Recall and Precision in Distributed Bandwidth Allocation

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***Abstract*— Recent work on QoS in Mobile Ad Hoc Networks (MANETs) has shown that bandwidth needs to be reserved in a distributed manner by also including interfering nodes. However, in practice, QoS protocols have difficulties to locally determine the set of nodes that actually interfere with a given transmission. To solve this problem, it is not uncommon to consider all nodes within a distance of k hops (k-neighbors) as interfering nodes. In this paper we use Monte-Carlo methods to study the correlation between the k-neighborhood of a node and the set of interfering nodes. We compute expected values for both *reservation recall* – the fraction of interfering k-neighbors to all interferers – and *reservation precision* – the fraction of interfering k-neighbors to all k-neighbors. The two metrics reflect the quality of a reservation and the loss of resources due to over-reservation. We further investigate the impact of different physical layer properties (e.g., fading) and network settings (e.g., network density) on the quality of the reservations. Our results indicate that existing reservation techniques to ensure QoS are inadequate and that new techniques are needed to efficiently implement QoS in MANETs.**

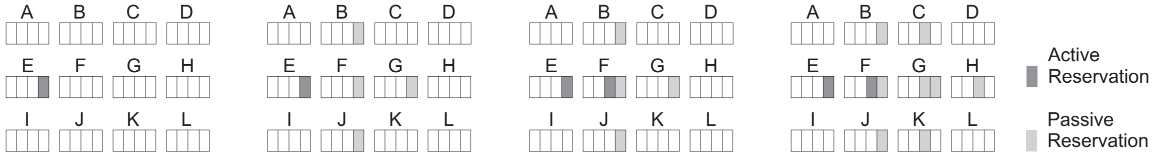
I. Introduction

There are two generic approaches to provide QoS: DiffServ[3] and IntServ [4]. In the DiffServ model, QoS is provided by prioritizing flows at the ingress nodes. In the context of Mobile Ad Hoc Networks (MANETs), DiffServ has the advantage that no state information on intermediate nodes has to be maintained and no explicit signaling is needed. However, in MANETs, every node is a potential ingress node, making admission control difficult. In addition, it has been shown that simply dividing the resources into several priority classes can not give any bandwidth guarantees to an individual flow [2]. For these reasons, most of the work so far on QoS for MANETs has been done using the IntServ model. In IntServ, QoS is provided through reservations along the transmission path. In MANETs, this is not an easy task due to the need to maintain the reservations in the presence of topology changes and bandwidth variations [13], [14], [10], [9]. In addition, the shared nature of the transmission medium requires reservations to be made not only on the transmission path (*active reservations*) but also on potential interfering nodes (*passive reservations*). As a result, recent work on QoS in MANETs has focused on distributed bandwidth reservation schemas that explore ways to efficiently place active and passive reservations on a MANET. For instance, [8], [7], [5], [12] use a distributed reservation scheme embedded in the MAC layer. Reservations are mapped to an equal amount of time slots at the MAC layer, and interference is avoided by notifying neighboring nodes not to transmit any data during these slots. As another example, [15] proposes a QoS routing scheme that takes neighborhood interference into account. The fundamental underlying problem for such distributed reservation schemas is how to locally determine the set of interfering nodes. Existing work bypasses this problem by using the notion of k-neighborhood: all nodes within a distance of k hops are considered as interfering nodes.

In this paper, we apply Monte-Carlo methods to analyze the impact of using the k-neighborhood to identify interfering nodes. We do so by introducing two novel concepts: *reservation precision* (how many nodes where reservations are placed are really interferers) and *reservation recall* (how many nodes where a reservation is needed are actually reserved). We then study how reservation recall and precision evolve as functions of node density, shadowing (radio fading). To the best of our knowledge, this is the first attempt at quantifying the impact of the use of the k-neighborhood on the efficiency of distributed bandwidth reservation schemas. By itself, this is an important contribution. Yet, the most significant contribution of the analysis is what it shows. Our results suggest that there is a inherent trade-off between the quality of a reservation and the amount of resources wasted due to over-reservations. In other words, current approaches can only achieve reasonable QoS guarantees by indulging in severe over-reservation. Considering that in practice effects like mobility or transmission errors would diminish the reservation quality even further, our analysis makes it evident that existing distributed bandwidth reservation techniques using the k-neighborhood approach are not feasible in MANETs unless traffic is severely restricted.

