Route Selection for Capacity Maximization in Multi-Rate TDMA-based Wireless Ad Hoc Networks

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***Abstract*—In this paper we address the issue of designing a routing scheme for ad hoc networks, which aims at maximizing the number of flows with satisfied bandwidth demands. In general, selecting a multi-hop wireless path for bandwidth-guaranteed flows is challenging because of the broadcast nature of the wireless medium. Thus, in this study we formulate the route selection problem by considering a synchronized multi-rate TDMA access scheme. Once the route is found, the radio resources are reserved as time slots in the TDMA frames along the path the flow takes. We demonstrate that selecting routes so as to maximize the number of accepted flows is an APX-complete problem (i.e., there are no polynomial-time approximation schemes), even under simplified rules for bandwidth reservation. This result is stronger than previously established in other studies. Guided by our analysis, we propose a new Cumulated Available Resources and Topology Aware (CARTA) routing heuristic, which selects routes bypassing heavily loaded and highly interfered network regions. Simulations performed with random topologies of up to 100 nodes and various traffic configurations show that CARTA obtains a more balanced utilization of the network resources, and up to 25% capacity increase than the second best metric from the literature we tested, at the cost of a limited increase in path lengths.**

I. Introduction

An ad hoc network is an autonomous system of stationary or mobile nodes equipped with wireless interfaces, which support multi-hop routing to form self-organizing and spontaneous networks without a central control. Thus, ease of deployment and decentralized operations make ad hoc networks attractive options for stand-alone use in case of infrastructure break-down, or as temporary extensions of fixed networks. However, ad hoc networks must also deal with the peculiarities of the wireless broadcast medium, and the limited and variable capacity of wireless links. As a consequence, designing multi-hop radio systems that make the best use of the radio resources has proven challenging, requiring cross-layer design of system functions [8], [9].

To maximize the utilization of the scarce wireless resources, the Medium Access Control (MAC) protocol plays a crucial role. Contention-based MAC protocols are widely employed in ad hoc networks, such as the CSMA/CA-based IEEE 802.11 [1]. However, it is well known that CSMA suffers performance degradations under high contention, and it incurs unpredictable access delays, which limits its ability to support different QoS requirements. On the contrary, in this work we consider a synchronous *multi-rate* TDMA-based ad hoc network, where time is slotted and nodes allocate time slots in TDMA frames to ensure error-free transmissions. Moreover, wireless links can support different transmission rates depending on the physical link quality. Note that time synchronization can be achieved either by listening to MAC beacon patterns and aligning time slots accordingly [18], or using an external source such as the GPS timing signals [17].

It is commonly recognized that TDMA-based scheduling is better suited to support QoS demanding flows, because it permits a more effective radio-resource reservation. In this study we are concerned with flows that require a guaranteed bandwidth, i.e., flow needing a certain bit rate in order to satisfy their QoS requirements. In this case the flow demands can be satisfied by reserving an appropriate number of time slots in the TDMA frames along the path the flow takes. Generally speaking, QoS provision and resource reservation in TDMA-based ad hoc networks involves two interdependent tasks. Firstly, it is necessary to find a path between source and destination nodes, which can satisfy the QoS requirements of that flow. Then, a feasible schedule for the required time slots should be computed along the selected route.

Scheduling has been extensively studied, and many scheduling problems have been shown to be NP-complete [6], [15], [16]. Thus, several efficient but sub-optimal algorithms for slot assignment in TDMA systems have been designed, which aim at maximizing the number of concurrent transmissions within a time slot, while maintaining the TDMA frame as small as possible [19]–[21]. Note that these schemes do not generally consider the QoS requirements of admitted flows. For these reasons, other studies have proposed to jointly perform scheduling and routing in TDMA-based ad hoc networks in order to find routes ensuring guaranteed bandwidths [2], or limited end-to-end delays [3], [22]. Nevertheless, previous studies [4], [23] have proven that, in a TDMA-based ad hoc network, the problem of selecting a path satisfying the bandwidth constraints is NP-complete.

This study departs from this previous work by looking for

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a routing scheme that both satisfies the QoS demands of new flows and that maximizes the use of the radio resources in the network. In other words, we consider the problem of maximizing the number of accepted bandwidth-constrained flows in a multi-rate TDMA-based ad hoc network. Note that we do not deal with the detailed protocol implementation of the reservation scheme: several solutions have been proposed both for reactive [23] and proactive routing schemes [24]. The purpose of this study is to assess the complexity of the maximum capacity problem, and to compare several routing heuristics that address it, evaluating their performances in terms of capacity (number of accepted flows), and the impact they have on the path length and load distribution.

In this work we provide the following main contributions:

- We model the maximum capacity routing problem for a multi-rate TDMA-based ad hoc network and we establish that the problem *maximizing network capacity is APX-complete*.
- We propose a new isotonic routing metric, called CARTA, which stands for *Cumulated Available Resources and Topology Awareness*, to solve the maximum capacity routing problem.
- We compare the performance of CARTA with three other existing routing schemes.

