general challenges and issues involving QoS support in MANETs are presented and discussed, this paper differs from these surveys in that it provides a graph theoretical background about this subject and focuses on the provisioning of QoS support in the TDMA (Time Division Multiple Access) environment. QoS routing protocols for CDMA-over-TDMA-based MANETs are considered in other papers[8−12]. In the latter protocol, a particular node's use of a slot on a link is dependent only upon the status of its 1-hop neighbor's use of this slot. However, in the

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Survey

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TDMA model, a node's use of a slot depends not only on the status of its 1-hop neighbor's use of this slot; its 2-hop neighbor's current use of this slot must be considered as well. This is due to the well-known hidden and exposed terminal problems[9,13], which must be taken into account.

There are several papers that address the subject of QoS routing in MANETs in different environments using different models and approaches[14−21]. In [17], Jawhar and Wu present and classify these approaches according to which of the existing best-effort routing algorithms (DSR, AODV, DSDV, TORA, etc.) they extend or are most closely related. In addition, some protocols are based on new algorithms. The QoS routing protocols that are discussed operate in both the network layer and the MAC layer which is equivalent to the data link layer in the OSI model. There are also design approaches, such as the IP-based quality of service framework for MANETs (INSIGNIA)[22−24] and the integrated mobile ad hoc QoS framework (iMAQ)[25], which are designed to support multimedia traffic and achieve better efficiency in terms of bandwidth and energy consumption through the implementation of inter-layer QoS frameworks. Other approaches include the one presented in [26], which is a distributed control architecture that allows the use of mobile robots to participate in routing and management of QoS flows. In addition, the paper in [27] presents a protocol named QOLSR which is an extension of the Optimized Link State Routing Protocol (OLSR). QOLSR uses IPv6 labelling and classification of data packets as well as metrics such as bandwidth and delay to select routes that satisfy QoS requirements.

The remainder of the paper is organized as follows. Section 2 provides a graph-theoretical foundation underlying interference-free scheduling and communication in the wireless environment. Section 3 discusses the existing QoS models. Section 4 presents an overview and a classification of QoS routing protocols in MANETs. Section 5 focuses on TDMA-based routing protocols for MANETs, including slot allocation issues, challenges, and solutions such as providing race-free operation and incorporating dynamic range bandwidth reservation. Section 6 discusses additional issues facing QoS support in TDMA-based MANETs. The last section presents conclusions and future research.

2 Graph-Theoretical Foundation for Broadcast Scheduling in TDMA-Based MANETs

2.1 Basic Models

In [28], Lloyd provides a theoretical background and a discussion of broadcast scheduling for TDMA-based MANETs. The paper presents the issue from an algorithmic perspective and provides a good classification of such networks and their relation with graph theory. From a graph-theoretical point of view, broadcast scheduling in MANETs is equivalent to distance-2 coloring[29,30] of a graph $G = (V, E)$ (distance-1 coloring is not sufficient and would cause interference such as the hidden terminal problem). Distance-2 neighbors of a node include all of its 1-hop or 2-hop neighbors. The corresponding problem is to produce an assignment of colors such that no two nodes are assigned the same color if they are distance-2 neighbors. An *optimal coloring* is a coloring that uses the minimum number of colors. A distance-2 coloring algorithm is considered greedy if it chooses the first available color (i.e., color with the smallest number) that can be assigned to a node without resulting in any conflict. The problem of finding an algorithm that provides distance-2 coloring of a graph using a minimum number of colors is NP-complete[30,31]. Obtaining a broadcast schedule for a network is abstracted from the distance-2 coloring of a graph. The color of each node can be given different meanings depending on the medium access protocol used. Namely the node color can be converted into a frequency in the case of Frequency Division Multiple Access (FDMA), code in Code Division Multiple Access (CDMA), or time slot in the case of Time Division Multiple Access (TDMA). Furthermore, two different types of broadcast scheduling algorithms can be identified. They are presented below.

2.2 Types of Broadcast Scheduling Algorithms

There are two main categories of broadcast scheduling algorithms: *centralized* and *distributed*.

In centralized coloring algorithms, there are three types of approximation algorithms for broadcast scheduling as follows.

1) *Traditional algorithms*, which pre-order the nodes according to a certain criterion and then apply a greedy strategy to color the nodes.

2) *Geometric algorithms*, which project the network onto simpler geometric objects such as a line and compute optimal distance-2 coloring for the projected points.

3) *Dynamic greedy methods*, which color the nodes in a greedy fashion but determine the order of the nodes in a dynamic fashion. Two algorithms which belong to the third type are *Progressive_min_deg _last* and *Continuous_color*. They both color the nodes using a greedy strategy but with different orderings of the nodes that are colored. The former colors the nodes starting with nodes that have higher degrees. The latter colors nodes in order of Euclidean distance from an arbitrary node. It relies on the fact that nodes in geographic proximity to one another must be distance-2 nodes to derive its approximation ratio.

Fig.1 shows an example of the application of *Progressive_min_deg_last* algorithm with the resulting distance-2 coloring of the graph. First, the nodes are sorted according to their node degrees. Then each node, taken in order (starting with the highest degree node), is greedily colored. In the TDMA environment, the resulting color context (colors are presented as numbers in the figure) corresponds to a transmission slot in a TDMA frame. Consequently, no two distance-2 nodes transmit using the same slot and transmission interference is avoided. Similarly, the color context can also be frequency, in the FDMA case, or code, in the CDMA case. Interference in both of these cases is also avoided.

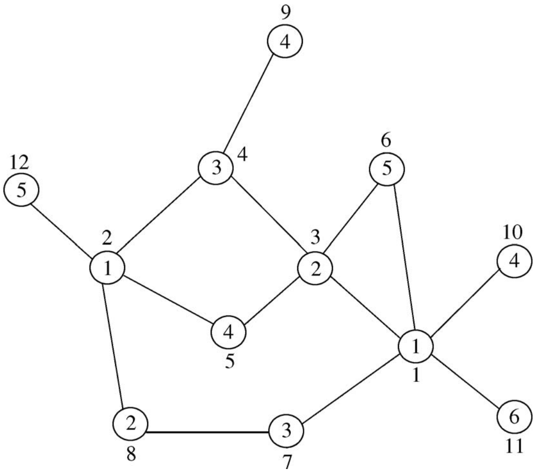

Fig.1. Distance-2 coloring of a graph using the *Progressive_min_deg_last* algorithm. The number outside the node is its sorted order according to node degree with highest degree node first, and the number inside the node is its resulting color which can correspond to its transmission slot in the TDMA frame. No two nodes that are 1-hop or 2-hop neighbors have the same color.

