Interference-aware Routing with Bandwidth Requirements in Mobile Ad Hoc Networks

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Abstract— **Mobile ad hoc networks are expected to deal with diverse multimedia applications demanding heavily QoS requirements. Several QoS routing algorithms have been proposed. However, most of these solutions do not take into account bandwidth demands and the quality of the selected paths in the routing process itself. We present an interference-aware QoS routing which considers the bandwidth demand based on a proposed QoS metric. A cross-layer design allows to perform this metric taking into account updated information of the interference and bandwidth environment. A multipath operation is performed so multiple paths with available bandwidth are formed during the route discovery process. By using the proposed metric it is possible to choose the best QoS route among several paths therefore performing a more appropriate resources allocation – distributed Call Admission Control (CAC)**

Keywords-component; QoS routing, ad-hoc networks, cross-layer, resources allocation.

I. INTRODUCTION

Nowadays, mobile ad hoc networks are expected to deal with diverse multimedia applications demanding QoS. In order to provide quality delivery to these applications, several QoS routing approaches [1] – [4] have been proposed, but it is still a challenging task due to the complexity of the dynamic environment of these networks. In order to facilitate QoS support in ad hoc networks, it is very important to solve the tradeoff between guaranteeing the requirements for the QoS provision with the best efficiency in the use of the networks resources. A cross-layer design tries to combine the functionality of the Routing layer with Medium Access Control (MAC) information and physical layer parameters to provide the routing algorithm with the more accurate information about the current status of the links in order to find the more appropriate path that is able to guarantee the QoS requirements during the whole connection. The proposed QoS routing includes a multipath approach to evaluate the possible available paths for a new connection differentiating them through a QoS metric, considered as a measurement of the bandwidth availability and the interference scenario. The operation of the proposed interference-aware routing algorithm in conjunction with an effective resource allocation in the MAC layer works as a distributed admission control (CAC) so that new QoS demanding applications can be efficiently allocated resources at the expense of the least QoS constrained connections, without disrupting the already QoS active ones. The remaining of the paper is organized as follows. Section II provides an introduction to the proposed QoS routing algorithm. Section III summarizes the effects of considering an interference-aware scenario. Simulation results are evaluated in Section IV and finally, some conclusions are provided in Section V.

II. THE QOS ROUTING ALGORITHM

A. *QoS routing protocol*

The activation of a QoS application is considered as a QoS flow that needs a stable route during the whole connection. In the simple Ad hoc On-Demand Distance Vector Routing (AODV [5]) operation, the source broadcasts requests packets (*RREQ*) referring this flow and each intermediate node rebroadcasts the first received copy of the *RREQ* until it reaches the destination, which sends a reply message (*RREP*) along the reverse path to the source. In terms of quality of service, several paths can satisfy the QoS requirements and the first request packet that reaches the destination does not actually identify the best path although it implies the lower discovery delay. This trade-off makes it difficult to choose the best solution. However, we can try to find a suboptimum path in terms of access delay but better satisfying the QoS requirements. The proposed QoS routing is a modified version of the Ad hoc On-demand Multipath Distance Vector Routing (AOMDV) protocol [6] which works in conjunction with a MAC TDMA layer (ADHOC MAC [7]) in a cross-layer operation. The multipath approach allows to find several alternative paths, although only the best one is selected according to certain QoS metric, and maintained for that flow. The proposed solution acts as a distributed admission control performed during the discovery process of the routing protocol.

B. *ADHOC MAC protocol*

Determining the bandwidth availability in an ad-hoc environment is not an easy task and it is basically dependent on the current MAC layer. In this proposal, a MAC TDMA layer based on the ADHOC MAC protocol has been considered. ADHOC MAC works on a slot synchronous physical layer and implements a completely distributed access technique capable of dynamically establishing a reliable single-hop Basic broadcast CHannel (BCH) for each active terminal. Each BCH carries signaling information, including priorities, which provides a prompt and reliable distribution of layer-two connectivity information to all the terminals. In this work, the proposed QoS routing algorithm interacts with the MAC layer in order to perform a distributed admission control and scheduling as well as an on-demand reservation mechanism that allows to efficiently allocate resources for QoS