The remainder of the paper is structured as follows. Section II presents the multi-rate TDMA-based ad-hoc network model used throughout the paper. Section III provides the complexity analysis of the problem and Section IV presents routing heuristics from the literature and CARTA, the one that we introduce here. Section V presents the results obtained in comparing CARTA to the state of the art in a simulation environment. Section VI discusses and concludes the paper.

II. Network Model

The network model that it is used throughout this study consists of a multi-hop wireless ad hoc network. All the nodes in the network are equipped with a single radio interface using the same wireless channel. This network topology can be represented as an undirected graph $G(V, E)$, where V is the set of nodes and E is the set of links. Link $e_{i,j}$ means that nodes i and j can communicate. The physical layer model determines which is the transmission rate $r_{i,j}$ that can be used for transmitting one packet from node i to node j. In this study we use the SINR to determine the physical-layer quality of the link. More precisely, if node i is transmitting to node j, and $\mathcal{T}_i$ is the set of other nodes that transmit concurrently with i, then the SINR of link $e_{i,j}$ is given by

$$SINR_{i,j} = \frac{P_{i,j}}{\sum_{k \in \mathcal{T}_i} P_{k,j} + \mathcal{N}_0} , \tag{1}$$

where $P_{i,j}$ is the received power at node j when node i is transmitting. This choice is motivated by inaccuracies of simpler models such as the protocol model or non-additive interference models [7]. From the $\text{SINR}_{i,j}$ value, node i determines the transmission rate to be used for sending a packet to node j based on the minimum SINR threshold for each transmission rate. More precisely, the receiver sensitivity varies with the modulation scheme used for transmissions. Then, a transmission rate can be successfully used only if the current SINR is above the corresponding receiver sensitivity. This allows us to precisely incorporate *rate diversity* in our study, which is one of the most important characteristics of deployed multi-hop wireless networks [12]. To coordinate the channel access the nodes in the network use a multi-hop TDMA-based MAC protocol, such as the one adopted in the IEEE 802.16 technology for ad hoc mode [27]. More precisely, the time is divided into frames of L slots of duration τ. To simplify the scheduling process we assume that the TDMA frames of all nodes in the network are perfectly synchronized, and that each node knows the TDMA reservations of other nodes so that to avoid packet collisions.

In this study we assume that a flow established between source s and destination d needs a certain bit rate, equal to $b_{s,d}$ bits per second, in order to satisfy its QoS. Thus, when a new bandwidth-constrained flow is generated, the QoS routing algorithm should find a network path between node s and node d with sufficient available resources. When this network path is selected, the scheduling algorithm reserves on each TDMA frame along the path the flow should take a number of time slots sufficient to satisfy the bandwidth requirements. In this study we assume to know the traffic demands for each source-destination pair. For example, demand information might be advertised through the network using some flooding mechanism, thus permitting a distributed computation of network paths.

Basing on the SINR physical model, a time slot t in the TDMA frame of node i can be reserved for a packet transmission to node j (i.e., it is a *free* slot), only if the time slot t is not yet scheduled to send of receive in neither i or j ; the packet transmission carried out by node i does not disrupt the simultaneous packet receptions of its neighboring nodes ;the packet reception at node j is not disrupted by the simultaneous packet transmissions of its neighboring nodes. As observed above, multiple time slots should be reserved on the same link depending on the requested flow bandwidth. More formally, let us denote with $\mathcal{P}_{s,d}$ the path established between source node s and destination node d using an appropriate routing metric. Then, for each link $e_{i,j} \in \mathcal{P}_{s,d}$ the number $x_{i,j}^{s,d}$ of free time slots needed to satisfy flow bandwidth requirements is given by

$$x_{i,j}^{s,d} = \left\lceil \frac{b_{s,d}}{R_{i,j}} \cdot \frac{1}{\tau} \right\rceil ,$$

where $R_{i,j}$ is the transmission rate used on link $e_{i,j}$. To simplify the scheduling process, for each link $e_{i,j} \in \mathcal{P}_{s,d}$, the transmitting node i reserves the first $x_{i,j}^{b,s}$ free slots, even if not consecutive. In other words our scheduling algorithm works similarly to the *first fit* algorithm, which is a fast but non optimal solution for the bin packing problem [13]. More complex approximation algorithms could be devised, but the design of optimal scheduling minimizing the probability of rejecting future flows is out of the scope of this study. Finally, it should be noted that in this study we do not consider the communication protocol overheads for propagating the TDMA reservation tables and the demand information between nodes.

