A Position-Based QoS Routing Scheme for UWB Mobile Ad Hoc Networks

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Abstract—**Ultra-wideband (UWB) wireless communication is a promising spread-spectrum technology that supports very high data rates and provides precise position information of mobile users. In this paper, we present a position-based quality-of-service (QoS) routing scheme for UWB mobile ad hoc networks. The scheme applies call admission control and temporary bandwidth reservation for discovered routes, taking into consideration the medium access control interactions. Via cross-layer design, it exploits UWB advantages at the network layer by using the position information in routing and bandwidth reservation and by supporting the multirate capability. Simulation results demonstrate that the proposed routing scheme is effective in end-to-end QoS support.**

Index Terms—**Admission control, cross-layer design, mobile ad hoc network, quality-of-service (QoS), routing, ultra-wideband (UWB).**

I. INTRODUCTION

WIRELESS mobile users are still in a great need to communicate in scenarios that do not have any available communication infrastructure, such as post-disaster rescues and business conferences. The ideal solution in this case is to form an ad hoc network, which is a collection of wireless mobile nodes that self-configure to form a network without an inherent infrastructure. Ultra-wideband (UWB) communication is a promising telecommunication technology that has several appealing key features such as low-power consumption, very high data rates, coexistence with other technologies in the same bandwidth, and precise location determination. Combining these features to the advantages of the mobile ad hoc networks makes UWB-based mobile ad hoc networks an ideal candidate for wireless personal area networks (WPANs). One of the most significant challenges for the design of such networks is the need to support the quality-of-service (QoS) requirements such as data rate, packet loss probability, and delay constraints. In this paper, we present a distributed resource allocation (via call admission control and resource reservation) scheme for single-channel multihop UWB-based mobile ad hoc networks. The proposed scheme is to ensure QoS support for various multimedia applications. In a multihop ad hoc networks, resource allocation must be coupled with an underlying routing protocol since it is done in a distributed fashion for a specific path, not for the whole network (centralized fashion). In fact, finding a path that simultaneously satisfies the bandwidth, delay, and packet loss requirements is proved to be an NP-complete problem [1]. Indeed, satisfying the bandwidth requirements only is an NP-complete problem when link interference is taken into consideration [2], [3]. The proposed resource allocation scheme is coupled with a routing algorithm, forming a QoS-aware routing protocol. With the capability of getting the high precision position information of mobile nodes in a UWB network, a proper route can be discovered without network flooding. The greedy perimeter stateless routing (GPSR) [4] is a position-based routing that has been proved to outperform many other existing routing protocols [5]. As a result, we propose an efficient position-based QoS routing protocol based on the GPSR, referred to as QoS-GPSR.

We follow a cross-layer design approach in order to provide QoS guarantees. Currently, contention-based medium access control (MAC) protocols (such as 802.11) are widely adopted. The cross-layer design of the QoS-GPSR has contention awareness [6]. The admission control decision at each node on the route is based on the bandwidth availability information provided by the MAC for the node and its neighbors in its carrier-sense range. The cross-layer design also enables QoS-GPSR to take into consideration the possible simultaneous transmissions of the nodes belonging to the same route when making bandwidth reservation, as the simultaneous transmissions affect the effective throughput [7]. The proposed resource allocation scheme can also work with centralized control time-division multiple-access (TDMA) MAC protocols such as 802.15.3, provided that a proper packet scheduling algorithm is in place.

The remainder of this paper is organized as follows. Section II describes the system model under consideration. The QoS-GPSR is presented in detail in Section III, and evaluated in Section IV based on computer simulations. Finally, Section V concludes this paper.

II. SYSTEM MODEL

We consider a single piconet with a limited number of nodes (e.g., in the order of 50 nodes). At any time, not all of these nodes are assumed to be active (traffic sources); some of them may be idle or work only as packet forwarders. The piconet is an ad hoc network that has only one common physical channel [8], [9]. Every node knows its own position. Each packet source can determine precisely the location of the packet destination [4]. All the traffic sources are assumed to be constant bit rate sources for simplicity, with different QoS parameters; namely, data rate, packet error rate (PER), and end-to-end delay bound or throughput. With a cross-layer approach in our design, more details of the physical layer, MAC layer, and network layer of the system are as follows.

