QoS routing with traffic distribution in mobile ad hoc networks

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ARTICLE INFO

Article history:
Received 26 May 2008
Received in revised form 22 October 2008
Accepted 26 October 2008
Available online 9 November 2008

Keywords:
Quality of Service
Routing
Mobility
Link prediction
Load balancing
Mobile ad hoc networks

ABSTRACT

Mobile ad hoc networks (MANETs) follow a unique organizational and behavioral logic. MANETs’ characteristics such as their dynamic topology coupled with the characteristics of the wireless communication medium make Quality of Service provisioning a difficult challenge. This paper presents a new approach based on a mobile routing backbone for supporting Quality of Service (QoS) in MANETs. In real-life MANETs, nodes will possess different communication capabilities and processing characteristics. Hence, we aim to identify those nodes whose capabilities and characteristics will enable them to take part in the mobile routing backbone and efficiently participate in the routing process. Moreover, the route discovery mechanism we developed for the mobile routing backbone dynamically distributes traffic within the network according to current network traffic levels and nodes’ processing loads. Simulation results show that our solution improves network throughput and packet delivery ratio by directing traffic through lowly congested regions of the network that are rich in resources.

1. Introduction

The emergence of real-time and multimedia applications and the widespread use of wireless and mobile devices have generated the need to provide Quality of Service (QoS) support in wireless and mobile networking environments [7]. Unfortunately, attempts to adapt QoS solutions developed for the Internet do not generally have great success [5,7]. This is due to the fact that Internet-based solutions were not designed to cope with constraints such as user mobility, high-error rates and scarce bandwidth found in the wireless communication environment. Moreover, over-provisioning as it is done in wired networks by adding resources to the network to cope with increasing demand is not possible in the wireless environment where resources are constrained and finite. Hence, to achieve the goal of providing high-quality services in next-generation wireless networks, it is necessary to implement new techniques that can guarantee QoS when considering the limitations imposed both by the end-user and the network.

This paper presents a new approach called quality of service mobile routing backbone over AODV (QMRB-AODV) for supporting QoS in mobile ad hoc networks. Our method makes use of a mobile routing backbone to dynamically distribute traffic within the network and to select the route that can support best a QoS connection between a source and its destination. Nodes in real-life mobile ad hoc networks (MANETs) are heterogeneous and have different characteristics. Based on these characteristics, our solution classifies nodes in a MANET as either QoS routing nodes, simple routing nodes that route packets through the network without providing special service provisions or transceiver nodes, that send and receive packets but cannot relay them. A mobile routing backbone is created using all nodes having routing capabilities. QoS support is realized by relaying packets having special requirements to nodes rich in resources and connected through stable links. To avoid starvation of best-effort packets both types of routing nodes have forwarding capabilities. The main advantage of QMRB-AODV is a better use of the available bandwidth by distributing the traffic through the network and by reducing the number of control messages needed to establish a route from a source node to a destination node.

The remainder of this paper is organized as follows. Section 2 presents an overview of QoS in mobile ad hoc networks. Section 3 describes our approach to improve QoS support in MANETs, presents the QoS mobile routing backbone and the routing algorithm used to discover new routes in the network; the routing mechanism has been integrated in the AODV (ad hoc on-demand distance vector) protocol and its performance evaluated by simulation. Simulation and results are discussed in Section 4. Finally, Section 5 concludes the paper.

2. Quality of service in mobile ad hoc networks

QoS is a collection of characteristics or constraints that a connection must guarantee to meet the requirements of an application
A connection can be characterized by a set of measurable requirements such as minimum bandwidth, maximum delay, maximum delay variance (jitter), and maximum packet loss rate. After accepting a connection request from the user, the network has to ensure that the requirements of the user’s flow are met throughout the duration of the connection [5].

In a mobile wireless communication environment the problem of guaranteeing QoS to users or applications is more complex than in a wired communication environment. Furthermore, the characteristics of mobile ad hoc networks complicate QoS support: the communication medium is unreliable and error-prone, bandwidth is often limited which limits the use of control messages, nodes are free to join, move or leave the network at any moment, making the topology entirely dynamic and unpredictable, battery energy as well processing power are generally low [4,24]. Moreover, for the MANET to retain its efficiency, the protocols at various layers may need to self-tune to adjust to environment, traffic and mission changes [8].

QoS support may be provided in many ways and at different layers of the networking stack. In the link layer, QoS MAC (medium access control) protocols attempt to offer a fair access to the communication medium to frames having particular service requirements. Several approaches are presented in [1,20]. However, the support provided by MAC protocols is limited to the neighborhood where the medium is shared and hence, they cannot offer end-to-end QoS support.

At the network layer, routing protocols are the main mechanism. Best-effort routing protocols as found in the Internet aim to maximize network performance from an application point of view while minimizing the cost imposed on the network in terms of capacity. There are three classes for such protocols in mobile ad hoc networks. Reactive or on-demand routing protocols create a route between a source and the destination on a per-request basis and are generally well suited to a MANET’s dynamic topology. AODV is one of the best-known reactive protocols for ad hoc networks [4,10]. The protocol builds a route to a destination only if a source needs to reach it. Each mobile host operates as a router and routes are obtained as needed with little or no reliance on periodic advertisements. AODV provides loop-free routes even while repairing broken links. Because the protocol does not require global periodic routing advertisements, the demand on the overall available bandwidth is substantially less than in those protocols that necessitate such advertisements. Although AODV does not depend specifically on particular aspects of physical medium across which packets are disseminated, its development has been largely motivated by limited range broadcast media such as those utilized by infrared or radio frequency wireless communications adapters.

Proactive routing protocols are similar to their wired counterparts in the sense that they keep track of routes for all destinations in the network. The routing tables are periodically refreshed to take into account the dynamic behavior of the network. The two main drawbacks with this class of routing protocol are that it generates a high volume of communication overhead needed to keep the routing tables current with topology and they suffer poor routing performance when mobile nodes are highly mobile [4,34]. Indeed, proactive protocols fail to respond fast enough to highly dynamic topologies where route failures and changes occur frequently. Finally, there are position-based routing protocols that find routes through the network based on the geographical position of the destination. The position of the destination node can be found either using external information provided by GPS (global positioning system) or through triangulation-like techniques.