II. Problem Statement

Figure 1 shows how a distributed bandwidth allocation process looks when the set of interfering nodes is approximated with a 1-hop neighborhood. The network consists of 12 nodes, labeled from A to L. Every node has a maximum of 4 nodes that are considered as neighbors: the one immediately to its left and right and the one above and below it (e.g., nodes B, E, G, J are neighbors of node F). We assume a simple TDMA-based channel allocation schema. We define an *active reservation* as the set of time slots to be used for transmitting data. A *passive reservation* is the set of time slots required to remain unused in order to not interfere with the transmission.



(a) Node E performs an active reservation to transmit data

(b) Node F performs a passive reservation to make sure the transmission from node E can be received correctly

(c) Node F performs an active reservation to transmit data

(d) Node G performs a passive reservation to make sure the transmission from node F can be received correctly

Fig. 1. Typical reservation process in the 1-hop case

Suppose node E wants to set up a bandwidth reservation for a one-way communication with node G. For simplicity, let the required bandwidth for the entire connection be 1 unit. To begin with, node E locally makes a local 1 unit active reservation to be used for transmitting data to its neighboring node F (In a TDMA-based system this corresponds to a reservation of one time slot). In a second step, node F has to make sure that the reception of the packet from node E is not disturbed by any transmission from interfering nodes. It does so by placing a passive reservation in its 1-hop neighborhood. In a TDMA-based system, this corresponds to informing all the neighbors not to transmit in any of the time slots node E uses to communicate with node F. In addition to the passive reservation, node F makes a 1 unit active reservation to transmit data to node G. Note that node F has both an active and a passive reservation at that time. In a final step, node G places passive reservations in its 1-hop neighborhood to make sure that it is not disturbed by any interfering node while receiving data from node F.

The problem with the reservation process shown in Figure 1 is that the 1-hop neighborhood does not match the set of interfering nodes for any node. In fact, wireless interference is complex and nodes far beyond the set of neighbors may actually interfere with a certain transmission. Many protocols use the k-neighborhood, with $k \in \{2, 3, 4, ...\}$, as an approximation for the interference area. Obviously, the larger k, the more interfering nodes will be covered, which increases the quality of the reservation. However, the larger k, the more likely it becomes that some of the nodes included in the k-neighborhood do not actually belong to the set of interfering nodes, leading to unnecessary reservations and wasted bandwidth. This is illustrated in Figure 2 in the case of a 2-neighborhood and for a possible arrangement of interferers.

The proportion of interfering k-neighbors to all interferers is called *reservation recall*. Reservation recall models the quality of a reservation. Ideally, the reservation recall for a given transmission would be one. This is the case when all interfering nodes are also covered by the k-neighborhood. The proportion of interfering k-neighbors to all k-neighbors is called *reservation precision*. Reservation precision models the amount of resources that are wasted due to a reservation. For instance, in a TDMA-based system, a low reservation precision would mean that most of the reserved slots could actually be used without disturbing any of the ongoing transmissions. Ideally, reservation precision would be one; this is the case if the k-neighborhood contains no nodes that are not interfering. In a perfectly distributed reservation, if the k-neighborhood exactly matches the set of interfering nodes, both reservation recall and reservation precision would be one. We will see that this is hardly the case in random topologies and that optimizing for recall is achieved at the cost of precision, and vice versa.