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The Physical Layer: Our system model supports the two main UWB proposals; namely, direct sequence (DS)-UWB [8] and multiband orthogonal frequency-division multiplexing (MB-OFDM) [9], in addition to the conventional impulse radio UWB technology [10]. The system model supports K channel access data rates, $R_1, R_2, \ldots, R_K$, with $R_1 < R_2 < \cdots < R_K$, and the corresponding transmission ranges are $D_1, D_2, \ldots, D_K$, respectively, with $D_1 > D_2 > \cdots > D_K$. The ranges are specified for the required PER and link success probability [8], [9]. The transmission data rate changes adaptively in a discrete manner as the distance between the communicating nodes changes. This adaptive rate change intends to maintain a fixed value for PER per hop. As in [9], the sensitivity of the receiver at the lowest rate R_1 is used for the clear channel assignment (CCA) mechanism, which is used to sense the carrier for the carrier sense multiple access/collision avoidance (CSMA/CA) protocols in the MAC layer. That is, the carrier sense range is at the D_1 range, and hence the nodes still can decode the transmission of each other at that range. Since UWB communication is limited to a short range for indoor [11] and indoor-to-outdoor environments, low mobility is considered.

The MAC Layer: The call admission control and reservation decisions at the network layer are closely dependent on the MAC layer. Here, we consider two single-channel MAC protocols: contention-based MAC and centralized control TDMA MAC protocols. The contention-based MAC protocol works similarly to 802.11 DCF [12]. Mobile nodes use CSMA/CA to access the single channel. When the channel changes its state from busy to idle, a random backoff procedure is initiated at every node to resolve any possible contention conflicts among competing nodes. To resolve the hidden terminal problem, the MAC layer has a mechanism such as the four-way handshake mechanism (RTS-CTS-DATA-ACK) that is implemented in 802.11 DCF. With the centralized control TDMA MAC protocol (such as IEEE 802.15.3), the control is done by a PicoNet controller (PNC), which is one of the network nodes. The exchange of control information is done by the direct communication between the nodes and the PNC. However, for data transmission, all the nodes can communicate directly with each other. In the TDMA-based MAC, time is partitioned to timeslots, and the access to the channel is done by assigning a timeslot to one (and only one) node that wants to transmit. The PNC allocates resources (i.e., timeslots) to the nodes on demand, according to a packet transmission scheduling algorithm. With the multiple data rates supported at the physical layer, the MAC layer at each transmitting node has a corresponding rate-adaptive algorithm.

The Network Layer: As indicated in Section I, the resource allocation at the network layer is coupled with the GPSR routing protocol. The GPSR uses a technique called greedy packet forwarding [4], [13]. In this technique, the sender of a packet includes the approximate position of the recipient in the packet. When an intermediate node receives the packet, it forwards the packet to the geographically closest neighbor with respect to the packet destination. This process is repeated at each discovered hop until the destination is reached, as illustrated in Fig. 1. When node A receives a packet destined to E, it forwards the packet to B, as the distance between E and B is less than that between E and any of A's other neighbors. After B receives the packet, it follows the same procedure, and so on, until E is reached.

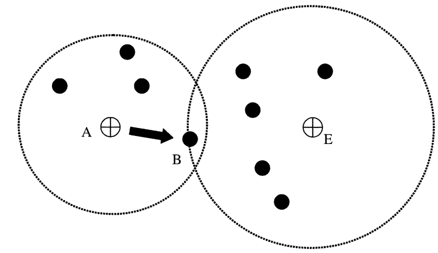

Fig. 1. Greedy forwarding, where node B is A's closest neighbor to E.

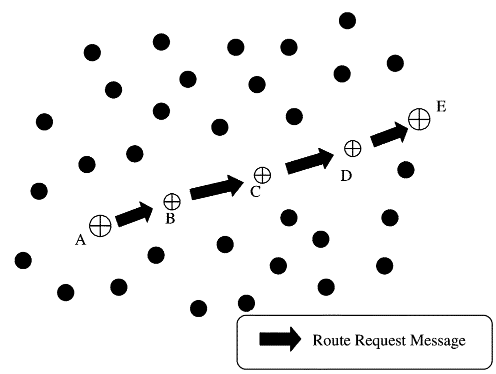

Fig. 2. Route discovery procedure.