III. Network Capacity problem complexity

This section studies the complexity of the Network Capacity maximization in a multi-rate TDMA-based ad hoc network. Different definitions can be adopted to evaluate the network capacity. One option is to consider a finite set of flow demands and try to maximize the cumulated data rate by progressively increasing each flow demand until one node gets congested [25], another option consists in considering a finite unordered set of flows and try to maximize the number of accepted flows in the set. The first one lacks fine granularity for investigating arbitrary traffic patterns, and the second one yields an unwanted bias on the set of accepted demands towards demands between closer nodes. Herein, we define the network capacity as the number of flow demands that can be supported by he network. We then assume that the network capacity is reached when a bandwidth-constrained flow must be rejected because its demands cannot be satisfied. The procedure depends on the order in which the sequence of demands is processed. For comparing the different routing schemes in Section V the results are averaged over simulation runs with randomised ordered sequences. This is obtained by choosing the source/destination pairs at random independently for each run.

According to the network model described in Section II, we define the problem of "*Maximizing Network Capacity* (MAX–NC)", i.e., maximizing the number of accepted flows which can be both routed and for which slots can be assigned.

- **Instance**: An undirected graph $G = (V, E, L, w)$, where V is a set of nodes and E is a set of edges. On each node $k \in V$ a TDMA-Frame of $L(k)$ slots with a duration equal to $\tau = 1$. To each edge $e \in E$ is associated a weight $w(e) = 1$ that corresponds to the coding scheme on the link. An infinite set $\mathcal{F}$ flow demands $f_1, ..., f_i, f_{i+1}, .., f_\infty$ from s_i to d_i. All flows require a bandwidth equivalent to 1 slot.
- **Solution**: An elementary path set $\mathcal{P}_n$ for a subset of flows $F_n = f_1,\ ...,\ f_i,\ f_{i+1},\ f_n \subset \mathcal{F}$ such that there exists a path p_i for each flow $f_i \in F_n$ that connects s_i and d_i and along which all slots can be assigned.
- **Measure**: Value of accepted flows n.

We can now state:

Theorem 1. *The problem of Maximizing Network Capacity in a TDMA-based ad hoc network is APX-complete, i.e., it is not approximable and there is no polynomial-time approximation scheme.*

Proof: First, it is trivial to note that the decision problem associated to the optimization problem $MAX-NC$ is NP-Complete by extension of the NP-Complete Remaining Capacity problem developed in [4]. To prove that it is also not approximable, we will work on a subset of the problem MAX–NC, or *instance* of the problem.For ease of reading, we refer to the above defined instance of MAX–NC problem as $MAX-NC1$.

The proof of non approximability for problem MAX–$NC1$ consists in establishing a one-to-one reduction of this problem to the MAX K-Satisfiability ($MAX\ K$–SAT) problem, which is known to be APX-complete [28]. Due to space limitations, we do not present here the complete proof of Theorem 1, but we sketch the proof line of reasoning. A complete proof can be found as a separate document [29].

For introducing the idea of the proof let us set $K = 3$. Furthermore, let us consider an instance G of the MAX 3–!!SAT problem composed of two clauses $\mathcal{I} = (a \wedge b \wedge c) \vee (\neg a \wedge b \wedge d)$, where $\wedge$, $\vee$, $\neg$ are the and, or and not boolean operators, respectively. Figure 1 depicts how the instance G can be transformed to and equivalent instance G' of the MAX–$NC1$ problem.

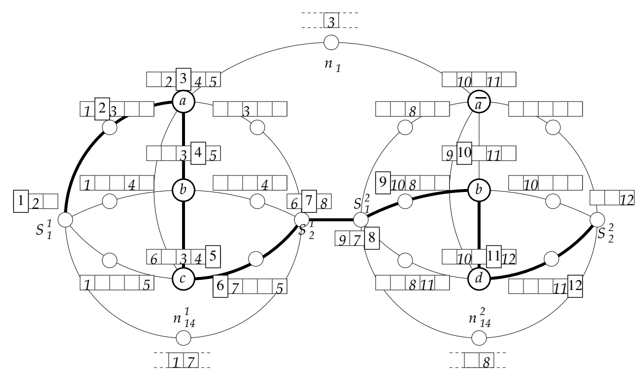

Fig. 1. Transformation of the instance G of the MAX 3–SAT problem to the instance G' of the MAX–$NC1$ problem.

In the network shown in the graph, some nodes are used to represents the literal of each clause. Let us assume that the number of remaining free slots for each node is distributed as follows:

- Nodes S_1^1, S_2^1, S_1^2, S_2^2 have a TDMA-Frame of 3 remaining free slots.
- Nodes that correspond to the literal have a TDMA-Frame of 5 remaining free slots.
- Node n_1 has 1 free slot left in its TDMA-Frame that can be chosen equally on one of the 5 slots of its TDMA-Frame.
- Nodes n_{14}^1, n_{14}^2 have 2 free slots left in its TDMA-Frame that can be chosen equally on two of the 5 slots of its TDMA-Frame.