As effective as best-effort routing protocols are at finding routes, they cannot efficiently support QoS in MANETs. Indeed, these protocols, by definition, optimize network performance and are not designed to take into account the QoS required by each flow when searching for routes. Thus, efficient QoS support using best-effort protocols can be at best accidental even if resource reservation schemes are used. Abolhasan et al. [6] provide a recent review of routing protocols developed for the ad hoc paradigm.

QoS routing protocols create routes using nodes and links that possess the resources required to fulfill QoS requirements. In other words, this category of routing protocol identifies routes in the network that obey the constraints required by the source application and selects between these routes the one to be used [22]. Further, QoS routing protocols must work together with resource management mechanisms to establish routes through the network that meet end-to-end QoS requirements, such as delay, jitter, available bandwidth, packet loss rate, hop count and path reliability. Finally, routing protocols supporting QoS must also deal with route maintenance. Indeed, since nodes in MANETs are free to move there is a certain probability that route failures may happen due to node mobility.

In [3], Shengming et al. propose a new predictive link metric that can reduce the impact of node mobility on QoS routing. This new metric is integrated in a link caching scheme and implemented in the dynamic source routing (DSR) protocol to provide it with adaptability to changing topologies caused by user mobility. In [18], Shen and Heinzelman present a QoS-aware routing protocol that incorporates an admission control scheme and a feedback scheme to meet the QoS requirements of real-time applications. The novel part of this protocol is the use of the approximate bandwidth estimation to react to network traffic. The protocol implements these schemes by using two bandwidth estimation methods to find the residual bandwidth available at each node.

Du [2] proposes a QoS routing scheme for heterogeneous mobile ad hoc networks based on two classes of nodes. A node can join the routing backbone if it has long transmission range, possesses bandwidth and is reliable. QoS routes are calculated based on bandwidth availability. Moreover, node location information is used to aid routing.

In [14], Conti et al. discuss a lightweight mechanism that enables reliable and efficient forwarding, and that mitigates the effects of adverse situations caused by cooperation misbehavior or network fault conditions. It uses a node’s local knowledge to estimate route reliability and multi-path routing to forward packets on the most reliable route. In [23], Shen and Rajagopalan propose an adaptive mechanism called protocol-independent packet delivery improvement service (PIDIS) to recover lost multicast packets. PIDIS provides its packet-delivery improvement services to any multicast routing protocol for mobile ad hoc networks by exploiting the mechanism of swarm intelligence to make intelligent decisions about where to fetch the lost multicast packets. Mottola, Cugola and Picco [29] propose a new content-based routing (CBR) protocol to organize a MANET’s nodes in a tree-shaped network. This network organization tolerates frequent topological reconfigurations and minimizes changes that impact the CBR layer exploiting the tree.

Chakrabarti and Kulkarni [15] present a novel way of preserving QoS guarantees in DSR by pre-computing alternate routes to a destination and using these alternate routes when the current route fails. Their method ensures that traffic load is balanced among the alternate routes but also that an appropriate amount of bandwidth will be available for a flow even when nodes move. In [16], Argyriou and Madisetti introduce a novel end-to-end approach for achieving the dual goal of enhanced reliability under path failures, and multi-path load balancing in MANETs. These goals are achieved by fully exploiting the presence of multiple paths. Shen and Thomas [26] propose a unified mechanism for a distributed dynamic management system which aims to maximize QoS and security while maintaining a minimum user acceptable level even as network resource availability changes. In order to achieve this...
objective, they use three basic elements: a policy-based security framework, multilayer QoS guided routing, and a proportional, integral, derivative controller. Li and Ephremides [28] propose a centralized algorithm of joint power control, scheduling, and routing. Perkins, Royer and Das [25] have added extensions for AODV to support QoS. Finally, Miller and Vaidya [21] introduce a generalized energy state saving protocol that maintains the desired end-to-end latency with relatively low energy consumption.

In [17], Giruka and Singha propose a self-healing on-demand geographic path routing protocol (OGPR) for mobile ad-hoc networks. In OGPR protocol, source nodes utilize the geographic-topology information obtained during the location request phase to establish geographic paths to their respective destinations. Geographic paths decouple node ID’s from the paths and are immune to changes in the network topology. In [35], Cheng and Heinzelman propose two new algorithms to discover long lifetime routes (LLRs) that allow traffic to remain continuous for a longer period of time. The proposed algorithms can be implemented as an extension to existing routing protocols, improving the performance of transport layer protocols without modifying them.

In wireless networks there is strong coupling among the traditional layers of the architecture, and these interactions cannot be ignored. One example is the interaction between routing in the network layer and access control in the MAC layer. Another one is the coupling between power control in the physical layer and scheduling in the MAC layer. Raisinghani and lyer [30] present a representative survey of cross-layer design strategies and discuss the benefits of cross-layer feedback on mobile nodes. In [24], Sristavastava and Motani survey current approaches to cross-layer design and introduce new areas for investigation. In their view, a complete QoS solution would require the interaction and cooperation of several components: (1) a QoS routing protocol, (2) a resource reservation scheme, and (3) a fair QoS medium access control layer. All these mechanisms should be closely knit together and exchange information in order to more efficiently support QoS.

Weiss et al. [27] present a combined layer two and three control loop, which allows prediction of link breakage in wireless ad hoc networks. The method monitors the physical layer transmission mode on layer two and exploits the gained knowledge at layer three. The mechanism is based on link adaptation, which is used in IEEE 802.11a WLAN (wireless local area network) to select the transmission mode according to the link quality. The process of link adaptation contains information that is useful to predict link stability and link lifetime. In [31], Neely and Urgaonkar introduce the notion of instantaneous capacity regions, and provide routing and scheduling algorithms that achieve network stability and fairness with respect to these regions. Their algorithms apply variations of backpressure, shortest path routing, and Lyapunov optimization techniques that feed of cross-layer information exchange. In [32], Klizovitch and Granelli propose a cross-layer congestion avoidance scheme for TCP in mobile ad hoc networks. Their scheme improves transport layer performance by gathering capacity information such as bandwidth and delay at the link layer. Finally, Comaniciu and Poor [33] introduce a hierarchical cross-layer design approach that increases significantly the overall energy efficiency of the network while moderately increasing computing complexity. Their approach is based on a joint adaptation of transmitting power and route selection that share information at different network layers.