In distributed coloring algorithms, there are two types of distributed algorithms as follows:

1) *Token passing algorithms*, in which a token is passed around the network, and nodes calculate their portion of the schedule when they receive the token. The token may contain some network information. Although the computation of the schedule is distributed, it is still done sequentially[28].

2) *Fully distributed algorithms*, in which each node calculates its own schedule based on its own information and information of nodes in its geographic vicinity. Schedules are computed in a parallel fashion, which makes such algorithms more scalable and practical.

Most TDMA scheduling algorithms in the literature fall under the second category[9–13,17,32,33], where the actual scheduling of slot transmissions is done based on information from the 1-hop and 2-hop neighbors of each node. This location information is sufficient to allow each node to calculate a conflict free schedule in this environment. The papers in [13, 32] contain the slot allocation rules and constraints that are used to ensure correct and collision-free slot assignment. As indicated earlier, a more detailed presentation of communication protocols that provide scheduling in TDMA-based MANETs is provided in subsequent sections in this paper.

3 QoS Routing Protocols: Models and Classification

In this section, the different QoS models used in literature are presented.

3.1 QoS Models in MANETs

Depending on the application involved, the QoS constraints could be available bandwidth, end-to-end delay, delay variation (jitter), probability of packet loss, and so on. Establishing multi-hop routes between nodes is not sufficient in this case. The discovered routes can only be considered if they provide guarantees of the QoS parameters, such as bandwidth required by the application. Let $m(u,v)$ be the performance metric for the link (u,v) connecting node u to node v, and let path $(u,u_1,u_2,\ldots,u_k,v)$ be a sequence of links for the path from u to v. Three types of constraints on the path can be identified[34,35]:

1) *Additive constraints*: A constraint is additive if $m(u,v) = m(u,u_1) + m(u_1,u_2) + \cdots + m(u_k,v)$. For example, the end-to-end delay (u,v) is an additive constraint because it consists of the summation of delays for each link along the path.

2) *Multiplicative constraint*: A constraint is multiplicative if $m(u,v) = m(u,u_1) \times m(u_1,u_2) \times \cdots \times m(u_k,v)$. The probability of a packet $prob(u,v)$, sent from a node u to reach a node v, is multiplicative, because it is the product of individual probabilities along the path.

3) *Concave constraint*: A constraint is concave if $m(u,v) = \min\{m(u,u_1), m(u_1,u_2),\ldots,m(u_k,v)\}$. The bandwidth $bw(u,v)$ requirement for a path between nodes u and v is concave. This is due to the fact that it consists of the minimum bandwidth between the links along the path.

Wang and Hou[35] provide a list of twelve combinations with multiple constraints. It has been proven in [36] that any multiple constraints with two or more type 1 and/or type 2 constraints are NP-complete; otherwise, they are tractable. As stated earlier, approximation methods exist for QoS constraints that are NP-complete. *Sequential filtering* is a commonly used approach, where multiple paths between two nodes u and v that satisfy a single metric first (such as bandwidth) are found, then a subset of these paths is eliminated by optimizing over a second metric (such as end-to-end delay), and so on.

In MANETs, high node mobility resulting in frequent topology changes can make satisfying QoS requirements unreachable. Consequently, it is required that the network be *combinatorically stable* in order to achieve QoS support[37]. This means that the changes in network topology must be slow enough to allow the topology updates to propagate successfully as required in the network.

QoS support of MANETs requires availability of network state. However, due to mobility and constant topology changes, the cost of maintenance of the network state is expensive, especially in large networks. In [38] the *imprecise network state model* is introduced. It provides a cost-effective method for providing QoS support based on imprecise network information. The majority of QoS routing protocols are reservation-based. Probe messages are sent through the network from the source to the destination in order to discover and reserve paths that satisfy a given QoS requirement. Due to the dynamic nature of the network, reserved QoS paths must be reaffirmed periodically by sending special control packets, called *refreshers*, along the path. Another approach, called *soft state*, relies on periodic time out at each node for path maintenance.

In addition, due to the difficulty of QoS support in the inherently dynamic environment of MANETs, some more "compromising principles" have been presented; *Soft QoS* and *QoS adaptation*. Soft QoS[39] indicates that there may be transient periods of time during which the QoS specifications are not honored. However, the QoS satisfaction is quantified by the total disruption time over the total connection time. This ratio must be above a specified threshold in order to fulfill the QoS requirements. In the *fixed-level QoS* approach, the reservation is defined in an n-dimensional space where the coordinates define the characteristics of the service[40]. On the other hand, QoS adaptation introduces the concept of *dynamic QoS*, where a range of QoS values, rather than a single point, is allowed to be specified by the application. This must be done through appropriate, flexible, and simple user interface which effectively maps the perceptual parameters into QoS constraints. The use of dynamic QoS provides more flexibility to the system and gives the network the ability to adjust the allocation according to the current availability of the required resources. The higher networking layers can then adapt to these changes. This adaptation can be achieved in different ways at different layers of the architecture. The physical layer, for example, can adjust the transmission power to react to more frequent bit errors. The link layer can incorporate more error control (detection and correction) codes as well as automatic repeat requests (ARQ) in reaction to changes in link error rates.

At the other end of the OSI stack, namely the application layer (multimedia video conferencing for example), different compression techniques with varying compression ratios can be employed to adapt the application to the changes in bandwidth, delay, and error rates without drastically compromising the perceived audio and video quality. As more resources become available, the quality of the presentation can then be adjusted to take advantage of the added resources. In addition to compression algorithms, other techniques are being investigated at this level including layered encoding, rate shaping, adaptive error control, and bandwidth smoothing.

It is important at this point to state that the QoS model defines the general approach, goals, and framework for providing QoS support in a network. It does not specify a particular protocol, design, or implementation details. Providing QoS support is done at each of the layers of the OSI model starting from the application layer and ending with the physical layer. Various protocols and specifications such as QoS user interface, routing, signalling, resource reservation, and error checking, measuring, and correcting must work and coordinate together in a collaborative and complementary fashion in order to satisfy the QoS requirements of the underlying applications. In this section, we focus on QoS routing, which is one of the most critical components in providing QoS support in MANETs.