The GPSR implements a simple beaconing protocol that provides all nodes with their neighbor's positions. In the protocol, each node periodically broadcasts its IP address and position via a beacon to its neighbors [4]. Note that the beacon broadcasting does not congest the network for two reasons: 1) in the multihop routing, the number of the neighboring nodes is substantially less than the total number of nodes in the network and 2) with low mobility, the frequency of the beacon broadcasting is not required to be high. The GPSR protocol is modified to work with our call admission control and reservation procedures for QoS support, as discussed in Section III.

III. QoS-GPSR

The proposed QoS-GPSR contains three main procedures: 1) route discovery; 2) admission control and resource reservation; and 3) route repair.

A. Route Discovery

Fig. 2 illustrates a network topology for the route discovery procedure. The procedure works as follows.

Step 1) The source node A starts to discover the route by using a modified GPSR protocol. The protocol is modified in two aspects. The first modification is to accommodate the multirate transmission capability of the UWB physical layer, as explained in the following.

- The node ID and location information are broadcast via the beacon to the carrier-sense range neighboring nodes.
- A neighbor list is generated. The list is ordered based on the distance between the neighbor and the destination by first listing the node closest to the destination.
- The first one-hop neighbor, which can be contacted with a rate higher than R_1, is selected

from the list. If no such neighbor exists, it takes the first node in the list (note that all the nodes in the list can be contacted with rate R_1).

Step 2) The source node A sends a "Route Request" message. The message contains the following traffic flow information: the total delay bound, the total PER bound, the flow ID, the node ID, and the current PER for every hop (note that the PER is fixed per hop).

Step 3) After that, node A starts a route discovery timer.

Step 4) Every node that receives the message updates the current accumulated PER value by the PER value for its hop. The node then compares that with the total required PER bound value given in the message. If the PER bound is exceeded, it sends a "Route Failure" message back to the source node. Upon receiving the "Route Failure" message, the source node starts the route discovery procedure again (without restarting the timer) to discover a new route as in Step 1), excluding the first node in the route that it has discovered before from its neighbor list in order to discover a completely new route. In this way, the packet loss bound will not be exceeded in any discovered route.

Step 5) If the PER bound is not exceeded, the node appends its ID and its current location to the packet. This is the second modification to the GPSR protocol. With the modification, the protocol uses a source route that is found in every data packet. This source route contains the IDs of the route's nodes in addition to their locations. This means that each route is discovered only once and, after that, a kind of virtual circuit is established between the source and the destination. The introduction of the source route adds an overhead to the packet, but the overhead is not significant for three reasons: 1) the two-dimensional position of each node is encoded to four bytes; after adding the Internet protocol (IP) address (node ID), the total overhead per node is 8 bytes [4]; 2) in a small-scale ad hoc network, a single route is not expected to contain a large number of nodes; and 3) with very high data rates in UWB transmission, data packets having a large payload (in the order of thousands of bytes) are reasonable.

Step 6) The node records necessary information of the traffic flow in a table, referred to as Traffic Flow Table, and then starts discovering another intermediate node as node A does in Step 1) and forwarding the "Route Request" message to the node, and so on, till the destination is reached.

Step 7) If the route discovery timer is expired before the flow is admitted, the source node A sends an "Admission Stop" message to every node in the route to cancel the flow and to stop any running activity associated with it.

B. Call Admission Control

Before describing the call admission control procedure, we will shed more light on MAC contention awareness and simultaneous transmission features.

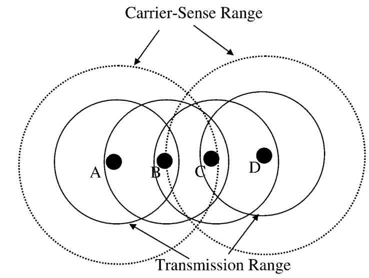

Fig. 3. Contention among nodes.