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differentiated communications. To this purpose, the access and reservation strategies proposed in [8] have been considered in order to provide a reservation based mechanism to handle the access to data user resources and a simple but efficient traffic differentiation by exploiting the in band signaling provided by the ADHOC MAC protocol. The basis of this strategy relies on the use of the BCH capabilities to signal the request before the access, in such a way that collisions can be theoretically avoided (Book In Advance Strategy – BIAS). Pre-emption can be carried out in order to allocate resources for high priority services despite the lower priority ones. The policy used to resolve the conflicts in reservation is explained in detail in [8].

C. QoS metric: path bandwidth calculation process

The AOMDV routing protocol has been adapted to include a modified version of the path bandwidth calculation algorithm [9] explained in [3] to measure the available bandwidth considering the whole path. The basic idea of this algorithm is to find the available TDMA slots that can be used for transmitting in every link along the path avoiding hidden and exposed terminal problems [10] so that these slots, if reserved, would be interference-free. The measurement is performed and updated in each node during the discovery phase. The path bandwidth calculation ends in the destination node, and the calculated value represents the maximum available bandwidth between the source and the destination.

The actual implementation of the algorithm operates as explained next. According to the MAC level information, a node k is aware of the available slots for transmitting without interfering other connections (SRT_k set) and the available ones for receiving without collision (SRR_k set). The ADHOC MAC protocol includes the capability of using priorities to give QoS at the MAC level. Since preemption of reserved slots with lower priority is possible when resources of high priority are demanded, the set of available slots for the new QoS flow in the routing level will include these slots as available. High priority reservations are protected from preemption. During the path bandwidth calculation and the *RREQs* propagation in the discovery phase, the set of available slots for communication in link *(i, j)* is calculated in node *j* and denoted as PB_{ij}. Avoiding hidden and exposed terminals to have interference-free communications requires the set of transmitting slots to be disjoint in three consecutive hops. According to this rule, each intermediate node appends its own *SRT* to the *RREQ* packet but also the PB_{ij} calculated in the previous two hops. With this information, in addition to the *SRR*, the next node receiving this *RREQ* can calculate again the sets of slots to make them disjoint to the new link and update the appended information before forwarding the *RREQ*. The number of available slots in each set is reduced to the minimum value in the three hops used to compute them. When the destination node receives the *RREQ*, the dimension of the last availability set determines the total available bandwidth in the path. If it matches the requirements, it will be considered to be compared according to its metric in the final decision, after waiting for several *RREQs* (multipath). Once a path is selected, the destination node sends the *RREP* packet through the reverse path to the source. The more updated information of the actual available set in every link will be in the 3-hops-downstream neighbour, according to the path bandwidth calculation process. Therefore, to have an updated version of the available slots, during the reply phase a node sends back the more updated ones it has, appending this information to the *RREP*. When a node receives a *RREP*, it updates the sets to be forwarded but also selects the effective slots to transmit, according to the demands, from the available set in the corresponding link.

When an intermediate node receives a *RREQ* for a new flow, it updates a QoS metric (1) – (2) appended in the *RREQ*, and evaluates if the QoS requirements are met. Only those packets received from paths with a valid metric are forwarded. Repeated *RREQs* are no directly dropped in the destination node in order to perform a multipath operation so that several paths can be discovered and finally one can be selected.

$$BW_{metric,RREQ} = \begin{cases} 0.5 \cdot N_{av,link} / N_{RREQ} & N_{av,link} < N_{RREQ} \\ 0.5 \cdot \left(1 + N_{av,link} / N_{\max,link}\right) & otherwise \end{cases} \quad (1)$$

$$BW_{metric,PATH} = \min\left(BW_{metric,RREQ}\right) \quad (2)$$

where $BW_{metric,RREQ}$ is the BW value measured in the previous link, $N_{av,link}$ is the number of available slots in that link and N_{RREQ} is the number of slots that matches the demanded bandwidth. $N_{max,link}$ is the maximum number of slots that could be theoretically available, according to the path-bandwidth calculation algorithm. $BW_{metric,PATH}$ is the more restrictive value in the path, equal to the last link BW_{metric}.