3.2 Compromising Principles and Layered QoS Support

Due to the difficulty of QoS support in the inherently dynamic environment of MANETs, some more "compromising principles" have been presented; *Soft QoS* and *QoS adaptation*. Soft QoS[39] indicates that there may be transient periods of time during which the QoS specifications are not honored. However, the QoS satisfaction is quantified by the total disruption time over the total connection time. This ratio must be above a specified threshold in order to fulfill the QoS requirements. In the *fixed-level QoS* approach, the reservation is defined in an n-dimensional space where the coordinates define the characteristics of the service[40]. On the other hand, QoS adaptation introduces the concept of *dynamic QoS*, where a range of QoS values, rather than a single point, is allowed to be specified by the application. This must be done through an appropriate, flexible, and simple user interface which effectively maps the perceptual parameters into QoS constraints. The use of dynamic QoS provides more flexibility to the system and gives the network the ability to adjust the allocation according to the current availability of the required resources. The higher networking layers can then adapt to these changes. This adaptation can be achieved in different ways at different layers of the architecture. The physical layer, for example, can adjust the transmission power to react to more frequent bit errors. The link layer can incorporate more error control (detection and correction) codes as well as automatic repeat requests (ARQ) in reaction to the changes in link error rates.

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4 Overview of QoS Routing Protocols

A critical component in providing QoS support in MANETs is the routing algorithm. The chosen routing algorithm must discover and reserve routes that meet certain constraints between source and destination nodes. This QoS constraints include bandwidth, delay and delay jitter, and error rate. In addition, such routes must be as stable and as reliable as possible in order to satisfy the stringent requirements of QoS in multimedia and real time applications.

At the network layer, QoS support can be categorized into three categories which differ depending on the means of providing such support[41]. 1) *QoS routing protocols*: where QoS requirements such as bandwidth and delay are included into the route discovery process. This approach offers the ability to provide more robust QoS support, since this support is designed to be an inherent part of the routing protocol. 2) *QoS signalling*: where reservation and release of resources is done at a signalling layer above the routing protocol. By using this strategy, the QoS reservation and maintenance mechanism is decoupled from the routing protocol. This provides the signalling mechanism with the ability to work with different routing protocols and allows it to include more admission control and flow management features in a simpler manner. However, this comes at the price of more overhead, which naturally comes with the additional layer. INSIGNIA[22–24] uses this strategy. 3) *Coupling between the QoS mechanism and the routing protocol*: this is a compromise between the first two approaches. The signalling protocol provides feedback to the routing algorithm about the QoS status of the route and can ask the routing protocol for alternative routes if the current one does not meet the QoS requirements. INORA (INSIGNIA+TORA)[22–24,41] is an example of such protocols. Subsequently, in this section several QoS support protocols are presented. Although protocols of the second and third categories are mentioned, more focus is applied to the protocols in the first category.

From a routing algorithm perspective, QoS routing protocols that exist in the literature are based on their classic best-effort counterparts. These routing algorithms belong to one of three categories: 1) Reactive (on-demand) such as DSR (Dynamic Source Routing), AODV (Ad hoc On Demand Distance Vector), and TORA (Temporally Ordered Routing Algorithm); 2) Proactive (table-driven) such as DSDV (Destination Sequenced Distance Vector); and 3) Hybrid such as ZRP (Zone Routing Protocol) which groups nodes into geographic zones. It is proactive between nodes within individual zones and reactive between zones.

4.1 Extensions of DSR

Examples of QoS routing protocols which represent extensions of the DSR algorithm are the following. Liao and Tseng *et al.*[13] present a DSR-based routing protocol for TDMA networks which reserves a QoS path with a certain amount of required bandwidth using a slot reservation mechanism. Jawhar and Wu[32] extend this protocol to improve its performance by solving racing conditions and including other optimizations. Liao and Tseng *et al.*[33] also present a ticket based routing algorithm which allows an intermediate node to extend the route request using multiple links with its neighbors if no single link has enough bandwidth to satisfy the request. Also, Zhu *et al.* in [42] present a Five-Phase Reservation Protocol (FPRP) for QoS support in synchronous TDMA-based MANETs. FPRP performs the tasks of channel access and node broadcast scheduling simultaneously.

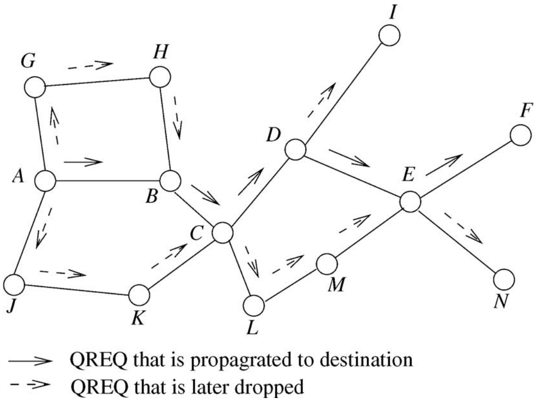


Fig.2. QoS-AODV — Propagation of RREQ message from source node A to destination node F.

4.2 Extensions of AODV

Other QoS routing protocols represent extensions of AODV. Gerasimov *et al.* present a protocol named QoS-AODV in [9, 10]. This protocol includes bandwidth calculation in the route discovery mechanism. Each node keeps a *schedule* containing information about the time slot reservation status of its neighbors. The authors include modified AODV HELLO messages which contain slot reservation information. An example of QoS-AODV route discovery is shown in Fig.2. The route request

(RREQ) message is forwarded only if the required bandwidth is available at each link with each node considering its own slot information as well as that of its one-hop and two-hop neighbors. At each intermediate node, the RREQ message is augmented with QoS bandwidth information. The destination sends an RSV message to the source to confirm slot reservation. The algorithm uses a URSV message to release slot resources in case of multiple reservations at intermediate nodes due to race conditions. In [43], Zhu *et al.* present an AODV-based QoS routing protocol in TDMA networks. It incorporates an algorithm for calculating end-to-end bandwidth on a path. It uses soft-state timers to release slot reservations if the route is not constantly used to send data.