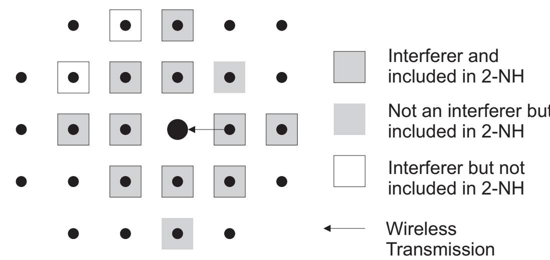


Fig. 2. A possible arrangement of a 2-hop neighborhood and interfering nodes.

The remaining part of this paper is structured as follows. The next section describes the network model. In section IV we define reservation precision and recall. These two metrics are then used in section V to assess distributed bandwidth reservations in random networks. The paper concludes with section VI.

III. Network Model

Let $\mathcal{N}$ be the set of nodes in the network. We assume $x_n \in \mathcal{R}^2$ to be the coordinate of node n, identifying the node's position with respect to a rectangular area $\mathcal{A}$. We consider the set $\mathcal{N}$ of nodes to be uniformly distributed in $\mathcal{A}$. Each node n in the network is supposed to transmit with a signal power $P_n^{\mathrm{t}} \in [0, \infty[$. We use the tuple notation (n', n) to refer to the transmission from a node n' to a node n. For a certain signal propagation function ϑ, $P_{n \leftarrow n'} = \vartheta(P^{\mathrm{t}}_{n'}, |x_n - x'_n|) \in [0, P^{t}_{n'}]$ denotes the power of the received signal at node n due to the transmission (n', n). In the simplest case, ϑ is a direct function of the distance. The path loss radio propagation model, for example, defines $\vartheta_{pl}(p, l) = p \cdot (l/l_0)^{-\rho}$ for some path loss exponent ρ, and l_0 as a reference distance for the antenna far-field. A more sophisticated model is the log-normal shadowing

Algorithm 1 Computes interfering nodes

Input: Transmission $(n^{'}, n) \in \mathcal{D}_n$
Output: Minimum Set of interfering nodes $\mathcal{M}_{n \leftarrow n'}$

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M_{n←n'} := ∅;
L := sort(N \ {n, n'}) such that n'' ≺ n''' ⟷ P_{n←n''} < P_{n←n'''}
M* := ∅;
for all n'' ∈ L do
    M* := M* ∪ {n''}
    if κ_sinr(n', n, M*) = 0 then
        M_{n←n'} := M_{n←n'} ∪ {n''}
    end if
end for
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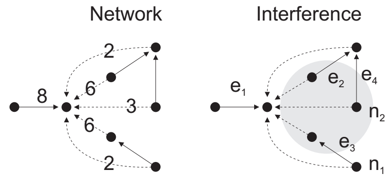


Fig. 3. Computing the set of interfering nodes. The straight line arrows represent the transmissions. The dotted arrows denote signals which contribute to the interference noise of transmission e_1. The weight assigned to an edge corresponds the signal strength. We assume the thermal noise P^* used in Equation 2 to be 1. According to Algorithm 1, nodes in the grey area are considered as the smallest set of nodes such that the remaining cumulated interference does not prohibit transmission e_1 to be established.

radio propagation [11]:

$$\vartheta_{sh}(p,l) = p \cdot (l/l_0)^{-\rho} \cdot 10^{\chi/10} \tag{1}$$

where χ is a gaussian random variable with zero mean and standard deviation σ and ρ is the aforementioned path loss exponent. In case of $\sigma = 0$, there is no random effect and $\vartheta_{sh} \equiv \vartheta_{pl}$. In this work, we assume the physical signal propagation to be symmetric. Thus, the gaussian random variable X involved in the computation of $P_{n \leftarrow n'}$ is the same as the one involved in the computation of $P_{n' \leftarrow n}$[1]. From practical measurements, however, it is known that the signal strengths $P_{n \leftarrow n'}$ and $P_{n' \leftarrow n}$, corresponding to transmissions of two identical radio transmitters, may not always be equal. This is due to tiny differences of the radio hardware and is taken into account in our model by the power distribution P_n^{t}.