D. Race condition and parallel reservations

Some of the problems that arise when reserving resources during the on-demand routing process in an ad-hoc network are the race condition and the parallel reservations problem [9], [11]. The race condition occurs when multiple reservations happen simultaneously at an intermediate node, and parallel reservations arise when two parallel paths are being reserved without common intermediate nodes, but when two or more of this nodes are 1-hop neighbors. When the reservation has not been performed yet, for example, during the discovery phase, and no additional considerations about these effects are taken into account, a node can select the same available slots for different connections, so it will collide in the future and one or even all of them will be blocked due to transmission failures although an available path had been found. In [9], these problems are partially solved by considering an allocated state for the slots selected in the reply phase of the QoS routing, according to the path bandwidth calculation algorithm, before they are actually reserved. In this status, a slot is not considered as available for new QoS flows trying to be allocated resources, therefore avoiding future collisions. Since this allocated status is only applied in the reply phase of the process and not during the discovery, collisions are not fully avoided, but the blocking probability is considerably reduced [9].

E. QoS Monitoring

Once a path is selected according to its QoS metric, the variability in the network conditions would make infeasible to maintain this path without a mechanism of QoS monitoring and path updating. In the normal operation of the routing protocol nodes react to broken links sending error messages to inform the neighborhood about this event. New discoveries arise, as soon as the involved nodes realize the phenomenon, but this mechanism only alerts about "broken links", assuming the path is unviable, whereas in a "QoS environment" links can be still viable although the bandwidth is not enough for covering the QoS demands of a specific connection. The proposed QoS routing performs an updating process using certain routing information piggybacked in the DATA-ACK packets, similar to that sent during de *RREQ-RREP* phase, which allows to realize if the QoS constrains are not met anymore, so the source of the connection can try to rediscover the path.

III. A REALISTIC INTERFERENCE SCENARIO

A. SIR model scenario

In a basic distance model scenario, connectivity among nodes is only based on Euclidean distances. In this situation, all nodes in the transmission range can correctly decode only one transmitted packet. If more than one neighbour transmits, a collision occurs. Transmissions one hop away are not sensed, which can lead to hidden and exposed terminal problems, but if the MAC signalling can avoid them, totally collision-free transmissions are possible and the reuse capability is theoretically maximized. In the case of the considered ADHOC MAC protocol, once a reservation in a slot is made, since all the potential interferers can be aware of this transmission thanks to information received in the corresponding BCHs, they will not transmit and the collisions are totally avoided, unless pre-emption of lower priority reservations. When considering a realistic interference scenario the correct reception of a packet is based on the received Signal to Interference Ratio (SIR), as it is shown in (3), and it is not only dependent on the distance, in contrast to the basic model.

$$SIR_{rx,i,j}^{k} = \frac{P_{tx,i}^{k} \cdot L_{i,j}}{\sum\limits_{\substack{n\in N_{tx}\\ n\neq i}} P_{tx,n}^{k} \cdot L_{n,j} + P_{noise}} \geq SIR_{th} \qquad (3)$$

where $SIR^{k}_{rx,i,j}$ is the received SIR in node *j* from node *i* in the slot *k*, $P^{k}_{tx,i}$ is the transmitted power by node *i*, $L_{i,j}$ the path loss in the link *(i, j)*, P_{noise} is the thermal noise power and N_{tx} is the set of transmitters in slot *k*. SIR_{th} is the minimum required SIR to correctly decode the signal, and equals the theoretical SIR_{rx} (considering there is no interference) for a $L_{i,j}$ due to the distance range (basic model). A particular user can sense an effective power for transmissions farther than the theoretical one-hop neighbours, although it cannot decode the signal. This interference power can affect the ongoing transmissions then reducing the reuse capability and the network capacity.