4.3 Extensions of TORA

Another category of QoS routing protocols comprises extensions of the famous link reversal routing algorithm TORA. Gerasimov *et al.* present a protocol named QoS-TORA for TDMA networks. In this protocol the source first establishes a best-effort route to the destination and then uses it to send a bandwidth query (BQRY) message with the number of required slots. The destination then broadcasts an update bandwidth (UBW) message that contains the number of slots required. Intermediate nodes forward the UBW message to the source if enough bandwidth is available. In doing so they consider the reservation information of their own slots as well as those of their 1-hop and 2-hop neighbors. The source node receives all UBW messages and can decide which path to use. The multiple paths received by the source give QoS-TORA more flexibility than QoS-AODV, which only allocates one path, in case of link breakage. Fig.3 shows the propagation of the BQRY and UBW messages between the source and destination nodes. Simulation results show that QoS-TORA provides higher throughput than QoS-AODV in cases of higher mobility.

In [41] Dharmaraju *et al.* present another TORA-based QoS routing protocol for MANETs called INORA. INORA is a network layer QoS support mechanism that makes use of the INSIGNIA in-band signaling mechanism and the TORA routing protocol for MANETs. The signaling layer is loosely coupled with the TORA routing protocol. Feedback about the QoS status of the existing route is used by the signaling layer to provide admission control and management of the data flows in the network. INORA may ask the routing protocol, TORA, for another route if the QoS measurements of the current route do not meet the QoS requirements of the application. Periodic as well as on-demand QoS reporting provides end-to-end status information about the current route (e.g., bandwidth indicator) and measured delivered QoS (e.g., packet loss, throughput) to the source. The latter can then downgrade a current route from reserved to best-effort if this is allowed by the application. INORA can also use the flow status information to provide load balancing control for data flows in the network.

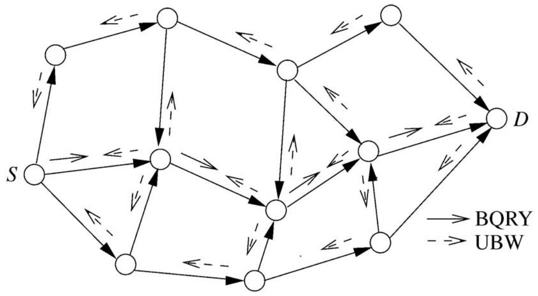


Fig.3. DAG in the QoS-TORA protocol. The figure shows the propagation of the BQRY message from the source node, S, to the destination. The destination node, D, responds with the UBW message which contains the application ID, number of slots, and source node ID.

In [44], Gupta *et al.* propose a network layer protocol that represents an extension of the INSIGNIA protocol discussed earlier. It provides for a localized link repair mechanism that can be used with 802.11 or other link layer protocols that provide link failure information to the upper layers of the network.

4.4 Extensions of DSDV

In [45], Lin introduces the MACA/PR (Multiple Access Collision Avoidance with Piggy-back Reservation) protocol. It is an asynchronous network based on the collision avoidance MAC scheme used in the IEEE 802.11 standard. MACA/PR avoids collisions due to the hidden terminal problem by establishing an RTS-CTS (request to send - clear to send) dialogue. MACA/PR uses an extension of the DSDV protocol for QoS routing. As shown in Fig.4, the protocol defines a *cycle* to be the maximum interval allowed between two real-time packets. The first data packet in a multimedia stream uses an RTS-CTS exchange and reserves the path for all subsequent data packets. The RTS and CTS messages specify the length of the data packet. The ACK packet serves the purpose of renewing the reservation along a link and blocking the neighboring nodes from transmission during the specified reserved time. Each node maintains a reservation table, which keeps track of transmit and receive reserved windows of all stations within range. During route establishment only links with the required bandwidth are used.

In [46], Manoj *et al.* propose a MAC layer protocol

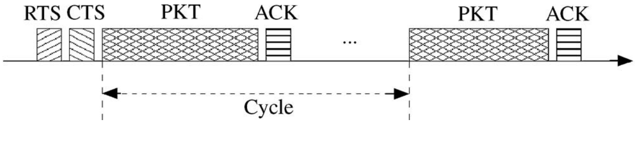


Fig.4. MACA/PR protocol: RTS-CTS-PKT-ACK$\cdots$PKT-ACK sequence. A *cycle* is the maximum interval allowed between two real-time packets.

Table 1. QoS Routing Algorithm Classification

QoS routing	Net. Layer	Syn./ Asyn.	Comm. Mode	BE Routing	React./ Proact.	Comments
Gerasimov *et al.*[9]	net./MAC	syn.	TDMA	AODV	react.	QoS-AODV.
Gerasimov *et al.*[10]	net./MAC	syn.	TDMA	TORA	react.	QoS-TORA.
Ho *et al.*[47]	net.	syn.	TDMA	ODQoS	react.	ODQoS (On-demand QoS-based routing protocol).
Liao *et al.*[13]	net.	syn.	TDMA	DSR	react.	QREQ from source to dest. allocating slots. QREP from dest. to source reserves slots.
Liao *et al.*[33]	net.	syn.	C-o-T or FDMA	DSR	react.	Multi-path QoS (ticket-base) routing.
Manoj *et al.*[46]	MAC	asyn.	N/A	DSDV	proact.	Ext. of 802.11 DCF function.
Lin[45]	MAC	asyn.	N/A	DSDV	proact.	Flexible reservations within a cycle.
Lin *et al.*[48]	MAC	asyn.	C-o-TDM	N/A	react.	CDMA-over-TDMA. Each cluster has different code.
Lin *et al.*[49]	net.	syn.	C-o-T	DSDV	proact.	Destination does calculate of the path BW.
Lin[50]	net.	syn.	C-o-T	DSR	react.	RREQ packets to find paths and calculate BW.
Sheu *et al.*[51]	MAC	asyn.	N/A	Lower level	react.	Compliant with 802.11. RTS-CTS-Asyn. Data-ACK channel access.
Wang *et al.*[52]	net.	syn.	N/A	QRMP (DSR-like)	react.	QoS routing with mobility prediction.
Dong *et al.*[53]	net.	gen.	gen.	SRL (DSR-like)	react.	Supernode-based Reverse Labelling Algorithm.
Zhu *et al.*[43]	net.	syn.	TDMA	AODV	react.	BW calculate integrated with AODV protocol.
Dharmaraju *et al.*[41]	net.	gen.	gen.	TORA	react.	INORA: Uses signalling done at higher level than routing.
Gupta *et al.*[44]	net.	gen.	gen.	TORA	react.	Extension of INSIGNIA.
Zhu *et al.*[42]	net.	syn.	TDMA	FPRP (DSR-like)	react.	Five-phase reservation protocol.

gen.: general, it also indicates applicability to all cases of that classification (higher level); C-o-T: CDMA-over-TDMA; C-o-TDM: CDMA-over-TDM.

named Real-Time MAC (RTMAC) for MANETs, which extends the MACA/PR protocol discussed earlier. The protocol divides the transmission time into successive super-frames. It relies on the flexibility of placement of reservation slots (of variable start and finish times) and the use of holes (short free slots which otherwise cannot be utilized) within the super-frame. The protocol applies different schemes such as first fit and best fit to reserve slots for sending data, which are named connection-slots.