### 3. QoS support using a mobile routing backbone

The fundamental principle driving our approach is that realistic mobile ad hoc networks will likely be heterogeneous. Indeed, most real-life MANETs will be composed of several types of nodes, each type having different communication and processing characteristics, and we aim to identify nodes whose capabilities will enable them to participate efficiently in a mobile routing backbone (MRB). Moreover, some of these nodes will be able to provide enhanced QoS services while others will provide plain routing capabilities. Hence, our approach focuses on node classification where mobile nodes can be either QoS routing nodes (QRN), simple routing nodes (SRN), or transceiver nodes (TN). It is worth mentioning that not all nodes will take part in the MRB. Indeed, nodes that do not have enough battery energy to support the added burden of routing packets or for which the links connecting them to their neighbors are not stable enough, for example, will not participate in the MRB. These nodes will still be able to communicate with any possible destination provided that they possess a link connecting them to a node in the MRB.

#### 3.1. QoS support metrics

In our approach, called QMRB-AODV, a MRB is created based on the characteristics of mobile nodes in the network. Paths connecting source and destination nodes are found on this MRB. Four QoS support metrics (QSMs) are used to differentiate nodes in the network and identify the ones that can take part in the MRB, and to guide the route discovery process. These metrics are computed for pairs of nodes. Thus, for three nodes $a$, $b$, $c$, where node $b$ shares a link with nodes $a$ and $c$, the computed value of metrics for node $b$ might be different depending on which node computes it.

A node’s static resources capacity (SRC) is defined by the size of its packet queues $Q_{queues}$ (MB), the speed of its CPU $C_{CPU}$ (GHz), the measure of power of the battery $C_{battery}$ (mW), and the maximum available bandwidth $C_{bw}$ (kbps). These node characteristics are weighted by $\gamma_{src}$, $\beta_{src}$, $\gamma_{src}$, and $\delta_{src}$, respectively, in such a way that their sum equals 1 and that $\gamma_{src} > \beta_{src} > \gamma_{src} > \gamma_{src}$. Thus, a node’s SRC can be computed using

$$ SRC = \gamma_{src} Q_{queues} + \beta_{src} C_{CPU} + \gamma_{src} C_{battery} + \delta_{src} C_{bw}. $$

The dynamic resources availability (DRA) value of a node is an indicator of its current load in resource usage. Even if a node possesses the required capacity, it may not provide the desired service if its resources are already allocated to other connections. Hence, this metric can help guide the route discovery process towards less congested nodes where resources are available. We consider the same characteristics as for the static resources capacity metric (queues, CPU, battery and bandwidth) with the difference that we use the usage rate to determine their values. The usage rate can be computed using formula (2)

$$ Usage\ rate = \frac{\text{quantity of the resource that is being used}}{\text{available quantity for the resource}}. $$

and the DRA is computed using formula (3)

$$ DRA = 100 - (\gamma_{dra} U_{queues} + \beta_{dra} U_{CPU} + \gamma_{dra} U_{battery} + \delta_{dra} U_{bw}). $$

The following weights are used, $\gamma_{dra}$, $\beta_{dra}$, $\gamma_{dra}$ and $\delta_{dra}$, with the constraint that they must sum up to 1, and in such a way that $\gamma_{dra} > \beta_{dra} > \gamma_{dra} > \gamma_{dra}$. In the DRA metric, the most important component is the node’s remaining battery life followed by the available bandwidth. For example, if a node has no energy left, even though other resources may be available, it will not be able to provide the service required by a connection. This is why the weights in the DRA metric are not in the same sequence as in the SRC metric; their dynamic importance to the protocol is different than their static importance.

We define the neighborhood quality (NQ) of a node as the number of nodes in its neighborhood that are able to forward packets, or in other words, that can be routers. The higher the value of this
metric, the higher the probability that a node in this neighborhood can be selected to take part in a route.

Link quality and stability (LQS) is defined as the power of the signal received by the node and the statistical stability of its links. For the stability component, we use the statistical link stability method developed by Gerhartz [9] where the probability that a link can be used for a time period \( t \) is given by

\[
P_{d}(d) = \frac{\sum_{t=0}^{\infty} d_{i}D(t)}{\sum_{t=0}^{\infty} D(t)},
\]

where \( d \) is the current lifetime of a link, \( d_{i} \) is the average residual lifetime of a link, \( D(t) \) is a statistical table where each entry corresponds to link durations and contains the number of links that subsisted for that duration and \( d + d_{i} \leq N \), and \( N \) is the number of time intervals used for statistical sampling.

In certain cases, it is preferable to know the residual lifetime of a link given a probability determined in advance. Thus, even if the residual lifetime of the link is not high but if the probability chosen is, there is high likelihood that the link will persist for that time. This is the alternative we chose. Hence, based on formula (4), it is possible to compute a link’s residual lifetime for a given quintile-\( \alpha \):

\[
Q_{\alpha}(d) = \max \{d_{i} | P_{d}(d) \geq \alpha\},
\]

where \( P_{d} \) is the probability that the link might persist for time \( d_{i} \), and \( \alpha \) a value between 0 and 1. The higher the value of \( \alpha \), the higher the probability of a link persisting for an additional time \( d_{i} \) but also the more difficult to find such a link. Hence, the value chosen for \( \alpha \) is a tradeoff between link stability and the likelihood of finding such a link.

Using this method requires that each mobile node in the network records the lifetime of the links that it encounters. Thus, each time a node detects a new link with a neighboring node, it starts a counter that ends only when the link is broken. The measured link lifetime is a real value, noted \( d_{m} \in \mathbb{R} \), and is expressed in milliseconds. The measured link lifetime is then put in a discrete format and recorded in a table \( D \) where \( D \in \mathbb{R} \). The table is divided in \( N+1 \) entries where the size of the table \( N \) is the maximum possible link lifetime and each entry the number of links that have persisted for a given time.