B. Interference-awareness

A realistic study of an interference scenario in terms of its impact in the MAC level is carried out in [12], where the proposed solutions demonstrate how the capacity reduction can be lessened increasing the MAC layer complexity. Our cross-layer scheme integrates some of these proposals which are briefly summarized next.

The bandwidth measurement is performed based on the available slots selection made by the MAC layer according to the path bandwidth calculation. This selection considers that the slots must be interference-free, assuming that the transmitted signalling in the BCH allows to perform collision-free slot reservations. However, nodes that are unable to decode the distant nodes signalling are not totally free from suffering interference, since the cumulative power can affect the supposed collision-free transmissions. Indeed, the weaker is an active link, the more significant is this potential interference since its transmission actually has an effective SIR near the limit of detection. Moreover, the MAC layer assumes a perfect knowledge of the resources availability. However, a user can be unaware of the status of some slots since it is unable to decode the information transmitted in the BCH of some distant node that can be affected by this user's transmissions, therefore taking a wrong decision of their availability. Consequently, the call admission control procedure can erroneously allocate slots for new QoS flows without enough totally free resources. If a beacon signal is transmitted by the receiver in these busy slots, in addition to the BCH signalling, the probability of collision is reduced, since the hidden terminal problem can be avoided in case that the potential interferers cannot decode the BCH but can sense the beacon signal.

The collision-free property of the reserved slots, theoretically provided by the access scheme [8] is not ensured any more due to the potential distant nodes interference. This effect is even more critical for the admitted QoS connections. The cross-layer implementation of the QoS routing performs the resources allocation according to the available slots selected during the path bandwidth calculation process. Upon selection of the transmitting slots within the availability set received in the *RREP*, these slots are considered in the MAC level as a set of high priority slots to be maintained in the corresponding link (CAC slots). Once the reservation is correctly performed, it is supposed to be permanent. However, when these slots are considered again for a new resource allocation, the cumulative interference can disrupt the transmission, hence making the reservation lost. As these CAC slots are required to be maintained, the MAC level will try to persistently reserve them again, but future failures are still potential, even more with a high traffic load, since there are more distant nodes which are unaware of these slots reservations. If there are persistent failures, but the BCH signaling does not inform of the other reservations that are colliding, this set of slots are constantly considered as available, leading to a persistent unrecoverable failure in the QoS path. In order to overcome these problems, the interference-aware proposal includes a policy based on avoiding slots with persistent failures despite their apparent availability. When a reservation in a supposed available slot reaches a maximum number of failures due to collisions, this slot is temporarily included in a *blacklist* to be avoided.

Despite these partial solutions, the resource allocation can be more effective if the slots likely to fail are avoided in the routing operation. A quality measurement in order to avoid the weaker links can be included as a SIR_{metric} into the routing process to reduce this real interference problem. A proposal for this metric is shown in (4) – (5).

$$SIR_{metric,RREQ} = \left(\alpha, n_{bads\_partial}\right)$$
$$\alpha = \prod_{i,\, links\ \Delta_{SIR} > 0} \beta_i \ , \qquad \beta_i \in \{0, \alpha_1, \alpha_2, \alpha_3, \alpha_4\} \qquad (4)$$
$$for\ \Delta_{SIR,i} \in \{(-\infty, 0), (0, K_1), (K_1, K_2), (K_2, K_3), (K_3, \infty)\}$$

$$SIR_{metric,PATH} = \sqrt[n_{hop} - n_{bad}]{\alpha}, \quad n_{bad} = n_{bads\_partial}^{last\_RREQ} \qquad (5)$$

where $SIR_{metric,RREQ}$ is a metric about the SIR margin Δ_{SIR} in the previous link with regard to a SIR_{target} and K_1, K_2, K_3, K_4, α_1, α_2, α_3 and α_4 are configurable values according to the scenario (margins depending on the QoS requirements). $n_{bads\_partial}$ is the number of previous hops with a margin below zero. $SIR_{metric,PATH}$ is the SIR_{metric} value along the whole path, where the quality measurement is estimated as the geometric average of the SIR_{metric} in the good links (SIR over target). The SIR_{target} value is selected over the minimum SIR_{th} in order to mitigate the effect of a potential not sensed interference. The margin of the received SIR over the SIR_{target} is calculated considering an estimated received power from the previous hop neighbour through its BCH transmission and no additional interference but the noise (free slot).