4.5 Summary of QoS Routing Protocols

In addition to the categories mentioned above, there exist other protocols which are not direct extensions of DSR, AODV, TORA, and DSDV. Table 1 contains a classification of the current QoS routing protocols in the literature. The table contains the following columns. First the QoS routing protocol is listed. Then, "Net. Layer" column indicates the networking layer within which the protocol is designed to operate. The "Syn./Asyn." column indicates whether the protocol operates within a synchronous or asynchronous environment. The "Comm. Mode" column indicates the communication network assumed such as TDMA, CDMA-over-TDMA, and so on. The "BE Routing Prot." column indicates the best effort routing protocol that is extended by or is most closely related to the corresponding QoS protocol. The "Proact./React." column indicates whether this QoS protocol is reactive (on-demand) or proactive (table-driven). Then the "Comments" field contains additional information about the QoS protocol. There are other parameters which can also be considered, such as whether or not a protocol is location assisted, which were not included in the table. More information about these protocols and their classification can be found in [17]. In subsequent sections in this paper some of the routing protocols for TDMA-based wireless networks are discussed in more detail.

5 QoS Routing Protocols for TDMA-Based Wireless Networks

In this section, a DSR-based on-demand QoS routing protocol designed by Jawhar and Wu[32] is presented. This protocol extends an earlier version presented by Liao and Tseng[13]. The implementation of the protocol assumes a TDMA synchronous networking environment. In this network, communication between nodes is done using a synchronous TDMA frame. The TDMA frame is composed of a control phase and a data phase[12]. Time synchronization is not addressed in this paper. This can be achieved by either: (a) listening to network data traffic and aligning time slots accordingly (align to the latest starting point of a complete packet transmission by 1-hop neighbors); or (b) using external sources, such as GPS (Global Positioning System) timing signals[54].

5.1 Basics

Fig.5 shows the TDMA frame structure for a TDMA network (or a TDMA cluster) of N nodes. Each node in the network has a designated control time slot (control slots 1 through N in this example), which it uses to transmit its control information, but the nodes in the network must compete for use of the data time slots (data slots 1 through M in this example) in the data phase of the frame.

The TDMA environment is a single channel model. This model is generally practical and less expensive because only a relatively simple transmission mechanism and antenna design are needed. However, this model imposes on the designer the constraints of the hidden terminal and exposed terminal problems. The routing protocol must account for these problems and on one hand have appropriate mechanisms to avoid hidden terminal interference, and maximize channel reuse by taking advantage of the exposed terminal transmissions on the other hand. Consider the example in Fig.6(a). A *hidden terminal* problem in a wireless environment is created when two nodes which are out of range of each other, B and C for example, transmit to a third node A, which can hear them both. This creates a collision of the two transmissions at the "middle node" A. An *exposed terminal* is illustrated in Fig.6(b). Nodes A and C can still transmit to nodes B and D, respectively, even though they are exposed to each other's transmissions.

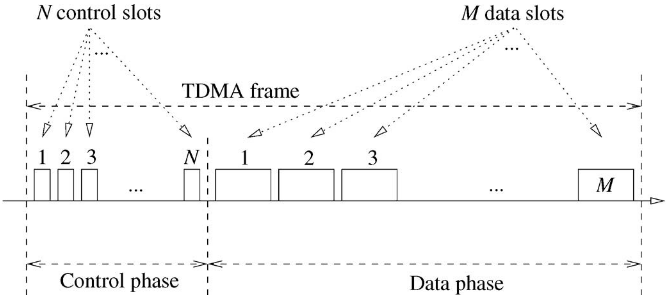


Fig.5. Structure of a TDMA frame for a network of N nodes and M data slots per frame. Each node has a fixed control slot. Nodes compete over the use of data slots.

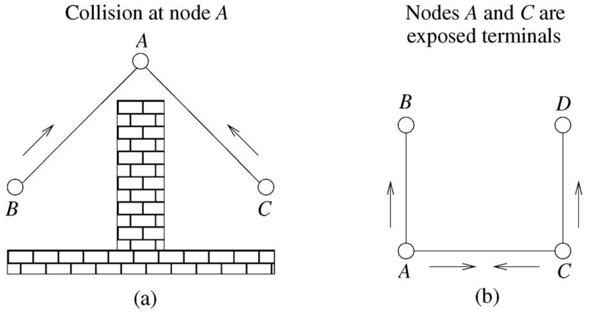


Fig.6. (a) Hidden terminal problem creating a collision at node A. (b) Exposed terminal problem. Nodes A and C are transmitting to nodes B and D, respectively, and are exposed to each other's transmissions.

In order to prevent interference in the TDMA environment, a time slot t is considered free to be allocated to send data from a node x to a node y if the following conditions are true[13]:

1) slot t is not scheduled for receiving or transmitting in neither node x nor y;

2) slot t is not scheduled for receiving in any node z that is a 1-hop neighbor of x;

3) slot t is not scheduled for sending in any node z that is a 1-hop neighbor of y.

5.2 Overview of a TDMA-Based QoS Routing Protocol

The following is an overview of the protocol presented by Jawhar and Wu[32]. When a source node S wants to reserve a QoS path to send data to a destination node D, it sends a QREQ message that includes the number of slots (bandwidth), b, required for the requested QoS path. If and when the QREQ message reaches node D, this means that there was a QoS path from S to D which was discovered, and there were at least b free slots to send data from each node to each subsequent node along the discovered path. These slots are now marked as *allocated* in the corresponding nodes. In this case, node D unicasts a QREP reply message to node S. This message is sent along the nodes in the allocated path. As the QREP message propagates back to the source node, all of the intermediate nodes along the path must confirm the reservation of the corresponding allocated slots (i.e., change their status from *allocated* to *reserved*). The timing and propagation of the QREQ and QREP messages are controlled by timers, a queueing process, and synchronous and asynchronous slot status broadcasts, which are discussed in detail in [32]. In addition, the destination broadcasts a deallocation message which will cause all of the nodes that allocated slots that were not a part of the final discovered path to free up these slots. Compared to the method of having the allocation of the slots simply time out, this method is more effective since it quickens the deallocation of unused slots to increase slot utilization and network efficiency.