1) MAC Contention Awareness: In single-channel MAC, the channel is inherently shared among all the mobile nodes. This shared medium is different from the wired shared medium in that every node has its own view of the state of the communication channel [6]. For instance, in Fig. 3, the traffic from node A impacts both node B (in the transmission range of node A) and node C (in the carrier-sense range of node A). Also, although node A knows that nodes B and C are sharing the channel with it, it does not know about any other nodes that share the channel with node B if they are out of node A's carrier-sense range. For example, if the channel rate is R b/s and both node D and node C are using the channel each with $R/4$ b/s, the average available channel bandwidth is $R/2$ b/s for node B. However, node A sees the average available channel bandwidth for itself and for nodes B and C is $3R/4$ without knowing about D. The MAC contention is handled in QoS-GPSR as follows.

- Every node calculates its average available channel time by monitoring the network activities to measure the channel idle time T_{idle}. The channel is considered idle if the node is not in one of the following states [6]: 1) the node is transmitting or receiving a packet; 2) the node senses a busy carrier larger than its carrier-sense threshold; and 3) the node receives a message indicating the reservation of the channel for some time such as RTS or CTS if the (RTS-CTS-DATA-ACK) handshaking is used.
- The fraction of the local available channel time for a node can be estimated every T_p period of time [6]

$$T_{\text{local}} = \frac{T_{\text{idle}}}{T_p}. \quad (1)$$

  This estimation is relatively accurate and simple as compared with other methods [6].
- The node sends a broadcast message to its neighbors in its carrier-sense range to indicate the required channel time of the flow and ask for the availability of the channel.
- Based on (1), the neighbors compare the available channel time with the time already used and the time already reserved (if any), as to be illustrated in the admission control procedure.

2) Simultaneous Transmission: The per-flow throughput for an ad hoc network where a chain of nodes are engaged in the transmission of a data traffic flow is studied in [7]. As illustrated in Fig. 4, the chain starts from the source node 1 and ends at the destination 6. When a node transmits, it occupies the full channel rate. In the absence of interference, if node 1 and node 4 (in Fig. 4) cannot transmit at the same time, but node 5 can,

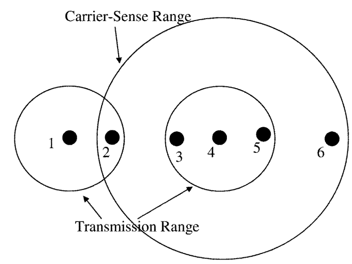

Fig. 4. MAC interference among a chain of nodes.

the per-flow throughput is 1/4 of the single-hop throughput since only one node (out of nodes 1–4) can transmit at a time.

Note that our network topology is different from that illustrated in Fig. 4 since it is not a chain topology. On the other hand, the traffic source and the intermediate nodes for a new flow use only the available free bandwidth (not the maximum channel rate) which is taken into account by the idle time calculations. As a result, the throughput given in [7] can be applied to our ad hoc network; however, the per-flow throughput reflects the traffic throughput as seen by the flow destination. For instance, if the source transmits at a rate of R_b (for a route similar to Fig. 4), the destination receives a traffic throughput of $R_b/4$, as compared with R_b in the case where the destination is only one-hop away from the source.

Taking into account multiple hops and simultaneous transmissions, the QoS is supported as follows.

For delay-sensitive applications, the destination equally divides the required end-to-end delay bound among the nodes that cannot transmit simultaneously. Each node should have the amount of bandwidth required to achieve its individual delay bound. For throughput-sensitive applications, the destination assigns a bandwidth to every node, which is equal to the source rate multiplied by the number of hops with no simultaneous transmission (i.e., $4R_b$ in the previous example). Every node compares the available bandwidth with the bandwidth required to achieve the delay bound or throughput. If there is no sufficient bandwidth, the node rejects the flow.

3) Call Admission Control for a CSMA/CA-Based MAC: The call admission control starts after the route is discovered. Consider the route as shown in Fig. 5, where the nodes are labeled by $A, B, \ldots, E$ from the source to the destination. The call admission control and bandwidth reservation procedure is proposed in the following.

Step 1) After the destination (node E in Fig. 5) receives the "Route Request" message, it records the source route and the locations of all the nodes in the route. The destination E knows, by simple calculations, which nodes of the route can transmit packets simultaneously. The destination then assigns the required bandwidth to every node in the route, based on the application type (delay-sensitive or throughput-sensitive).

Step 2) The destination (node E) sends an "Admission Request" message to the node in front of it (node D in Fig. 5). The message contains the flow ID, the source route, and the bandwidth required for every node in the route.