Depending on the scenario, a dropping policy, as in the case of the BW_{metric} can avoid selecting any path with weak links. However, an excess in eliminating *RREQs* can make it more difficult to find an available path, so the decision can be only to take an ordering policy to select the best path.

IV. PERFORMANCE EVALUATION

In order to evaluate the performance of the routing protocol, we have built up an event driven simulator in C++ which implements the functionalities of the proposed cross-layer design, considering the ADHOC MAC protocol interacting with the modified AOMDV, including the path-bandwidth calculation algorithm integrated in the routing process. The simulator functionalities allow to emulate a realistic ad-hoc environment, with a transmission range fixed to 500 m, considering a transmitted power of 20 dBm, and a Kammerman propagation model. As first step of analysis, we simplify the physical layer assuming neither fading nor shadowing in the calculation of the received power. Interference among users is considered in the physical level. The connectivity among terminals is determined by the ability of decoding the BCH transmissions according to the received SIR (SIR model scenario). Results have been obtained considering static conditions, with a topology of 25 terminals randomly positioned within a square area with edge equal to 2 Km and CBR traffic sources (64 kbps – 2 TDMA slots). The MAC radio frame subdivision [8] consists of 25 BCH slots and 50 slots for additional data user communications. In order to evaluate the proposed QoS routing, the measured parameters are delay of correctly received packets and throughput, calculated as the ratio among dispatched and offered traffic expressed in packets. The proposed QoS routing has the facility of dealing with connections as best effort traffic (BE Routing) or considering them as QoS flows (QoS routing), including the BW_{metric} (BW) and also the SIR_{metric} (BW-SIR).

The proposed routing is based on the implementation in [9] including the interference-awareness to reduce the degradation in performance from the basic distance model, as it can be observed in Fig.1. The capacity reduction in a realistic scenario makes the throughput drop, but the QoS Routing still overcomes the best effort strategy.

Fig.2, Fig.3, Fig. 4 and Fig. 5 compare the different routing strategies (BE, QoS using only BW_{metric} or also SIR_{metric}) versus the same offered traffic in terms of throughput, blocking probability and throughput of admitted connections. The basic QoS routing strategy, only considering the BW_{metric}, allows to better allocate the resources admitting only the connections that have found the required slots during the discovery phase. Although in the best effort strategy all the connections are dispatched, since there are not actually enough resources, congestion forces to discard packets, then reducing the total throughput as well as increasing the delay, as it is shown in Fig. 5.

Nevertheless, the great improvement obtained in a basic distance model cannot be observed in the realistic scenario, since the interference degrades the performance of the admitted connections, even making a poor allocation since the availability is not appropriately checked. If the SIR_{metric} is included in the routing process, connections with weaker links likely to fail are discarded. The blocking probability increases, which can be observed in Fig. 3, but the global network throughput is improved, since collisions are drastically reduced. Thanks to that, the admitted connections experience a remarkable QoS improvement both in throughput and delay, as it is shown in Fig. 4 and Fig. 5.

Fig. 1, Fig. 2, and Fig. 3 include a dashed blue line that represents the QoS (BW) Routing performance without taking into account the necessary modifications explained in Section III to overcome the problems stemmed from a realistic scenario (BASIC MODE). As the traffic load increases, the blocking probability rapidly rises, leading to a drastic reduction in the network throughput. This degradation is considerably lessened with an interference-aware design. The individual throughput of the admitted connections is slightly worse, since there are more admitted connections, but the total amount of dispatched throughput is better scheduled and the global network throughput experiences a great improvement.