5.3 Detailed Example of the Slot Allocation Process

The process of reserving slots at a node for a particular path is not trivial. In determining which slots can be allocated, the node must take into account each slot's allocation status in its 1-hop and 2-hop neighbors, and make sure that the slot allocation rules specified earlier are observed. In order to illustrate the slot allocation process, consider the example in Fig.7. Node A wants to reserve a QoS path to node F with $b = 3$ (i.e., 3 slots). Node A sends a QREQ message to reserve the path. The QREQ message travels through the nodes on its way to F and arrives at node C. Node C will now try to allocate slots for this QREQ message to send to each of its 1-hop neighbors, if there are b slots available to send from itself to this neighbor.

Let us consider the process of calculating the number of slots available to send from node C to its 1-hop neighbor, node D. Node C has slot allocation information for itself and for all of its 1-hop and 2-hop neighbors including node D, since each node is required to notify its 1-hop and 2-hop neighbors of the allocation status of its slots. Node C realizes that it cannot allocate slots 1, 2, 5, 7, and 8, because they are scheduled by nodes C and D to send or receive (slot allocation rule 1). It cannot use slots 3 and 4 because they are scheduled to receive in its 1-hop neighbors, nodes B and G, respectively (slot allocation rule 2). Furthermore, node C cannot use slot 10, because it is scheduled to send in node E, which is a 1-hop neighbor of the node it intends to send to, node D (slot allocation rule 3). However, node C can use slot 6 to send to node D even though it is scheduled to send in node B. This is the exposed terminal problem. In fact, it would be more desirable for node C to allocate this slot to send to node D; this would increase channel reuse, a desired goal in wireless communications. Node C can also use slot 9 even though it is being used to send from node I to node H, since this does not violate any of the slot allocation rules. Consequently, there are 6 slots that are available to be used to send data from node C to node D (slots 6, 9, and 11–14). Since the QREQ message only needs 3 slots, node C is able to forward the QREQ message to node D.

Assume that, after the calculation above, node C allocates slots 6, 9, and 11 to send from itself to D, and broadcasts the QREQ message. In [13], node C does not keep track of this allocation, which is only remembered in the forwarded QREQ message. So, until node C receives the corresponding QREP message from the destination F, slots 6, 9, and 11 will remain *free*. They will only change status from *free* to *reserved* when and if the corresponding QREP message arrives from node F on its way to node A to confirm the slot reservations of the QoS path $A \to \cdots \to B \to C \to D \to E \to \cdots \to F$. This poses no problem so long as no other requests arrive at node C during the period between forwarding the QREQ and receiving the corresponding QREP message. However, consider a situation where, during this period, another request arrives at node C from another source node J trying to reserve a QoS path from itself to node K with $b = 5$. Node C in this case will look at its slot status tables and will see no allocations for slots 6, 9, and 11–14. In [13], node C will proceed to reserve some of these slots for this newly requested path causing *multiple reservations* of the same slots for different paths. This is a race condition which results in data collisions at node C during the data transmission phase.

A simplified and generalized representation of this problem is shown in Fig.8(a), where the two different QoS paths $A \to \cdots \to B \to \cdots \to C \to \cdots \to D \to \cdots \to E \to \cdots \to F$ and $G \to \cdots \to B \to \cdots \to H \to \cdots \to C \to \cdots \to I \to \cdots \to E \to \cdots \to J$, are being reserved simultaneously. The two paths pass through common nodes B, C, and E leading to race conditions. The paper in [32], presents another possibility of a race condition which is due to a *parallel reservation problem*. An example of this race condition is shown in Fig.8(b). In this case, we have two parallel paths, $A \to \cdots \to B \to \cdots \to C \to \cdots \to D \to \cdots \to E \to \cdots \to F$ and $G \to \cdots \to H \to \cdots \to I \to \cdots \to J \to \cdots \to K$, that are being reserved by request messages QREQ1 and QREQ2 respectively. Intermediate nodes B and E, of the first path, are 1-hop neighbors to nodes H and J, of the second path, respectively. Here a similar race condition will take place when the $QREQ1$ message arrives at node B and later at node E allocating the required number of slots, which are still considered free until $QREP1$ arrives. In the meantime slots can be allocated by nodes H and J for the $QREQ2$ message with the assumption that the slots allocated at nodes B and E for $QREQ1$ are free. It is easy to see that this situation can lead to a race condition which will create interference when data transmission is done later along the two "parallel" paths.

In [32], a protocol is proposed to solve the race conditions described earlier and enhance network performance. The protocol uses a more conservative strategy. This strategy is implemented using the following features: 1) Three states for each slot that are described earlier: *reserved*, *allocated*, and *free*. 2) Wait-before-reject at an intermediate node with three conditions to