Step 3) Node D first calculates the fraction of its local available channel time using (1), and then calculates the remaining fraction of channel time using (2) and (3) given by

$$T_{\text{remaining}} = T_{\text{local}} - T_{\text{reserved}} \tag{2}$$

$$T_{\text{reserved}} = \sum_{n=1}^{N} \frac{B_{n(\text{req})}}{B_{n(\text{access})}} \tag{3}$$

where T_{local} is the fraction of the local available channel time calculated from (1), $B_{n(\text{req})}$ is the bandwidth in bits per second required for a previously reserved flow segment to achieve its QoS requirements, $B_{n(\text{access})} \in \{R_1, R_2, \ldots, R_K\}$ is the channel access rate in bits per second to be used by this flow segment, and N is the number of segments for the flows that requested reservation before. A flow segment (indexed by n) is uniquely identified by node ID, flow ID and hop index since each node in the network can sense the segments of all running flows within its carrier-sense range. Basically, the ratio of $B_{n(\text{req})}$ to $B_{n(\text{access})}$ is the average fraction of the channel time that will be used by the flow segment. If the remaining channel time is less than the required one, the admission fails at node D; otherwise, node D temporarily reserves this bandwidth (channel time) for the flow. The reservation information is recorded in a table called "Flow Reservation Table." The table includes the flow ID, reserved bandwidth $B_{n(\text{req})}$, the hop index, the ID of node that reserved the flow, and the access rate of the node $B_{n(\text{access})}$.

Step 4) Depending on the outcome of Step 3), if node D can admit the flow, it broadcasts a "Reservation Request" message to all its carrier-sense neighbors, asking for their bandwidth availability. The message contains information of the bandwidth required for transmitting from D to E, flow ID, hop index, and its channel access rate. If node D cannot admit the flow, it sends an "Admission Refused" message to the node just in front of it in the route (node C in Fig. 5).

Step 5) In the case that D sent an "Admission Refused" message to node C, node C starts a route repair procedure (to be described). In the case that D sent a "Reservation Request" message, the neighboring nodes check their local available bandwidth in the same way as node D does in Step 3). If a node finds out there are sufficient resources available, it

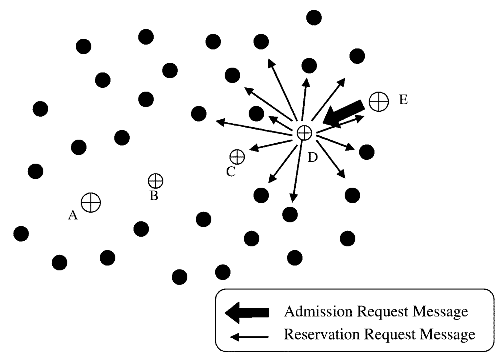

Fig. 5. The beginning of the call admission control procedure.

reserves this bandwidth temporarily for the flow, records the message information in the Flow Reservation Table and sends the "Reservation Accepted" message; otherwise, the node sends a "Reservation Refused" message.

Step 6) Node D acts according to what it has received from its neighbors. If the reservation is accepted from all the neighbors, it forwards the "Admission Request" message to the node just before it in the source route (node C in Fig. 5), and node C in turn starts the same procedure from Step 3); otherwise, if node D received a reservation refusal, it sends an "Admission Refused" message to node C which in turn starts a route repair procedure.

Step 7) The procedure is repeated up to the source node.

It is worth noting that the bandwidth reservation is temporary since the idle time calculations take into consideration any traffic flows already in service. This reservation aims at preventing any false calculations that may occur if several flows are competing to be admitted at the same time.

4) Call Admission Control for Centralized Control TDMA MAC: In this MAC, the PNC is in charge of the resource reservation and the assignment of timeslots. Multiple transmissions in the same timeslot are not allowed. The bandwidth reservation for any node lasts until the node cancels it. The admission control procedure is presented in the following.

Step 1) When the destination (node E in Fig. 5) receives the "Route Request" message, it records the source route and then assigns the bandwidth required for every node in the route, using only the total number of hops.

Step 2) The destination (node E) sends an "Admission Request" message containing the flow ID, source route, and the bandwidth required for every node in the route to its predecessor in the source route (node D in Fig. 5).