Let $\mathcal{F}$ be an infinite set of flows such as f_1 has to connect A_1 and n_{14}^1, f_2 has to connect A_2 and n_{14}^2 and all flows $f_{3 \leq i \leq \infty}$ have to connect s_1^1 and s_2^2.

Maximizing the number of accepted flows consists in first finding a path for flow f_1, then, for flow $f2$ and so on. It is trivial to note that the first two flows f_1 and f_2 can be routed. The problem appears for the third flow f_3, the one from s_1^1

to s_2^2. The key idea behind the proof is the following: if this flow f_3 can be routed without pre-empting any of the two first flows then a true assignment exists for the MAX 3–SAT problem. If no path can be found to route the flow f_3 without pre-empting either f_1 or f_2, then no true assignment for the MAX 3–SAT problem can be found. These two statements would ensure a one-to-one mapping of both instances of the problem.

In this example, the path $S_1^1 \rightarrow a \rightarrow b \rightarrow c \rightarrow S_2^1 \rightarrow S_1^2 \rightarrow b \rightarrow d \rightarrow S_2^2$ is routed without pre-emption and without saturation of any of the nodes. First, the node S_1^1 emits a packet (that is received by the four unnamed nodes). Then one of these four nodes emits the packet to the node a and so on until reaching node S_2^2. None of the nodes are congested. This solution in the instance of the $MAX{-}NC1$ problem corresponds to the solution $\{a = true, b = true, c = true, d = true\}$ and it is also a true assignment in the MAX 3–SAT problem. Let us emphasize that nodes a and $\overline{a}$ cannot belong to the path at the same time. We thus see that maximizing the number of clauses with a true assignment corresponds exactly to maximizing the number of accepted flows.

The complete proof reported in [29] show how to generalize this construction for the problem reduction. ■

IV. Routing Heuristics

In this section we deal with the design of a novel QoS-aware routing metric, which aims at maximizing the capacity of a TDMA-based ad hoc network. In our study we focus on a special class of routing metrics classified as *isotonic*[1] [5], because they permit efficient (i.e., with polynomial complexity) and loop-free computation of minimum-weight routing paths. Moreover, we consider a proactive routing scheme where nodes obtain exact knowledge of the network topology and link costs, and then apply Dijkstra's algorithm to establish the minimum-weight routing paths between each source/destination pair. In this study we are not concerned with topology information dissemination protocols, since many efficient schemes are already available (e.g., MPR-based flooding protocol proposed for OLSR [26]).

In the following, we firstly outline three QoS-aware routing metrics that we will use in the performance evaluation, which are representative of the most relevant routing approaches previously proposed in the literature. Then, we describe the routing metric proposed in this paper, identifying how it differs from the others.

A. Existing heuristics

- **Interference Aware Resource Usage (IRU)**: The IRU metric [**?**] for link $l_{i,j}$ between nodes i and j is defined as:
$$IRU_{i,j} = ETT_{i,j} \times |N_i \cup N_j| \ , \qquad (2)$$
where N_i is the number of node i's neighbors, and ETT$_{i,j}$, as introduced in [10], is the expected transmission time for link $l_{i,j}$, computed considering the link bandwidth $R_{i,j}$ (i.e., the transmission rate).
- **Heuristic based on the remaining capacity of forwarding nodes neighborhood (HN(1))**: The heuristics HN [4] assigns to each node $i \in V$ a weight equal to:
$$HN_i = \sum_{j \in N_i \cup i} \frac{1}{RC_j} \ , \qquad (3)$$
where RC_j is the *remaining capacity* of node j, which is computed as the number of free time slots in the TDMA frame of node j, and N_i is the 1-hop neighborhood of node i.
- **Load-Aware ETT (LAETT)**: This metric was originally proposed in [25].
$$LAETT_{i,j} = ETT_{i,j} \times \frac{1}{RC_i + RC_j} \ . \qquad (4)$$
As illustrated in formula (4), LAETT combines the ETT metric and the remaining capacity at the two end points of each communication link.

The IRU metric has the nice property of being a contention-aware metric because it accounts for the number of potential interfering nodes. However, it is also load-agnostic because it considers only the link capacity and not the remaining radio resources currently available on the link. Differently from the IRU metric, HN(1) introduces load-dependent information in the routing decision because it considers the utilization of channel resources due to the local traffic load, so as to assign a higher cost to highly loaded links. To some extent, the LAETT metric estimates the *marginal cost* of adding a new flow on the link $l_{i,j}$, and it assigns a low cost to links that have high *cumulated* remaining capacity.