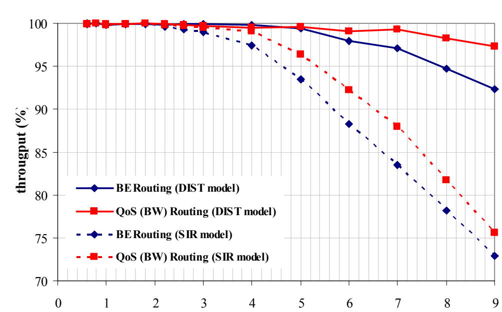

Figure 1. Throughput for connections of 64 kpbs. Distance (DIST) vs. realistic sir (SIR) model

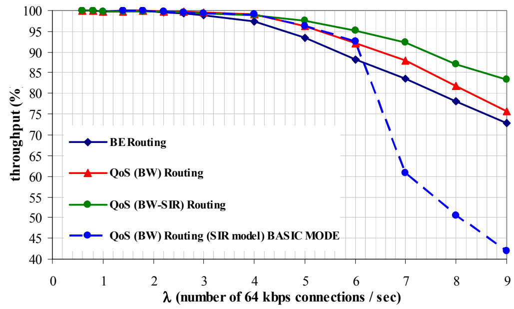

Figure 2. Throughput for connections of 64 kpbs. BE, QoS (BW) and QoS (BW-SIR) Routing strategies.

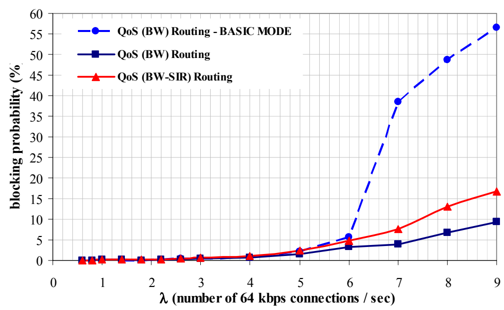

Figure 3. Blocking probability for QoS (BW) and QoS (BW-SIR) Routing

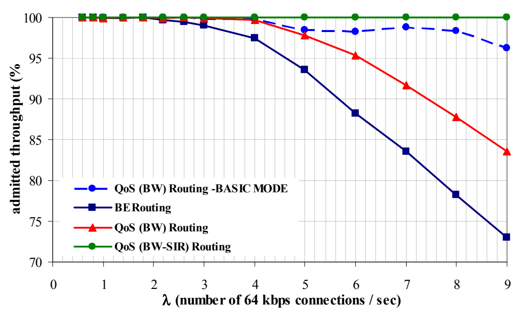

Figure 4. Throughput for admitted connections of 64 kpbs. BE, QoS (BW) and QoS (BW-SIR) Routing strategies.

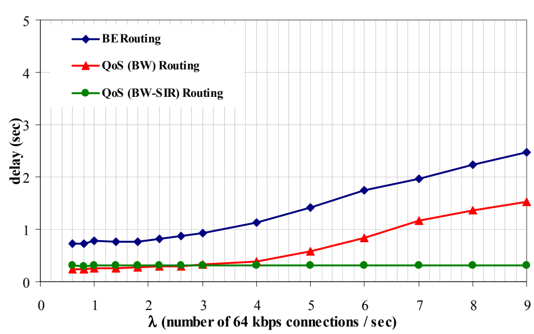

Figure 5. Mean Packet Delay for connections of 64 kpbs. BE, QoS (BW) and QoS (BW-SIR) Routing strategies.

V. CONCLUSIONS

This paper presents an interference-aware QoS routing in order to guarantee bandwidth requirements in ad-hoc networks in a realistic interference scenario. The joint operation of the AOMDV routing protocol with the ADHOC MAC protocol in addition to a path bandwidth calculation algorithm works as a distributed admission control that allows to flexibly allocate resources for bandwidth demanding connections. The optimum performance in a basic distance model scenario is degraded when considering the real interference, although the cross-layer interference-aware operation allows to reduce this degradation. Therefore, the total amount of offered traffic that can be effectively scheduled is still increased in front of a best effort strategy, although some of the connections can be blocked. However, this blocking probability implies in fact a reduction on the congestion of the network which allows to deal better with the admitted connections, which experience higher individual throughput and lower delay.

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