The second component, link quality, is defined as the power of the signal received by a mobile node. This component is used to refine the estimate of link lifetime. Each time a packet is received by the link layer, it is possible to measure the power of the signal that transmitted it. The closer the power of the signal gets to its nominal power, the higher is the quality of the link connecting the nodes. However, the quality of the signal depends greatly on the propagation environment. Hence, the power of the radio signal received by a node at a distance \( r \) of the transmitter node can be modeled by [12]

\[
P = \frac{P_{0}}{r^{\alpha}},
\]

where \( P_{0} \), the measure of power, is a constant between a pair of transmitter-receiver, \( r \) is the distance separating them, and \( n \) is a value between 2 and 4. In real-life, \( P_{0} \) would equal the nominal value of the transmission card used; this value may differ between cards. The value of \( n \) depends on the distance between the two nodes; when the nodes are close to 1 another 2 can be used, while when the nodes are near the limit of their transmission range a value of 4 gives a good approximation of the signal degradation.

In their work on link stability, Lim et al. [12] showed that even if two mobile nodes are at the limit of each others transmission range but within its boundaries, the stability of the link is strongly reduced since a small movement of one of the nodes could easily break the link between the two. Based on this observation, we define a new value called the threshold range \( r_{\text{threshold}} \) which is equal to 90% of the theoretical transmission range of a mobile node using an IEEE 802.11b wireless card:

\[
r_{\text{threshold}} = \frac{9}{10} r_{\text{max}}.
\]

When two nodes communicate, and the receiving node is at a distance greater than \( r_{\text{threshold}} \) from the sending node, the receiving node is said to be in the threshold region. The value of \( r_{\text{max}} \) is equal to the maximum transmission range of the card.

Hence, using the concepts of threshold range and threshold region we now define a threshold ratio \( P_{t} \), that is the strength of the theoretical signal received at maximum transmission range \( P_{\text{received}} \) over the strength of signal received at the threshold range \( P_{\text{threshold}} \). Both \( P_{\text{received}} \) and \( P_{\text{threshold}} \) are determined using formula (6). Thus, \( P_{t} \) characterizes the minimum quality signal accepted as a viable link:

\[
P_{t} = \frac{P_{\text{received}}}{P_{\text{threshold}}} \cdot 100 = \frac{P_{r}}{P_{\text{max}}} \cdot 100 = 65.61\%.
\]

When a packet reaches the link layer of the destination node, the ratio of the measured power signal over the threshold signal power is computed. It is worth noting that computation does not occur for every packet but for randomly chosen packets of a communication. Otherwise, this mechanism would impose too much processing and updates to be useful. Formula (9) is used to compute the measure ratio

\[
P_{mr} = P_{\text{measured}} \cdot P_{\text{threshold}}.
\]

Finally, the measured and threshold ratios are compared using formula (10)

\[
P_{mr} \geq P_{t}.
\]

Thus, a link with a measured signal having a power ratio inferior to the threshold ratio will not be used to forward packets. However, if the link connects a relay node to the destination node, packets will be forwarded to destination using this low quality link because no other direct link to this node is available.

The main motivation behind using two components to define the link quality and stability is that neither of them taken alone can provide guarantees on the quality or stability of a link. Hence, by using both of these two components, we limit the impact of each ones weaknesses. Indeed, the power threshold sub-metric is a short term indication of the “fitness” of the link, since it is computed regularly, while the statistic stability sub-metric provides a long term indication on the link’s stability. Link that are both “fit” and that are stable over time are the most interesting ones for QoS flows while links that are both unfit and unstable over a long period of time are the least suited to route QoS flows. Links that have one of the two metrics on the positive side (either very fit but relatively stable, or very stable and just on the border of being fit) are considered to be low quality links. However, those links can still be used to route best-effort traffic if no other link is present. Using this metric, links in the network can be labeled as high-quality link (HQL), low quality link (LQL), or unusable link (UL).

3.2. Establishment of the mobile routing backbone

The dissemination of information required to support QoS is done using the HELLO messages defined by the AODV [10] protocol and exchanged periodically by neighboring nodes. It is worth noting that HELLO messages are optional in AODV and that their use induces additional overhead. Nonetheless, the messages are neces-
sary especially in QoS support since the availability of resources as well as node and network states have to be disseminated in the network. HELLO messages are the most economical way of disseminating such information. Each mobile unit in the network broadcasts a HELLO message containing the node’s SRC, DRA, NQ and its available bandwidth (BW) to all its neighbors when the HELLO_INTERVAL expires. This adds an overhead of 32 bytes per HELLO message. However, considering the size of the overhead and the periodicity of HELLO messages, it should not have a negative nor sensible impact on the protocol’s overall performance. Note that this information is computed by the sending node.

Node classification based on routing capabilities is realized by first computing its aptitude to play a specific role in the MRB:

\[ MN_{aptitude} = \mu_{SRC} + \eta_{DRA} + \sigma_{NQ} + \omega_{LQS} + \phi_{BW} \]  

(11)

where \( \mu, \eta, \sigma, \omega \), and \( \phi \) are coefficients associated, respectively, with a node’s static resource capacity, dynamic resource availability, neighborhood quality, Link quality and stability and bandwidth in such a way that their sum equals 1. As we have mentioned earlier, the DRA has a dynamic value that changes as a function of the node’s load while the SRC is static and is determined by the maximum resources available at that node. The weights of the \( \mu, \eta, \sigma \), \( \omega \) and \( \phi \) coefficients are such that \( \eta > \mu > \sigma > \omega > \phi \). Thus, we give precedence to the dynamic aspects of a node when determining its ability to play a particular role in the network. In doing so, the mobile routing backbone will evolve with time depending on traffic distribution, congestion present in regions of the network and the load of each node.

### 3.3. Route discovery algorithm

Route discovery is initiated when a node’s network layer first receives a connection request for a node that does not have an entry in its routing table. The route discovery process we propose is based on the one defined in the AODV [14] protocol where certain modifications were added to support QoS and node mobility.

The route discovery algorithm is used by each mobile node in the network when it initiates a new route discovery process or when it receives a new Route REQuest (RREQ) and wants to decide to which of its neighbors the RREQ should be forwarded.

The first step in the algorithm is to verify if the destination node is part of the QMRBNeighborList. If the node applying the algorithm is the source node, it forwards the packets to the destination. If it is an intermediate node and the flow requires QoS provisioning, it reserves the resources (bandwidth) and sends the RREQ message to the destination node indicating the bandwidth that was allocated for the flow, and if the flow does not require QoS, the node simply forwards the RREQ to the destination.