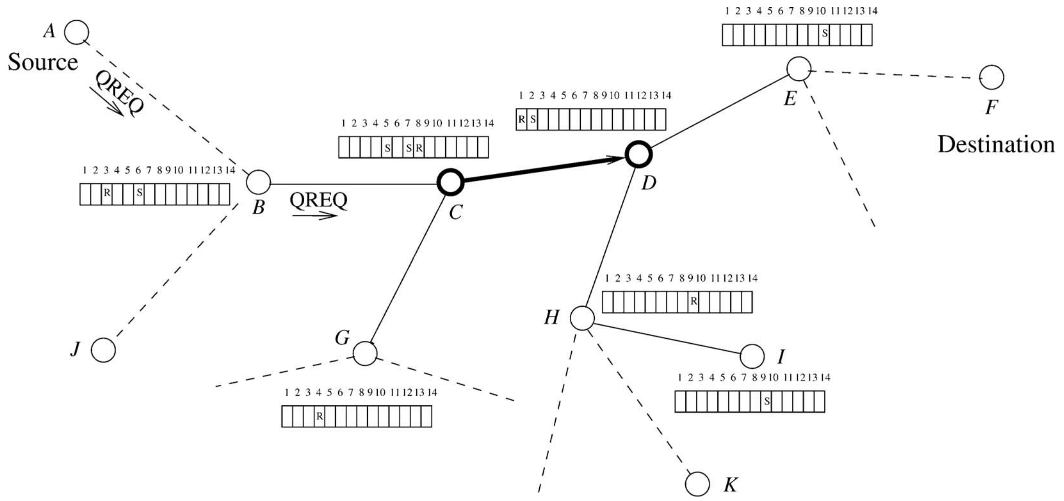
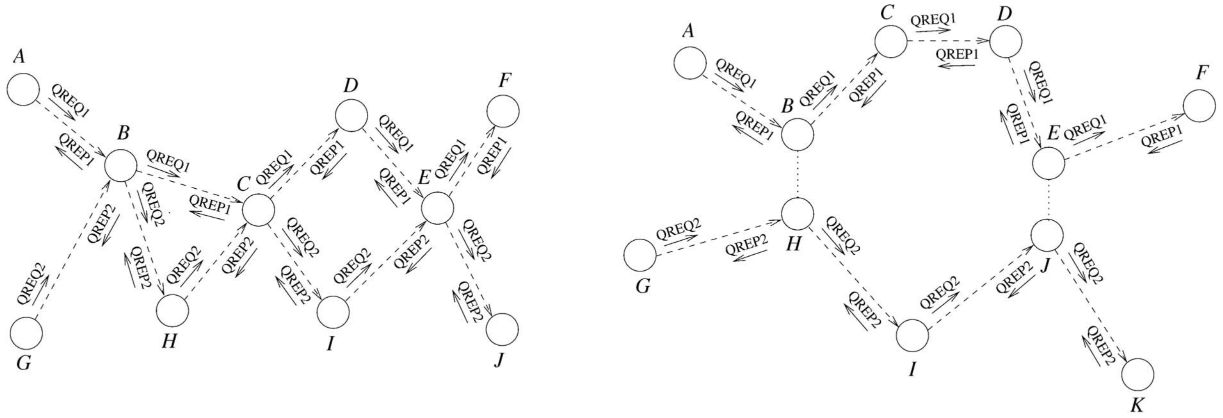


Fig.7. Illustration of the slot allocation procedure being done to determine the slots that are available to send data from node C to node D for a QREQ message arriving at node C. The figure shows the slot reservation status before the arrival of the QREQ message at node C. (R: scheduled to receive. S: scheduled to send. Empty: not scheduled to receive or send.)



(a) (b)

Fig.8. (a) Race condition of two QoS paths passing through common intermediate nodes. (b) Race condition of two parallel QoS paths passing through 1-hop neighbors.

alleviate the multiple reservation at intermediate node problem. (*conditon* 1: all required slots are free, *condition* 2: wait for allocated slots to become free, and *condition* 3: immediately drop or reject QREQ because not enough free or allocated slots are available). 3) TTL timer for allocated and reserved slots. 4) TTL timers for maximum total QREQ propagation delay allowed, and for maximum total QREQ/QREP delay allowed (i.e., maximum QoS path acquisition time).

5.4 Dynamic Bandwidth Reservation Protocol

In [55], Jawhar and Wu present a dynamic range bandwidth reservation protocol for wireless networks. It is an on-demand and source-based protocol for MANETs operating in the TDMA environment. In this protocol, a source node S, which needs to send data, sends a request message (QREQ) to reserve a QoS path to the desired destination node D. In the reservation message, the source node specifies a dynamic range $[b_{\min}, b_{\max}]$ of the number of slots needed to transmit the data. The intermediate nodes along the path try to reserve a number of slots, $b_{\rm cur}$, that is equal to the maximum number of slots that are "available" within this range ($b_{\min} \leq b_{\rm cur} \leq b_{\max}$).

The protocol also permits intermediate nodes to dynamically "downgrade" existing paths that are functioning above their minimum requirements in order to allow the successful reservation of the maximum number of requested paths. When the network traffic load is later decreased, the existing paths are able to be "upgraded" to function with higher bandwidth allowances that are close or equal to the maximum desired level ($b_{\max}$). The advantages of this added flexibility are: 1) It provides the network with an ability to adapt the resource reservation process to its traffic load conditions. 2) It provides a higher probability of successful allocation of the requested QoS path, and allows for better resource sharing, balancing, and utilization. 3) It provides means for *graceful degradation* of multimedia or real-time applications during periods of high network traffic.

6 Additional Issues for QoS Support in TDMA-Based MANETs

In this section, additional issues and investigations related to QoS support in TDMA-based MANETs are presented.

6.1 Selection and Use of Multiple Routes for More Reliability

In the routing protocols described earlier, when the destination receives QREQ messages, it only replies to the first one. In this process, one can consider several optimizations and improvements as follows. 1) Destination or source based selection of routes. The destination or the source can apply certain criteria to select one or more of the discovered routes when it successfully receives multiple QREQ/QREP messages. In addition to the primary route, secondary routes can be used for backup. The number of backup routes can also be a parameter that is proportional to the priority of the application, which could be a real-time application that cannot afford the delay incurred by a new route discovery phase, caused by failure of the current QoS path. 2) Combining the selection of routes with the prediction of link and route failure. As a result, the routing mechanism can switch to backup routes before the current path is broken.

6.2 Ticket-Based Forwarding of QREQ and Closed-Loop Feedback Control of Slot Allocation

During the route discovery phase of the protocol, an intermediate node allocates slots and propagates the QREQ message to all of its "capable" neighbors (neighbors to which it has a link with the required number of slots). Since the states of the corresponding slots are changed from *free* to *allocated* this can reduce slot utilization. In order to better control the allocation process, each intermediate node would only extend the QREQ message to a maximum of k capable neighbors. The parameter k can be specified by the application, or it can be a network parameter that is determined by simulation. Furthermore, the choice of which k neighbors would be considered to extend the searched path can be optimized based on certain criteria favoring nodes and links with characteristics such as: nodes with more available slots, less mobile nodes, links with less error rates, and more "reliable" links (which can be defined in different ways). Additionally, the parameter k can be dynamically changed by the source depending on the success rate of previous route discoveries. This success rate would be compiled, maintained, and communicated by the destinations. If previous searches had a higher success rate, the source can decrease k for better slot utilization. On the other hand, if the previous path reservations had a lower success rate, then k can be increased to enhance the probability of successful route discovery in future searches. In effect this establishes a *closed-loop feedback* mechanism which can be used to enhance the efficiency and robustness of the route discovery process and improve network performance.