Whether a signal from a node n' can be decoded correctly at node n in the absence, or the presence, of concurrent transmissions, is determined by the amount of interference perceived at the given node. To simplify later formalism, we define an interference function κ_{sinr} as follows:

$$\kappa(n^{'}, n, I) = \begin{cases} 1 & \frac{P_{n \leftarrow n'}}{P_n^* + \sum_{n'' \in \mathcal{I}} P_{n \leftarrow n''}} > \beta_{sinr} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

for some threshold β_{sinr} and P_n^* as the thermal noise perceived at node n. We now define $\mathcal{D}_n$ as the set of nodes that can correctly be decoded at node n in the absence of any other concurrent transmission:

$$\mathcal{D}_n = \{n^{'} \in \mathcal{N} \mid \kappa(n^{'}, n, \emptyset) = 1\} \tag{3}$$

Due to the different power levels of the nodes, it might happen that $n^{'} \in \mathcal{D}_n$ but $n \notin \mathcal{D}_{n'}$. Many medium access protocols, however, require symmetric links because they are based on acknowledgements. We therefore define the set of symmetric links in the network as

$$\mathcal{E} = \{(n^{'}, n) \in \mathcal{N} \times \mathcal{N} \mid n^{'} \in \mathcal{D}_n \wedge n \in \mathcal{D}_{n'}\}. \tag{4}$$

IV. Reservation Recall and Precision

Given a link $e = (n^{'}, n) \in \mathcal{E}$ and a set of nodes $\mathcal{Q}_{n \leftarrow n'}$ holding passive and active reservations for this link, we would ideally like $\kappa_{sinr}(n^{'}, n, \mathcal{N} \setminus \mathcal{Q}_{n \leftarrow n'})$ to be 1. This is the case when $\mathcal{Q}_{n \leftarrow n'}$ exactly matches the set of interferers for the given transmission. The minimum set of interferers $\mathcal{M}_{n \leftarrow n'}$ for a link $e = (n^{'}, n)$ can be computed by gradually testing κ_{sinr} with an increasing set of interferers, starting with the node $n^{''}$ contributing the lowest signal power $P_{n \leftarrow n''}$ (Algorithm 1). How the algorithm operates is demonstrated in Figure 3 based on a small example network of 7 nodes.

Reservation recall and precision are comparisons of the set of interferers with the k-neighborhood. The k-neighborhood is defined to be the set of all nodes that can be reached within k hops, including the node itself. Which nodes can be reached within k hops from a given source node is determined by the routing function $\eta : \mathcal{N} \times \mathcal{N} \longrightarrow \mathcal{P}(\mathcal{E})$. For a given source-destination pair $(n^{'}, n)$ the resulting route simply consists of the set[2] of edges included in the sequence $e_0, e_1 ... e_{k-1}$, with $e_i = (n_i,\ n_{i+1}) \in \mathcal{E}$ and $n_0 = n^{'}$ and $n_k = n$. With the routing function η, the k-neighborhood of a node n is

$$\text{k-NH}_n = \{n^{'} \in \mathcal{N} \mid |\eta(n^{'}, n)| <= k\}. \tag{5}$$

Reservation recall and precision are formally defined on a per edge basis. Reservation recall $R^k_{n \leftarrow n'}$ is the ratio of interfering k-neighbors to all interferers:

$$R^k_{n \leftarrow n'} = \frac{|\ \text{k-NH}_n \cap \mathcal{M}_{n \leftarrow n'}\ |}{|\ \mathcal{M}_{n \leftarrow n'}\ |}. \tag{6}$$