Step 3) Upon receiving the "Admission Request" message, node D sends a "Reservation Request" message to the PNC, indicating the required bandwidth and its current access rate.

Step 4) The PNC decides the acceptance or the refusal of the reservation based on the packet scheduling algorithm.

Step 5) If node D receives a "Reservation Accepted" message, it forwards the "Admission Request" message to its predecessor in the route (node C in Fig. 5); otherwise, if node D receives a "Reservation Refused" message from the PNC, it sends an "Admission Refused" message to node C.

Step 6) If node C receives an "Admission Refused" message, it will start a route repair procedure. On contrary, if node C receives an "Admission Request" message, it will repeat Step 3) and so on till the source is reached.

C. Route Repair

The route repair procedure is initiated if any of the following cases has happened: 1) a node, except the source, receives an "Admission Refused" message from the node that follows it in the source route; if the source node receives an "Admission Refused" message, it will initiate a route discovery procedure again but without restarting the route request timer and 2) a node is no longer able to communicate to the next node in the source route (as indicated in Fig. 6). In both cases, the next node is considered lost. The route repair procedure proceeds as follows.

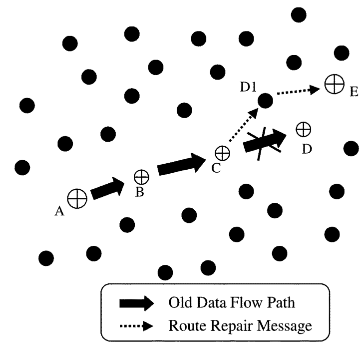

Fig. 6. Route repair procedure.

Step 1) The node that initiates this procedure (node C in Fig. 6) starts to discover another route originating from it to the destination. This is done by repeating Step 1) of the route discovery procedure, after excluding the lost node from its ordered neighbor list.

Step 2) Node C sends to the newly discovered node ($D1$ in Fig. 6) a "Route Repair" message. The message has the same content as the "Route Request" message.

Step 3) When a node (such as $D1$) receives the "Route Repair" message, it first checks if the PER bound given in the message will be exceeded or not as in Step 4) of the route discovery procedure. If the PER bound is exceeded, the node sends a "Route Failure" message back to the node from which it received the "Route Repair" message; otherwise, it repeats Steps 1) and 2) until the destination is reached.

Step 4) When the destination receives the "Route Repair" message, it compares the old source route with the new source route. It then assigns a delay bound value for each node in the new part of the route, starting from the node where the old route broke. This is the same as what the destination has done earlier in the route discovery procedure.

Step 5) The destination starts a route repair timer, and sends two messages. The first is an "Admission Request" message in order to start an admission control procedure for the newly discovered part. The second one is an "Admission Cancel" message, which contains the old route and a one bit flag that indicates whether the node belongs to the new route or not.

Step 6) Every node that receives "Admission Cancel" message and does not belong to the new route removes all the route information.

Step 7) The new admission control procedure ends at the node where the old route broke. The flow is resumed at that time. When the destination starts receiving data, it stops the repair timer.

Step 8) If the route repair timer is expired before the flow is resumed, the destination sends an "Admission Stop" message to every node in the route to cancel the flow and to stop any running activity associated with it.