6.3 Expanding Ring TTL for Route Discovery

Research can also investigate TTL-based expanding ring search to find and reserve QoS paths. This strategy can be used to control the amount of path request messages (QREQ) that are flooded through the network in the discovery phase. The source would first initiate route discovery with a relatively small TTL (in number of hops). After a time out period, another QREQ is sent with a higher TTL value. The TTL value could be increased exponentially or arithmetically, until either a path is found or a total flood is used in the worst case. This process would also control the length of the discovered path which affects the amount of end-to-end delay in the data transmission phase. The trade off in this case is as follows. A smaller initial TTL value and/or smaller subsequent increases would limit the number of slot allocations in the discovery phase, but would increase the probability of successful reservation in each trial and the corresponding QoS path acquisition time. On the other hand, a larger initial TTL value and/or larger subsequent increases would cause more slot allocations to be done in the discovery process, but would also decrease the path acquisition time. Either strategy can be deployed depending on the requirements and limitations of the application layer and user selectable parameters. It is also possible to dynamically adjust these values based on a measured feedback of path acquisition success rate as described earlier.

6.4 Traffic Differentiation and Prioriterization

In order to improve QoS support for higher priority traffic, MANET QoS protocols can use traffic differentiation and prioriterization techniques that are similar to those used in wired networks with adjustments and adaptations for the wireless environment. The priority level can be implemented and used in different manners. For example, during the route discovery process higher priority routes can be allowed to preempt existing lower priority routes or cause them to be downgraded to successfully reserve new QoS paths. A protocol that uses this strategy for TDMA-based MANETs was presented earlier[55]. Furthermore, research can identify applications that can survive a small disconnection time (maximum allowable disconnection time) in case the current QoS path is broken and a new path is able to be discovered before a predetermined time out period. The quality of service in this case can be the average amount of bandwidth used within a certain amount of time or the percentage of the time during which the application has a valid connection.

6.5 Investigation of QoS Delay Parameters

Delay constraint is also one of the important QoS parameters that many applications such as multimedia audio and video have. Protocols can incorporate several delay related parameters, features, and controls into their QoS support components. The following are some items that can be considered. Research could investigate the use of algorithms to minimize end-to-end delay (EED) of data transmission by "intelligent" allocation of the slots, according to their positions in the TDMA frame. Some research has been done in this area[56], but more possibilities can be considered. Specifically, EED can be one of the QoS related constraints that are incorporated into the path discovery process. This can be done by including it in the QREQ message that is initiated by the source. As the QREQ message propagates through the nodes to the destination, each intermediate node calculates the current EED by adding the accumulated EED to its own. If the calculated EED is higher than the required EED, then the message is dropped. Otherwise, the node forwards the QREQ message with the accumulated EED in it. Also, the EED consideration can be done before queueing the QREQ message at an intermediate node to wait for slots to be freed[32]. In this case the protocol would consider the positions (and corresponding EED) of the allocated slots for which the QREQ message is waiting (to be converted to free status) before queueing the QREQ message. In addition, positions for slots used in different QoS paths can also be changed dynamically as QoS routes are being discovered, maintained, and released in order to better fit the EED requirements of the corresponding sessions.

6.6 QoS Support in Heterogeneous MANETs

Many MANET environments have heterogenous nodes and links. For example, nodes can be personal mobile computer systems (typically with limited battery power, transmission range, etc.), vehicular systems (typically with more power, bandwidth, transmission range, and wider range of mobility, etc.), airplane borne systems of different types, or satellites. In such an environment QoS path selection should favor nodes which have: 1) more reliability (measure and maintain a reliability factor for each node); 2) more power (to save power consumption in limited power nodes); 3) longer range (to minimize the number of hops); 4) more bandwidth; 5) less mobility leading to smaller probability of link failure (measure and maintain a mobility factor for each node); 6) smaller error rates (error rate measurement and maintenance should be done in each node). We can also consider the proper geographic deployment of more stable, powerful nodes (move-and-stop nodes placed on mobile systems such as vehicles, etc.) among more mobile ones to provide a higher degree of QoS support, which might not even be possible otherwise due to certain factors such as high node mobility or high error rates.

6.7 Directional Antennas in MANETs

Another emerging area of research is the use of directional antennas in MANETs. This is a very exciting and promising approach which allows for maximizing the spacial reuse of the precious wireless medium. Several researchers have done some work in this area[54,57–60]. In [54] Bao *et al.* present a protocol for transmission scheduling in MANETs using directional antennas. In the model used by the authors, each node can transmit or receive using k different directional antennas. Each antenna has a coverage angle defined by a beam width β. The horizon seen by a node is evenly divided into $360/(\beta/2) = 720/\beta$ segments. Every two adjacent segments define one group. A group corresponds to the coverage of a directional beam from the node, and a segment (half a group) determines the minimum angular separation of two neighbors for receiving non-interfering individual antenna beams. Consequently, $720/\beta$ groups are identified. This segement/group information is used by the nodes to keep track of the angular location of their one-hop neighbors and must be used during the route discovery and data transmission phases in addition to the slot reservation information.

The basic spacial reuse advantage provided by directional antenna systems is based on the following fact. In the omnidirectional TDMA environment, a slot that is used to transmit data to a 1-hop neighbor, y, of a node x cannot be used to transmit to other one-hop neighbors of x. However, in the directional antenna TDMA environment, the same slot can be used to transmit data by x to one or more of its other 1-hop neighbors as long as these neighbors do not belong to the same angular group as y, or each other (relative to x). The distributed protocol described in [54] allows each node to determine the slots that can be used to send and receive in the TDMA frame without the possibility of interference. Although other researchers have presented additional protocols that can be used in this environment, much research is still needed to explore the exciting possibilities in this area. We are currently working on a slot reservation protocol for directional antenna TDMA wireless networks.

7 Conclusions and Future Research

As wireless networks and devices continue to proliferate and penetrate all aspects of communications in the twenty-first century, providing support for multimedia and real time applications becomes an important function of the underlying communications protocols. This is done by requiring such protocols to provide QoS guarantees that satisfy the stringent requirements imposed by these applications. In this paper, we discussed QoS support in wireless networks. After presenting a graph-theoretic background, QoS routing protocols in MANETs in general and specifically in the TDMA-based MANETs were classified and discussed. Additional issues for QoS support in TDMA-based MANETs were presented.

The issue of QoS support in MANETs is important, and challenging. This research is and will remain to be an essential and crucial component in the communication field and especially in the next generation of wireless networks and applications.

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