If the destination node is not found in the neighbors list, the algorithm checks if the QoSFlow label in the RREQ is set. If it is, the algorithm will try to find nodes in its neighborhood that can provide the QoS required by the flow. Hence, for all the nodes in its QMRBNeighborList, it successively selects the nodes that have the QRN_NODE label and verifies that their resources usage rate is inferior to that of QRN_MAX_USAGE, the maximum usage rate allowed for QRN routing nodes. This ensures that nodes that are already heavily used will not be further overloaded. Furthermore, the algorithm verifies that the neighbors’ available bandwidth is at least superior or equal to the minimal bandwidth required by the flow, that the neighboring node possesses a neighborhood quality of at least MIN_NQ (a MIN_NQ of 1 means that there is at least one QRN in the neighborhood of that node), and that the link connecting the current node and its neighbor is a high quality link. If all the aforementioned conditions are met, a RREQ message is sent to the corresponding neighbor node, a new entry is recorded in the nodes routing table, and bandwidth resources are reserved for the flow. It is worth mentioning that resources are reserved using a soft state that releases resources if the state is not refreshed periodically as when links on the path break or the route discovery is not successful, for example. Moreover, we consider symmetric links where resources are reserved for both directions. Indeed, the basic AODV [10] protocol only supports symmetric links, where the RREP message (containing the resource reservation information) is forwarded along the path established by the RREQ message. If symmetric links were not supported, the receiving node would have to initiate its own route discovery and piggyback the route reply on the new route request. However, link asymmetry is generally temporary and caused by interference, differing radio capabilities or signal power adjustments. Hence, in most situations, we can consider that the asymmetry will not persist beyond a certain multiple of the HELLO_INTERVAL.

At any step, while the algorithm is searching for neighbors to send the RREQ messages to, if a condition is not met, the algorithm selects the next node in the QMRBNeighborList and verifies that the conditions are met. If no nodes in the list were found and the node applying the algorithm is the source node, it waits for a period \( t_{no\_routes\_found} \) and initiates a new route discovery. The node can initiate at most three consecutive QoS-enabled route discoveries before reverting to the best-effort variant of the algorithm. Otherwise, if the node is an intermediate node, it simply stops and waits for other RREQ messages coming in from the source.

Each intermediate node that receives a RREQ message applies the route discovery algorithm. The mobile nodes that receive a RREQ for the first time (any subsequent RREQ that has the same pair of source–destination address will be discarded) will send the RREQ to its selected neighbors after:

- incrementing by one unit the number of hops in the path;
- if the RREQ has the QoSFlow label set, allocating an amount of bandwidth between \( bandwidthLowerLimit \) and \( bandwidthUpperLimit \) as a soft state;
- indicating in the RREQ message the allocated bandwidth (the \( bandwidthUpperLimit \) is updated with the value of the allocated bandwidth).

RREQ messages are propagated from one node to another until they reach the destination node. It is worth noting that several RREQ messages may never reach the destination because no path was found, for example. In the particular case where no RREQs reach destination, the source node waits for a period \( t_{no\_routes\_found} \) and sends a second round of RREQs. This wait period allows nodes to move to other locations, destroying old paths and creating new ones.

The route selection phase is initiated when the first RREQ message reaches the destination. The responsibility of choosing the best possible path devolves upon the destination node. In this phase, the destination will choose the path, if several exist, that:

- has the lowest number of hops;
- the highest allocated bandwidth, if it is serving a QoS flow.

If several paths connecting the source node to the destination node exist, all having the same characteristics, one is chosen randomly. Since our protocol uses a soft-state resource reservation mechanism, the resources reserved on the other paths that were not chosen are released after a time \( T_{resource\_release} \). The resource reservation protocol simply pre-reserves bandwidth for incoming QoS flows. If the pre-reserved path is the one chosen for the flow, the reservation is confirmed during route confirmation. The mechanism allows for multiple simultaneous reservations that can exceed the quantity of bandwidth available on that link. If the reservation is confirmed and if bandwidth is available it is
allocated to the flow. Otherwise, the flow is downgraded to best-effort service. In our mechanism, bandwidth for QoS pre-reserved flows is allocated in a first-in, first-out fashion.

3.4. Example of a route discovery and an update of the MRB

The MRB is formed in a distributed fashion. Each node sends periodically a HELLO message containing its label (whether it is a QRN, SRN, or TN), the value of the NQ and DRA metrics as well as its available bandwidth to all its neighbors. The diffusion of HELLO messages allows a node to signals its presence to its eventual neighbors, to compile statistical information on link quality and stability, and to propagate routing information. It is important to choose appropriately the periodicity of HELLO messages. Indeed, if the period is too large, the MRB will not be kept up to date as new connections arise, and if too short, the number of control messages exchanged will reduce the available bandwidth. Information contained in HELLO messages is extracted by the receiving node and inserted in the appropriate record of the MRBNeighborList or a new record is created if the node just entered this neighborhood.

A route discovery is initiated when a node wants to communicate with another node that is not part of its immediate neighborhood. Fig. 1(a), (b), (c) and (d) illustrate a MANET of 30 nodes where a mobile routing backbone has been established and updated.

In Fig. 1(a), at time $t_1$, node 5 wants to establish a communication requiring QoS with node 28. At the network layer on node 5, the first packets are queued since no path to node 28 is known and a new route discovery is initiated with 5 and 28 as the source and destination addresses in the RREQ message. Furthermore, the QoSFlow field in the RREQ packet is set to true, indicating that the flow has special requirements in terms of bandwidth. Two fields (bandwidthUpperLimit and bandwidthLowerLimit) are also used to indicate the upper and lower bounds of bandwidth that should be allocated to the flow. This RREQ message will be propagated to all neighboring nodes in the MRBNeighborList that have the QRN_NODE label, an available bandwidth superior to the minimum required, an NQ metric superior to 1 (meaning that they have at least one router in their neighborhood), for which the usage rate is lower than $QRN_{MAX USAGE}(25\%$ of available resources), and that are connected through high-quality links.

As we can observe in the same figure, node 5 sends RREQs to nodes 2 and 3 but not to node 4 since it is not a QRN and hence cannot provide QoS. Indeed, we save one RREQ by knowing that node cannot provide QoS. The same holds true for nodes 2, 9 and 29 where a few RREQs are saved because information on neighboring nodes is available. Since route discoveries are relatively frequent, because of node mobility, a reduction of route discovery control messages can be beneficial to overall network performance.