B. Proposed heuristic

The design rationale behind our proposed metric is to combine the advantages inherent to both IRU and LAETT metrics. Specifically, taking into account the number of interfering neighbors as IRU does, can help to outperform simple routing metrics such as ETT, which neglects location-dependent contention. Indeed, *topology-aware* routing metrics are best suited to find routes that minimize the inter-flow interference, i.e., the interference between adjacent links that are used by different network paths. On the other hand, when the traffic load is not uniform in the network it is also important to identify the congested network regions, where the available channel resources are low or even exhausted. In such situations, *load-aware* metrics (e.g. HN(1) and LAETT) can significantly increase the network capacity. In order to deal with the location-dependent interference and the uncertainty of traffic loads, we propose the **Cumulated Available Resources and Topology-Aware (CARTA)** metric, which combines the performance improvements of the three metrics above. Specifically, the CARTA metric assigns to each link $l_{i,j}$ a weight defined as follows:
$$CARTA_{i,j} = ETT_{i,j} \times \frac{|N_i \cup N_j|}{RC_i + RC_j} \ . \qquad (5)$$

[1]A metric is isotonic if the order of the weights of two paths are preserved if they are appended or prefixed by a common third path.

As illustrated in formula (5), first of all CARTA captures the link quality and rate diversity through the ETT cost. Secondly, it takes into account the number of nodes that will be interfered by a transmission on the considered link. Finally, it considers the cumulated remaining capacity to identify non-congested links. Hence, the proposed routing metric can provide a more accurate evaluation of the available network resources because it takes into account the exact number of free time slots that do not interfere with other transmissions. As shown in the next section, this approach permits to achieve a balanced utilization of TDMA frames, avoiding the rapid emergence of network bottlenecks.

V. Performance Evaluation

In this section, we use computer-based simulations to compare the performance of the routing metrics described above. In the following, we first describe the detailed set-up of the simulator, and then we present simulation results for random topologies of up to 100 nodes and various traffic configurations.

A. Simulation Environment

We have developed a discrete-event simulator of multi-rate TDMA-based ad hoc networks, which incorporates a realistic SINR-based physical model. We consider networks where n ad hoc nodes are deployed in an area of $2000m \times 2400m$. All nodes have a single radio and operate over a common channel. To evaluate the SINR at the receiving end of each link we use formula (1). Without loss of generality we assume that noise power $\mathcal{N}_0$ is negligible, while the path loss is modeled by a continuous attenuation function of the distance, i.e., $P_{i,j} = P_{tx}/(dist_{i,j})^c$, where c is the path loss exponent, and P_{tx} is the transmission power. In our simulations we consider $c = 3$, such as in [7], whereas the P_{tx} value is chosen so as to ensure that a packet transmitted at the lowest bit rate can be successfully decoded up to a distance $dist_{MAX}$ from the transmitter. As explained in Section II, the maximum transmission rate that can be supported by each link depends on the receiver sensitivity and the physical link quality. Table I lists the four discrete data rates used in our experiments [2] and the related minimum SINR requirements [14].

TABLE I
MINIMUM SINR VALUES FOR DIFFERENT DATA RATES.

Rate (Mbps)	5	10	20	40
SINR (dB)	5	8	12	21

Hence, we have chosen the P_{tx} value in such a way to obtain a SINR$= 5dB$ when $dist_{MAX} = 250m$, and there is not interference from other transmitters (i.e., $\mathcal{T}_i = \{0\}$ in formula (1)). Then, in our experiments we fixedly assign to each link the highest possible transmission rate that satisfy the SINR requirements shown in Table I. It is important to observe that this multi-SINR link model allows us to evaluate the performance of the routing metrics in network environments affected by rich rate diversity, without the need of introducing specific rate adaptation algorithms that could bias the experimental outcomes.

Regarding the MAC protocol, in our simulator we implemented a TDMA scheme, where a TDMA frame consists of 4000 time slots, and time slot duration is 0.5ms[3]. We assume that all the ad hoc nodes are perfectly synchronized. Furthermore, we assume that the information on slot allocations for each TDMA frame, link qualities, and traffic demands for each source-destination pair, is available at each ad hoc node. Thus, a source node can compute and assign the route, as well as determine the TDMA schedule[4] for each new admitted flow. These assumptions might be considered somewhat restrictive, especially because they neglect the communication overheads due to the exchange of this information. However, we use them to isolate the impact of the bandwidth reservation scheme and detailed routing implementation on the system performance, and we expect to relax them in future work.

In this study we have used UDP as the transport protocol for generating data traffic of QoS demanding flows. Specifically, we consider real-time CBR (Constant Bit Rate) flows because this permits to easily characterize each traffic flow through its fixed traffic demands. On the contrary, flow-controlled protocols, such as TCP, are in general less suitable for bandwidth reservation. If not otherwise stated, in the following tests source and destination nodes for each new flow are randomly selected, while the traffic demand is equal to 20Kbps for each new flow (i.e., one time slots for the maximum bit rate). If the source node is not able to find a feasible route for the new flow, this flow is rejected. The number of flows that have been accepted before the first rejection represents the network capacity. It is important to note that each independent simulation run uses a different flow arrival pattern, but different routing metrics are tested using the same patterns to assure fair performance comparisons.