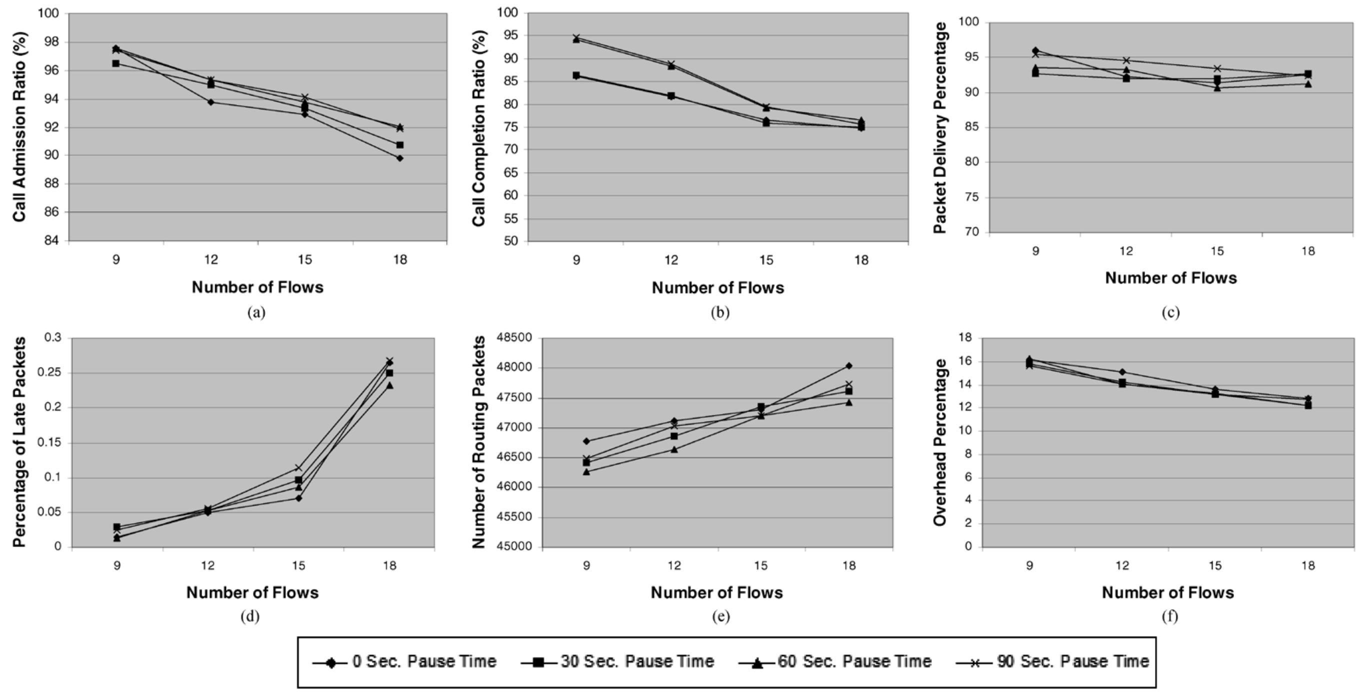

Fig. 7. QoS-GPSR performance evaluation. (a) Call admission ratio. (b) Call completion ratio. (c) Packet delivery percentage. (d) Percentage of late packets. (e) Number of routing packets. (f) Overhead percentage.

IV. Performance Evaluation

The performance of the proposed QoS-GPSR protocol is evaluated using the ns-2 simulator. The simulation model simulates nodes moving in an unobstructed plane [4] following the *random waypoint* model [5]. In the model, a node chooses its speed and its destination uniformly random, moves to the destination, then pauses for a while, and so on. A longer pause time means a lower mobility profile.

In the simulation, the ns-2 WaveLAN implementation for MAC 802.11 is used. This MAC implementation uses 2 Mb/s as a channel access rate which is far from what is proposed for UWB [8], [9]. The selection of this implementation is to compare the performance of the newly proposed QoS-GPSR protocol with some non-QoS routing algorithms given in [5] and to avoid any side effects that may arise from improper scaling of any of the MAC parameters for UWB. The simulation is done for a network of 50 mobile nodes with a maximum speed of 1 m/s. Each node is moving in an area of 670×670 m^2. The node radios have a transmission range of 250 m and a carrier-sense range of 550 m. Different pause times of 0, 30, 60, and 90 s are simulated. There are three QoS classes, differentiated in terms of bandwidth, delay bound, and PER: Class 1 has a transmission rate of 8 kb/s with a delay bound of 100 ms and PER bound of 10%, class 2 has a rate of 16 kb/s with a delay bound of 150 ms and PER bound of 8%, and class 3 has a rate of 32 kb/s with a delay bound of 200 ms and PER bound of 5%. We assume 1% PER per hop. A power control mechanism is in place to mitigate any channel fading impairments in the low mobility environment. The number of traffic flows varies from 9 to 18 with a step size of 3. The packet size of 1024 bytes is used. We ran the simulation for 900 s. The flows start at random time and continue for a session time uniformly distributed from 5 to 15 min (the whole simulation time). To the best of our knowledge, no benchmark metrics have been defined so far to evaluate the performance of QoS ad hoc routing protocols. We have measured the following six metrics.