When the RREQs finally reach destination node 28, a route is selected based on the highest allocated bandwidth and the lowest number of hops to the destination. The route selected in this example is composed of four intermediate nodes: 3, 7, 21 and 19. A RREP is sent by node 28 back to the source using the inverse route as illustrated in Fig. 1(b).

As mentioned earlier, the MRB is updated regularly as HELLO messages are exchanged between neighboring nodes. Fig. 5(c) shows the state of the MRB at time $t_2$ where the data transfer between node 5 and 28 has started.

At time $t_4$, illustrated in Fig. 1(d), several nodes have roamed from their original position; new links were created, others were broken and so on. In this figure, we can observe that node 5 still transmits data on the path found earlier. Furthermore, note that nodes 7 and 21 were downgraded from QRN to TN and SRN, respectively. These nodes were downgraded because they did not have sufficient available resources to remain a QRN or SRN, for node 7, and to remain a QRN, for node 21. Nonetheless, these nodes continue to forward packets as long as they do not roam elsewhere. Once the resources used to service the flow from node 5 to 28 are released, nodes 7 and 21 will regain their QRN status. This dynamic downgrade/upgrade of nodes in the MRB ensures that new connections requests will not be directed towards highly congested areas.

Still at time $t_4$, we see that node 4 wants to establish communication with node 28 using a basic service, both QRN and SRN nodes can participate, and both HQL and LQL link types can be used to support the flow. Once a RREQ reaches node 21, such as the RREQ from node 30, a new path to the destination is found since node 21 has an active path to node 28. If node 21 cannot provide the service, another path to destination will be chosen.

4. Simulation-based performance analysis

The mechanisms presented above were implemented in the QualNet Simulator [13], a scalable packet-level simulator with accurate radio and mobility models. The simulator implements various routing protocols. We chose AODV [10] as the basis protocol for our implementation since it provides all basic routing primitives. Moreover, our solution will be compared against AODV [10] and DSR [11].

Realistic simulation scenarios are critical to correctly assess the performance of mobile ad hoc networks. In our simulations, we considered MANETs uniformly distributed over a 1250 m x 1250 m area. Simulations were done for networks of 30, 50, 70, 90 and 110 nodes. By gradually increasing the density of mobile nodes on the simulation surface, our goal is to evaluate how effectively our protocol can dynamically distribute traffic within the network and select the route that best supports a QoS connection in varying network densities. The denser the network, the more effective our protocol is. Two types of node were considered: a node modeling PDA characteristics and another one modeling conventional laptop characteristics. PDA type nodes have less processing power, memory size and battery energy than laptop type nodes. Both types of nodes share an 802.11 wireless interface. The proportion of laptop nodes to PDA nodes is 2:1. The speed of mobile nodes varies between 0 and 40 m/s. Four pause time scenarios were simulated: 30, 60, 90 and 120 s. The mobile node speed and scenario pause time will have a major impact on our protocol’s ability to cope with the dynamic nature of the topology. The higher the speed and lower the pause time, the more difficult it will be to find stable routes. After running several simulations, we noticed that our protocol offers its best performance when the HELLO.Interval is set to Pause.Time / 2. Within that interval, each node’s information about its neighborhood is refreshed sufficiently often for our protocol to be able to react efficiently to a change in network topology.

The random-waypoint mobility model was chosen. This mobility model is one of the most utilized patterns in the literature since it offers the possibility to configure nodes’ mobility characteristics in a straightforward fashion. Ten runs were completed for each simulation scenario. There were 20 pairs of source-destination flows in all the scenarios simulated. Amongst those pairs, there were 10 CBR flows requiring QoS treatment, five HTTP flows and five FTP flows requiring a best-effort type service. At any moment during a simulation, there are always five simultaneous active source-destination flows. Table 1 shows a summary of simulation parameters.

Sections 4.1–4.4 show simulation results for network throughput, packet delivery ratio, messages overhead and end-to-end delay. Because of the number of scenarios simulated and the large quantity of data gathered, we have decided to present results for 50 and 110 nodes (with various mobile node speeds ranging from...
0 to 40 m/s), which we believe are a representative subset of all results. These scenarios show our protocol’s behavior in low density (i.e. 50 nodes) and high density (i.e. 110 nodes) mobile ad hoc networks. Results for other scenarios can be provided to interested readers upon demand.

### 4.1. Network throughput

The average network throughput is simply the number of data packets received by all destination nodes over the duration of the simulation. Fig. 2 (a) and (b) illustrate the average network throughput for AODV, DSR and QMRB-AODV as a function of mobile nodes’ speed for ad hoc networks of 50 and 110 nodes, respectively. The pause time for these simulation runs is 30 s. As we see on these figures, our protocol provides a higher average network throughput than AODV and DSR in most cases.

If we take a closer look at Fig. 2(a), we note that our protocol’s throughput is lower than DSR’s when mobile nodes move at average speeds of 20 and 30 m/s. The decrease in performance in this interval is 9% on average. Indeed, one of DSR’s ability is to cope well with small to medium sized networks that change rapidly, which is the case with this particular scenario. Nonetheless, we find that in the 0 to 40 m/s interval our protocol improves DSR throughput performance by 4.15% on average and AODV by 15.21%. In Fig. 2(b), QMRB-AODV has a clearly higher throughput than both protocols. On the overall speed interval, the improvement in throughput performance is 17.85% compared to AODV and DSR. This improvement, although it seems high is due in great part to the important decrease in throughput from DSR when mobile nodes move at a maximum speed of 30 m/s. We see that when the maximum speed reaches 30 m/s the throughput drops approximately to 220,000 from 300,000 bits/s at 20 m/s and increases back to the latter value when nodes’ maximum speed reaches 40 m/s. We cannot say that this is normal for DSR and must charge this performance drop to the simulation tool used. Moreover, for both the 50 and 110 nodes and across the whole speed interval, QRMB-AODV offers better performance than basic AODV. This performance gain can be attributed to the fact that each node in the network is rapidly aware (through periodical updates) of its two-

![Fig. 1. (a) Route discovery at time t₁ where node 5 searches for a QoS path to node 28. (b) Route reply at time t₂ from node 28 through nodes 10, 21, 7, 3 to node 5. (c) At time t₃, node 5 transmits date to node 28. (d) At time t₄, the MRB is re-computed. Some nodes have moved, others have been upgraded or downgraded. A new route discovery is being initiated from node 4 to 28.](image-url)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of simulation parameters.</th>
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<td>Parameter</td>
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<td>Area</td>
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<tr>
<td>Number of nodes</td>
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<td>RANDOM WAYPOINT</td>
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<td>Simulation time</td>
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</table>
hop neighborhood state (i.e. link state and node characteristics) and can therefore better identify stable QoS links. As the speed of mobile nodes increases, the ability of our protocol to use this information to deliver better throughput is even more distinguishable.