In the following we show the average results obtained by performing 400 simulation runs for each topology. When applicable, the figures report also the 95% confidence intervals, which are always very tight.

B. Simulation Results

The four metrics defined in Section IV have been implemented and compared by simulation. The first and main criterion considered in this study to evaluate the routing efficiency is the network capacity. The four heuristics are also compared in terms of path lengths and load distribution over the network.

1) Network capacity: Figure 2 shows the network capacity reached by each of the four routing heuristics for random networks of up to 100 nodes. First of all we can observe that CARTA heuristic outperforms the other considered routing

[2]These transmission rates are consistent with the data rates used on $802.11a/g$ links, and they have been selected to ease the scheduling process, as explained later in this section.

[3]Using this parameter setting, each time slot can deliver up to 20Kb of data when the highest transmission rate is used.

[4]The scheduling algorithm we have implemented in the simulator is the one we have described in Section II.

metrics in all the considered scenarios, while HN(1) achieves the worst performance. Furthermore, the shown results indicate that the number of accepted flows increases when considering larger networks. However, the network capacity increases faster for CARTA than for the other routing metrics. More precisely, in a 30-node network, the average network capacity using CARTA scheme is 11% (resp. 24% and 9%) greater than using IRU heuristic (resp. HN(1) and LAETT), while in a 100-node network the average network capacity using CARTA scheme is 25% (resp. 100% and 35%) greater than using IRU heuristic (resp. HN(1) and LAETT).

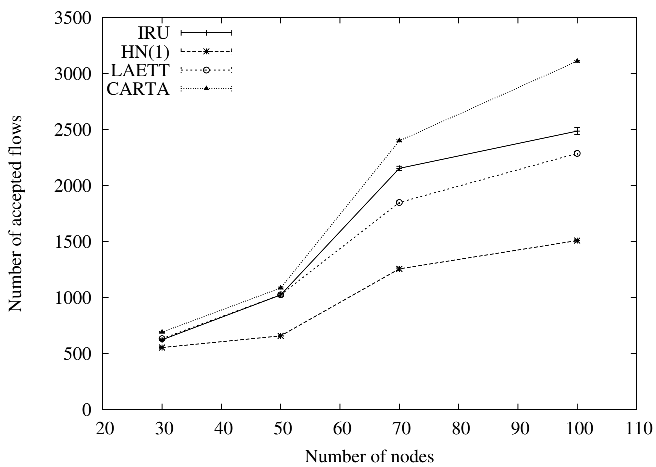

Fig. 2. Network capacity versus the network size.

By inspecting the per-flow routing decisions we found out that CARTA heuristic selects similar paths as IRU metric if the network is lightly loaded. However, since IRU is load-agnostic it can select a paths even if it has no remaining resources, whereas CARTA is able to find alternative routes bypassing highly loaded network regions. On the contrary, both HN(1) and LAETT suffer from a lack of topology awareness and route selection is performed considering only the estimated network load. As a consequence, it is possible to select a path for a new flow that consumes a high amount of radio resources even if a less greedy one exists. On the other hand, CARTA takes advantage and combines both topology and load awareness. It is also interesting to observe that IRU achieves higher network capacity than both LAETT and HN(1), which suggests that under random and uniform traffic patterns (i.e., all the nodes can be source and destination of data flows), topology information prevails over load information.

2) Path length: In Figure 3 we show the probability mass function of path length for the four heuristics and for a shortest path (in terms of number of hops) routing algorithm. These results are computed in a network of 100 nodes, but similar trends were obtained for the other network scenarios, and are not reported here due to space limitations.

The graphs indicate that HN(1) heuristic selects paths with the minimum length while LAETT returns the longest paths. On the other hand, IRU and CARTA have very close distributions. Indeed, as noticed previously, the behavior of CARTA heuristic differs from IRU only when the network becomes congested. In those conditions CARTA starts using longer paths than IRU to avoid highly congested network regions. From the shown results we can also draw two important conclusions. Firstly, the improvement on network capacity is achieved at the cost of a limited increase in path length. In a TDMA-based network this is generally equivalent to an increase of network delays. Secondly, there is a trade-off between the additional radio resources that are consumed using longer network paths and the benefit due to routing around highly congested or highly interfered regions.