Reservation precision $P^k_{n \leftarrow n'}$ is the ratio of interfering k-neighbors to all k-neighbors:

$$P^k_{n \leftarrow n'} = \frac{|\ \text{k-NH}_n \cap \mathcal{M}_{n \leftarrow n'}\ |}{|\ \text{k-NH}_n\ |}. \tag{7}$$

Let $\bar{R}^k$ and $\bar{P}^k$ be the average reservation recall and precision of a given network. For a concrete network deployment, $\bar{R}^k$ and $\bar{P}^k$ correspond to concrete numbers. For a certain network family, $\bar{R}^k$ and $\bar{P}^k$ could be considered as random variables. A network family might consist of, e.g., all networks

[1] Therefore $P_n^{\mathrm{t}} \equiv P_{n'}^{\mathrm{t}} \Rightarrow P_{n \leftarrow n'} \equiv P_{n' \leftarrow n}$

[2] Practically, a route would be modeled as a sequence rather than as a set; however, since we assume no loops and the order of the edges in a route is not important we prefer the set notion which simplifies further treatment.

with 200 nodes distributed uniformly in a rectangular of $2000m \times 2000m$. It would be of interest to know the expected average precision and recall ($E[\bar{P}^k]$ and $E[\bar{R}^k]$) for a given network family. Deriving the expected average precision and recall analytically would require determining the probability density function of the random variables. In this paper we do not pursue an analytical treatment of $E[\bar{P}^k]$ and $E[\bar{R}^k]$ but rather use a Monte-Carlo estimator. This is illustrated below on the example of $E[\bar{R}^k]$. We approximate the expected value of $E[\bar{R}^k]$ for a given network family by sampling over m realizations of the underlying random network, with X_i as a concrete set of node placements $\mathcal{X}$ in the area $\mathcal{A}$ and $f(\cdot)$ as the probability density function of $\mathcal{X}$:

$$\begin{aligned} E[\bar{R}^k] &= \int_{\mathcal{R}^{2N}} E[\bar{R}^k|\mathcal{X}=X]f(X)dX \\ &\approx \frac{1}{m}\sum_{i=0}^{m-1} E[\bar{R}^k|\mathcal{X}=X_i^*] \end{aligned} \tag{8}$$

Due to the linearity of the expected average reservation recall, $E[\bar{R}^k]$ corresponds to the expected reservation recall of a uniformly chosen edge.

$$\begin{aligned} E[\bar{R}^k] &= E[\frac{1}{|\mathcal{E}|}\sum_{(n,n')\in\mathcal{E}} R^k_{n\leftarrow n'}] \\ &= \frac{1}{|\mathcal{E}|}\sum_{(n,n')\in\mathcal{E}} E[R^k_{n\leftarrow n'}] = E[R^k_{n\leftarrow n'}]. \end{aligned} \tag{9}$$

We refer to R^k and P^k as the approximation values for $E[\bar{R}^k]$ and $E[\bar{P}^k]$.

In using Monte-Carlo methods to compute R^k and P^k, the paper also suggests a new approach to ad hoc network analysis in cases where pure analytical approaches fall short, and protocol specific network simulations are not generic enough.