Fig. 7(a) and (b) illustrate the average network throughput for AODV, DSR and QMRB-AODV as a function of mobile nodes’ speed for ad hoc networks of 50 and 110 nodes, respectively. This time, mobile nodes take a pause of 120 s between movements. On both these figures, the average network throughput for QMRB-AODV is higher than the throughput for AODV and DSR when mobile nodes move at maximum speeds higher than 10 m/s.

If we analyze results in Fig. 3(a), we note that even if the throughput of QMRB-AODV is lower than that of AODV for a maximum mobile node speed inferior to 10 m/s it monotonically increases for higher maximum speeds until it reaches approximately 425,000 bits/s at 40 m/s. Hence, the lower throughput found at 10 m/s is largely compensated by the throughput in the 20–40 m/s interval. Indeed, in that interval, our protocol’s throughput surpasses AODV’s and DSR’s by 12.34% and 12.67% on average, respectively. As for Fig. 3(b), QMRB-AODV has strictly higher performances than AODV and DSR. Our protocol improves throughput performance over the 0 to 40 m/s interval by 14.76% and 11.31% compared to DSR and AODV, respectively. Over the interval under consideration, the average performance difference with AODV is 2.10%, and 1.00% with DSR. Nonetheless, over the duration of a simulation, any increase in the packet delivery ratio can be considered beneficial to overall network performances.

If we look at the curves illustrated in Fig. 4(b), where the number of mobile nodes in the network was increased to 110, we note that the average packet delivery ratio has increased and is now 95.74% for QMRB-AODV, 93.32% for DSR and 92.42% for AODV. In fact, PDR performance for our protocol and AODV increased a little more than 2% and less than 1% for DSR when compared with the performances shown in Fig. 4(a) for an ad hoc network of 50 mobile nodes. Furthermore, we observe that the increase in network size had the effect of inverting the performance curves of AODV and DSR. Indeed, we can say that as the network size increases and consequently the number of connection requests, the PDR of AODV and QMRB-AODV increases because of their inherent reactive nature. Reactive protocols usually outperform proactive ones when the network grows or when mobility becomes an important

4.2. Packet delivery ratio (PDR)

The packet delivery ratio is the ratio of the number of data packets received by the destination to the number of data packets sent by the source. Fig. 4(a) and (b) compare the average packet delivery ratio for AODV, DSR, and QMRB-AODV with MANETs of 50 and 110 mobile nodes, respectively. Mobile nodes can move at speeds varying from 0 to 40 m/s with a pause time of 30 s.

In Fig. 4(a), we can see that the packet delivery ratio of QMRB-AODV is clearly higher than the one for AODV and DSR for mobile nodes moving at speeds equal or higher than 10 m/s. Indeed, the average PDR for our protocol in the 0 to 40 m/s interval is 93.47% while it is of 92.46% and 91.36% for DSR and AODV, respectively. The most important performance difference between our protocol and AODV occurs when mobile nodes move at a maximum speed of 20 m/s. At this speed, the average PDR difference of QMRB-AODV compared to AODV is 3.63% while it is only 1.19% compared to DSR. Over the interval under consideration, the average performance difference with AODV is 2.10%, and 1.00% with DSR. Nonetheless, over the duration of a simulation, any increase in the packet delivery ratio can be considered beneficial to overall network performances.

If we look at the curves illustrated in Fig. 4(b), where the number of mobile nodes in the network was increased to 110, we note that the average packet delivery ratio has also increased and is now 95.74% for QMRB-AODV, 93.32% for DSR and 92.42% for AODV. In fact, PDR performance for our protocol and AODV increased a little more than 2% and less than 1% for DSR when compared with the performances shown in Fig. 4(a) for an ad hoc network of 50 mobile nodes. Furthermore, we observe that the increase in network size had the effect of inverting the performance curves of AODV and DSR. Indeed, we can say that as the network size increases and consequently the number of connection requests, the PDR of AODV and QMRB-AODV increases because of their inherent reactive nature. Reactive protocols usually outperform proactive ones when the network grows or when mobility becomes an important
issues because the latter do not use routing tables and do no need as much fresh routing information as their proactive counterparts.

Fig. 5(a) and (b) shows the average packet delivery ratio for AODV, DSR, and QMRB-AODV with wireless ad hoc networks of 50 and 110 mobile nodes, respectively. Mobile nodes can move at speeds varying from 0 to 40 m/s with a pause time of 120 s. If we increase the pause time from 30 to 120 s, we see that the packet delivery performances of our protocol increase by 0.98% compared with AODV and 1.65% compared with DSR for an ad hoc network of 50 nodes, and 2.61% compared with AODV and 0.82% compared with DSR for 110 nodes. As was mentioned earlier, note that the performance curves of AODV and DSR invert themselves as the network increases in size, going from 50 to 110 mobile nodes. The only moment where our protocol underperforms AODV or DSR is when all the nodes in the network with 50 nodes are stationary and when the mobile nodes move at a speed of 20 m/s in the network composed of 110 nodes. In the first case, DSR's PDR is superior to QMRB-AODV, while in the second case it is AODV's PDR that is superior by 0.87%.

4.3. Messages overhead

Our simulation scenarios used a DSR configuration with caching turned on. In that particular configuration state, DSR seldom uses RREQ packets and thus, it will not be used as a basis for comparison.

Fig. 6 illustrates the number of RREQ packets found in the network for QMRB-AODV and AODV as a function of the number of mobiles nodes. Note that in Fig. 6 nodes are stationary. We can see that decrease in the number of RREQ packets used in the network for QMRB-AODV closely depends on the number of nodes in the network. Indeed, the greater the network density (the number of nodes in a given area) the lower the number of RREQ packets transmitted. This phenomenon can be explained by the fact that our protocol adds several constraints to the routing process, notably on the selection of links and nodes that can take part in a route. These constraints reduce the number of possible routes in the network and the number of RREQs sent. In a low density network, like the one with 30 nodes, these constraints can produce the exact opposite effect and generate more RREQs than with AODV.