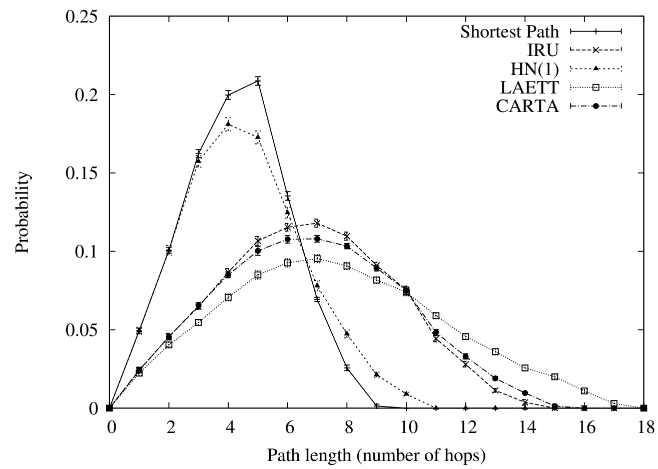

Fig. 3. Probability mass function of path lengths in a network of 100 nodes.

An alternative way for evaluating the impact of routing decisions on path lengths is to compare the properties of the selected routes for each source/destination pair. Specifically, we have computed the difference, in terms of hops, between the minimum hop-count path existing between each source/destination pair and the route chosen using the other routing metrics. Figure 4 shows the probability mass function of this difference. The results indicate that there is a non negligible probability that the LAETT metric selects routes more than 8 hops longer than minimum hop-count paths. Once again, IRU and CARTA behavior is very close.

VI. Discussion and Conclusions

In this paper we have considered the problem of routing bandwidth-constrained flows in multi-rate TDMA-based ad hoc networks, and we have shown that maximizing the number of accepted flows is APX-complete. This motivates the needs for designing low-complexity routing heuristics to address this optimization problem. To this end, in this paper we have proposed a novel routing metric called CARTA, which takes advantage of both topology and load awareness to select paths that route around highly congested and highly interfered network regions. Simulations results have confirmed that CARTA ensures a more balanced use of the network resource with respect to similar heuristics previously proposed in the literature, providing a significant improvement of network capacity at the cost of a limited increase in path lengths.

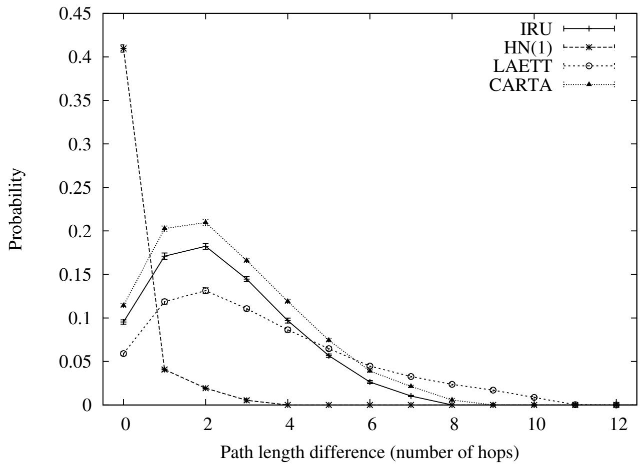

Fig. 4. Probability mass function of path length difference in a network of 100 nodes.

These results may motivate other studies that would aim at combining multiple QoS constraints. Specifically, in this study we were concerned with flows demanding a guaranteed bandwidth, while other QoS-constrained flows, such as a voice call or a video stream, could set delay requirements. Thus, we want to investigate how to extend CARTA scheme to deal with delay-constrained flows. Moreover, more efficient solutions could be devised if more information is available on the characteristics of the traffic patterns. For instance, it is feasible to assume that long-term statistics for traffic flows may be specified in terms of the probability of an ad hoc node to be the source or the destination of a new low. We plan to investigate how these distributions can be exploited in the routing decision process to minimize the probability of rejecting future flows.

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REFERENCES

[1] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification*, IEEE Computer society Std. 802.11, March 2007.

[2] W. Liao. Y.C. Tseng, and K.P. Shih "A TDMA-based bandwidth reservation protocol for QoS routing in a wireless mobile ad hoc network", in *Proc. of IEEE ICC 2002*, vol. 5, pp. 3186–3190, May 2002.

[3] D.D. Vergados, D.J. Vergados, C.Douligeris, and S.L. Tombros, "QoS-Aware TDMA for End-to-End Traffic Scheduling in Ad Hoc Networks", *IEEE Wireless Communications*, vol. 13, no. 5, October 2006.

[4] G. Allard, L. Georgiadis, P. Jacquet, B. Mans, "Bandwidth Reservation in Multihop Wireless Networks: Complexity, Mechanisms and Heuristics", *International Journal of Wireless and Mobile Computing*, 2004.

[5] Y. Yang, J. Wang, R. Kravets, "Designing Routing Metrics for Mesh Networks", in *Proc. of IEEE WiMesh'05*, 2005.

[6] T. Moscibroda, and R. Wattenhofer, "The Complexity of Connectivity in Wireless Networks", in *Proc. of IEEE INFOCOM 2006*, pp. 1–13, April 2006.

[7] A. Iyer, C. Rosemberg, and A. Karnik, "What is the Right Model for Wireless Channel Interference?", in *IEEE Trans. on Wireless Comm.*, 2009.