- Call acceptance ratio, defined as the ratio of the number of the admitted flows to the number of the offered flows.
- Call completion ratio, defined as the ratio of the number of the completed flows to the number of the admitted flows.
- Successful delivery percentage, defined as the ratio of the number of packets delivered successfully to the total number of packets transmitted.
- Percentage late packets, defined as ratio of the packets that arrived after the delay bound to the total packets received.
- Number of routing packets, which is a non-QoS routing metric used to indicate the number of routing (nondata) packets sent.
- Percentage overhead, defined as the percentage of the number of overhead bytes in both data packets and routing packets to the number of bytes in data packets.

Fig. 7(a) shows the relation between the number of offered flows and call acceptance ratio for different pause times. It shows that QoS-GPSR is capable of admitting the flows with a ratio of 94%–98% for up to 12 offered flows, regardless of the pause time. In general, with a constant total bandwidth of the single channel, as the number of offered flows increases, the ratio decreases and the pause time has a negative impact on the call acceptance ratio (which remains to be over 90% for up to 18 offered flows).

Fig. 7(b) shows the relation between the number of offered flows and the call completion ratio for the admitted flows. A call is considered to be dropped if more than 50% of its packets are not delivered successfully. It is observed that the call completion ratio generally decreases as the number of flows increases. The QoS-GPSR protocol is able to achieve more than 95% call completion ratio for nine offered flows with pause times of 60 and 90 s. It is clear that the QoS-GPSR protocol is affected by the mobility profile. As user mobility increases, the chances of a broken path increases, resulting in a degraded performance of QoS GPSR. Note that QoS-GPSR is designed mainly for indoor applications which normally have low mobility profiles.

Fig. 7(c) shows the average percentage of packets successfully delivered for each pause time for different number of offered flows. The figure does not show an increasing or decreasing trend since the percentage of successful packet delivery depends on both the number of flows admitted and the number of flows dropped. It is observed that QoS-GPSR performs very well in terms of packet delivery. It delivers successfully 90%–95% of the packets for all cases with any pause time. Generally, higher user mobility negatively affects the delivery percentage.

Fig. 7(d) shows the percentage of packets that arrived after the delay bound. It is obvious that QoS-GPSR is very successful in satisfying the end-to-end delay requirement. In the worst case, the late packets do not exceed 0.27% of the packets successfully delivered.

Fig. 7(e) shows the number of routing packets versus the number of offered flows. This is a non-QoS parameter. We use this parameter to measure the cost of the QoS support in the QoS-GPSR protocol by making a performance comparison with the previous GPSR protocol [4] and other routing protocols [5]. The number of flows that have been used in [4] and [5] was quite high (30 flows) but with very low data rates in order of 2 kb/s, which corresponds to a similar traffic load as to our case (a smaller number of flows with higher data rates) [5]. It is observed that the order of the number of routing packets compares very well with non-QoS routing protocols such as destination sequential distance vector (DSDV), which has approximately 41 000 routing packets and TORA which has more than 50 000 routing packets. However, compared with GPSR (having approximately 16 000 routing packets), the QoS-GPSR protocol has a larger number of routing packets, due to its QoS support mechanisms.

Fig. 7(f) shows the overhead percentage for a different number of offered flows. The overhead percentage decreases as the number of flows increases. This results from a relatively increased number of data packets sent for a lower number of flows, due to a higher ratio in both call admission and call completion. The maximum percentage overhead does not exceed 16%, which seems to be acceptable taking into account the distributed control in an ad hoc environment and the extra cost for QoS support.

V. Conclusion

We have proposed the QoS-GPSR protocol for UWB mobile ad hoc networks, which provides per-flow end-to-end QoS guarantees in terms of packet loss and end-to-end delay or effective throughput depending on the applications. The QoS-GPSR protocol efficiently utilizes the network radio resources by using the precise position information provided by UWB to discover the shortest possible path to the destination. After that, it starts the call admission control and reservation procedures on the discovered path. The admission control takes into consideration the MAC interactions to ensure that the new flow will not affect the QoS provisioning to other existing flows. Simulation results demonstrate that the QoS-GPSR protocol is effective and efficient in the end-to-end QoS provisioning.

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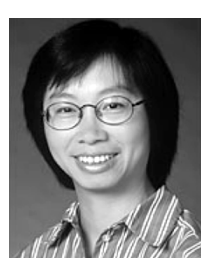

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