In the case where the network has a higher density and a low to moderate mobility, our protocol produces the desired behavior since the number of quality links and nodes are in sufficient quantity and the probability that the required resources are available is higher. This behavior can be clearly observed on Fig. 6. Indeed, the decrease in the number of RREQs for our protocol compared with AODV is 1.22%, 5.84%, 7.67% and 10.03% for wireless ad hoc networks of 50, 70, 90 and 110 nodes.

Fig. 7(a) and (b) shows the number of RREQ packets found in the network for QMRB-AODV and AODV as a function of the number of mobiles nodes for speeds of 10 and 40 m/s, respectively. The pause time for these simulations is 30 s.

The first thing to note in these figures is that the decrease in the number of RREQ packets generated by our protocol is greater when mobile nodes move at low speeds. Indeed, if the mobility is too important, independent of the mobility support mechanisms used, links between nodes will break, the available routes will not be usable and new route discoveries that generate RREQs will be required. In the particular case of QMRB-AODV, a low mobility might even be beneficial to overall network performance since node mobility redistributes resources within the network while giving our mobility support mechanisms time to adapt. Thus, if we analyze the results shown in Fig. 7(a) and (b), we observe that QMRB-AODV reduces the number of RREQs on average by 7.92% when compared to AODV when the maximum speed of mobile nodes is 10 m/s. This reduction in RREQs is of 3.49% when nodes move at speeds of 40 m/s.
Fig. 8(a) and (b) shows the number of RREQ packets found in the network for QMRB-AODV and AODV as a function of the number of mobile nodes for speeds of 10 and 40 m/s, respectively. The pause time for these simulations is 120 s. On this figure we observe the trend described earlier, that is, a more pronounced decrease in RREQs when nodes move at low or moderate speeds. For a maximum speed of 10 m/s, the number of RREQ packets generated by our protocol is 5.47% lower than the number generated by AODV. Furthermore, there are 3.78% less RREQs generated by our protocol than by AODV for a maximum speed of 40 m/s.

4.4. End-to-end delay

The end-to-end delay (ETED) is the time taken by a packet from the moment it is transmitted on the network by the source node to reach the destination node.

Fig. 9(a) and (b) illustrates the average ETED in an ad hoc network of 50 and 110 mobile nodes as a function of node speed. The pause between mobile node movements is 30 s. We can clearly see on both these figures that the average ETED for AODV and QMRB-AODV is smaller than that of DSR for the whole 0 to 40 m/s speed interval. Nonetheless, it is difficult to separate the ETED performance of AODV and QMRB-AODV since their corresponding curves often intersect.

In Fig. 9(a), we note that the average ETED for AODV is 0.040 s while the ETED for QMRB-AODV is 0.043. In Fig. 9(b), where the mobile node count increases from 50 to 110, QMRB-AODV's ETED decreases by 0.004–0.039 s while AODV's ETED increases to 0.046 s. Overall, we observe that the delay remains pretty stable. Nonetheless, QMRB-AODV's ETED is clearly inferior to that of AODV for the 20–40 m/s speed interval. Hence, we can say that when node mobility increases and the network has higher density, QMRB-AODV offers better ETEDs than AODV.

Fig. 10(a) and (b) illustrates the average ETED in an ad hoc network of 50 and 110 mobile nodes as a function of node speed. This time, the pause between mobile node movements is 120 s. Once again, as was observed with the results in Fig. 9(a) and (b), DSR's ETED is much higher than that of AODV or QMRB-AODV over the whole 0 to 40 m/s interval.

In Fig. 10(a), for a 50 node ad hoc network, we observe that the ETED for QMRB-AODV is much smaller than AODV's when mobile nodes move at maximum speeds of 10 m/s. For every other value, AODV offers better delays. Nonetheless, over the 0–40 m/s interval, QMRB-AODV's ETED is 5.37% superior to AODV's, which represents a 5.04 ms difference. On Fig. 10(b) we clearly see that for the 10–30 m/s interval, the delays offered by QMRB-AODV are strictly inferior to those offered by AODV. Further, as the number of nodes in the network increases from 50 to 110, AODV's ETED increases from...
0.039 to 0.043 s while QMRB-AODV’s delay decreases from 0.044 to 0.037 s, a 7 ms gain.

As we have seen in Figs. 9 and 10, the performance of the protocols clearly depends on the network topology and size. These two parameters influence traffic and directly affect the packet arrival process at each forwarding node. In reactive protocols such as AODV, DSR or QMRB-AODV, as the topology becomes more dynamic and routes break, there is an increase in the number of route requests on the network. This, in turn, increases the average queuing time for packets leading to a higher end-to-end delay. The fact that our protocol offers comparable or better ETED performance (in the case of highly mobile and dense networks) when compared to AODV is due to the fact that it imposes constraints on the routes that can be selected and used to deliver packets. Thus, more packets tend to be forwarded by the same highly capable nodes and accumulate in their queue. Nonetheless, as the density of the network increases, QMRB-AODV’s mechanisms allows it to select better routes (with stable and strong links) than AODV, thus decreasing its average ETED.

5. Conclusion

This paper emphasized the importance of considering nodes’ characteristics in order to provide better support for QoS in mobile ad hoc networks. Our solution is articulated around several QoS support metrics that enable node classification. Nodes in a heterogeneous MANET are either QoS routing nodes, simple routing nodes that route packets through the network without providing special service provisions or transceiver nodes, that send and receive packets but cannot relay them. A mobile routing backbone is created using all nodes having routing capabilities. QoS support is realized by relaying packets having special requirements to nodes rich in resources and connected through stable links. To avoid starvation of best-effort packets both types of routing nodes have forwarding capabilities. We studied the performance of QMRB-AODV and compared it with the performances of AODV and DSR. The results show that it outperforms both protocols in packet delivery ratio. The main benefit of QMRB-AODV is that it makes better use of available bandwidth by distributing traffics through the network and by reducing the number of control messages needed to establish a route from a source node to a destination node (when compared to AODV). Moreover, the strength of our approach lies in its simplicity and on the adaptability of our mechanisms to other protocols.

References