[8] M. Conti, and S. Giordano, "Multihop Ad Hoc Networking: The Reality", in *IEEE Communications Magazine*, vol. 5, no. 4, pp. 88–95, April 2007.

[9] M. Conti, G. Maselli, G. Turi, and S. Giordano, "Cross-layering in mobile ad hoc network design", in *IEEE Network*, vol. 37, no. 2, pp. 48–51, February 2004.

[10] R. Draves, J. Padhye, and B. Zill, "Routing in Multi-Radio, Multi-Hop Wireless Mesh Networks," In *Proc. of ACM MobiCom*, Philadelphia, PE, USA, Sept. 26–Oct. 1 2004, pp. 114–128.

[11] M. Genetzakis and V. Siris, "A Contention-Aware Routing Metric for Multi-Rate Multi-Radio Mesh Networks". In *Proc. IEEE SECON 2008*, San Francisco, CA, USA, June 16–20, 2008, pp. 242–250,

[12] J. Bicket, D. Aguayo, S. Biswas, and R. Morris, "Architecture and Evaluation of an Unplanned 802.11b Mesh Network", In *Proc. of ACM MobiCom'05*, Cologne, Germany, Aug. 28–Sept. 2 2005, pp. 31–42.

[13] M.R. Garey and D.S. Johnson. *Computer and Intractability: A guide to the Theory of NP-Completeness*. W. H. Freeman, 1979

[14] J. Yee and H. Pezeshki-Esfahani, *Understanding wireless lan performance tradeoffs.* November 2002. Available at http://www.commsdesign.com.

[15] O. Goussevskaia, Y. Oswald, and R. Wattenhofer, "Complexity in Geometric SINR", in *Proc. of ACM MobiHoc'07*", pp. 100–109, September 2007.

[16] A. Ephremedis and T. Truong, "Scheduling Broadcasts in Multihop Radio Networks", in *IEEE Trans. Comm.*, vol. 38, no. 4, pp. 456-460, 1990.

[17] W. Zhu, "TDMA Frame Synchronization of Mobile Stations Using a Radio Clock Signal for Short Range Communications", in *Proc. of IEEE VTC'94*, vol. 3, pp. 1878–18882, June 1994.

[18] X. Zhong, S. Mei, Y. Wang and J. Wang "Synchronization in TDMA ad hoc network" In *Proc. of VTC2004-Fall*, Vol. 7, pp.:5011–5014, September 2004.

[19] S. Salcedo-Sanz, C. Busono-Calzon, and A. R. Figueiral- Vidal, "A Mixed Neural-Genetic Algorithm for the Broadcast Scheduling Problem", in *IEEE Trans. Wireless Commun.*, vol. 2, no. 2, pp. 27783, 2003.

[20] W. Wang, Y. Wang, X.-Y. Li, W.Z. Song, and O. Frieder, "Efficient Interference-Aware TDMA Link Scheduling for Static Wireless Networks", in *Proc. of ACM MobiCom 2006*, pp. 262–273, September 2006.

[21] H. Shi, L. Wang, "A hybrid neural network for optimal TDMA transmission scheduling in packet radio networks", in *Proc. of IEEE IJCNN '05*, vol. 5, pp. 3210–3213, August 2005.

[22] I. Jawhar and J. Wu, "A race-free bandwidth reservation protocol for QoS routing in mobile ad hoc networks", in *Proc. of IEEE HICSS04*, pp. 1–10, January 2004.

[23] C. Zhu and M.S. Corson, "QoS routing for mobile ad hoc networks", in *Proc. of IEEE INFOCOM 2002*, vol. 2, pp. 958–967, June 2002.

[24] M. Kas, I. Korpeoglu, and E. Karasan, "OLSR-Aware Distributed Channel Access Scheduling for Wireless Mesh Networks", in *Proc. of IEEE WCNC 2009*, April 2009.

[25] H. Aiache, V. Conan, L. Lebrun, and S. Rousseau, "A load dependent metric for balancing Internet traffic in Wireless Mesh Networks, in *Proc. of IEEE MeshTech 2008*, pp. 629–634, September 2008.

[26] T. Clausen and P. Jaquet. Optimized Link State Routing Protocol (OLSR). RFC 3626, October 2003.

[27] M. Cao, W. Ma, Q. Zhang, and X. Wang, "Analysis of IEEE 802.16 mesh mode scheduler performance", in *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 14551464, Apr. 2007.

[28] R. Kohli, R. Krishnamurti, and P. Mirchandani, "The minimum satisfiability problem", *SIAM J. Disc. Math.*, vol. 7, pp. 275-283,1994.

[29] R. Bruno, V. Conan, S. Rousseau "Maximizing the number of accepted flows in TDMA-based wireless ad hoc networks is APX-complete, *Tech. Report*, URL: http://arxiv.org/abs/0904.0742v1