V. Precision and Recall in Random Networks

A. Network settings

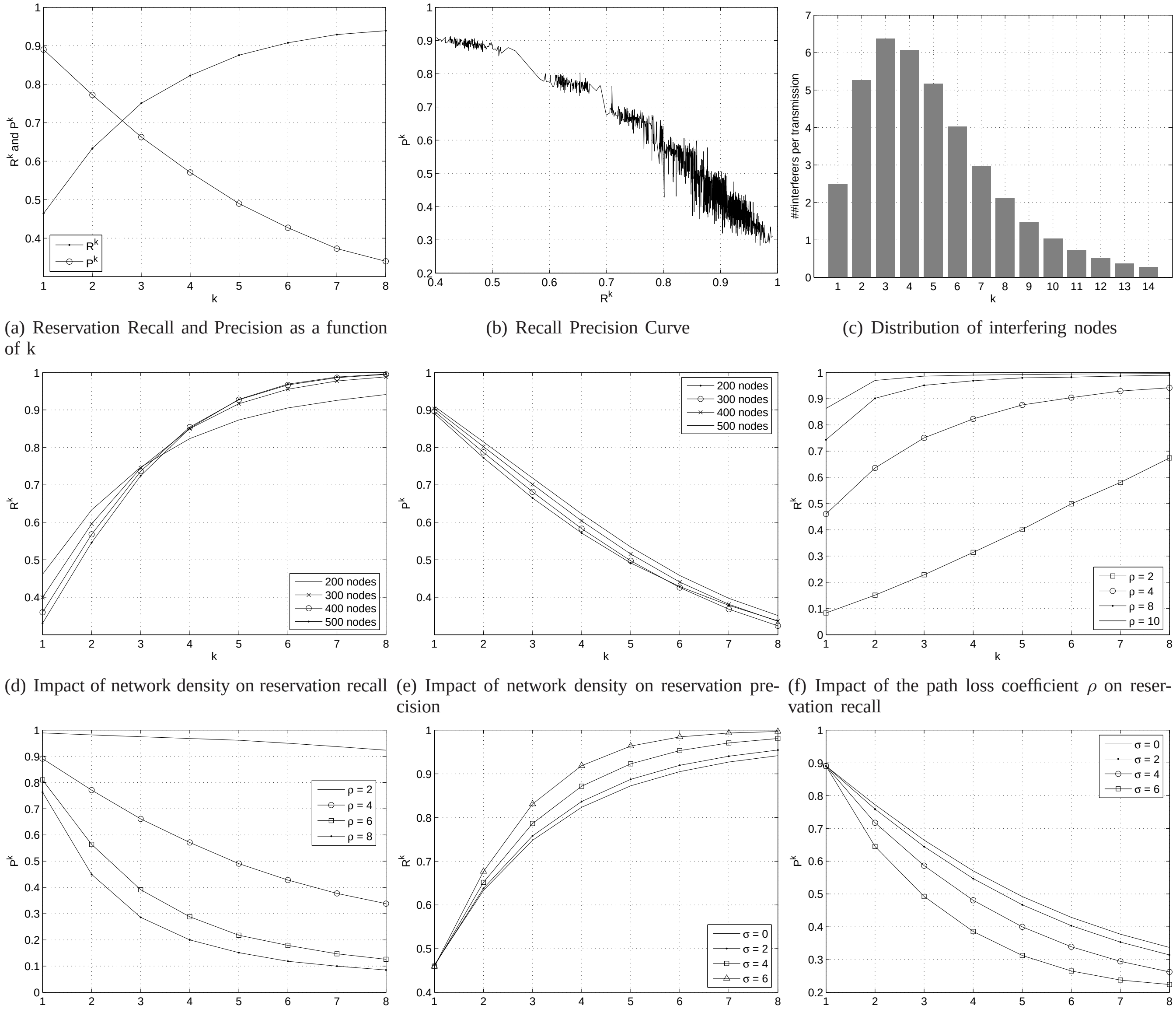
We study reservation recall and precision, R^k and P^k, under different network densities and signal propagation settings. The network configurations we consider consist of randomly deployed nodes within a square of varying size. We use the log-normal radio propagation model (Equation 1) and if nothing else is mentioned, the path loss coefficient ρ and the shadowing deviation σ are fixed to be 4 and 0 respectively. For the interference model (Equation 2) we use a threshold β_{sinr} of 4 decibel, which is the lowest tolerable threshold of an Orinocco PCMCIA Silver/Gold wireless network card so that it can still function at a rate of 1Mbps [1]. The transmission power for every node is kept constant and the thermal noise P^* is adjusted in a way that the resulting transmission range becomes $200m^2$. We use Equation 8 with a sample size m of 1000. For routing, we use the shortest path algorithm by Floyd and Warshall [6]. In order to minimize the effect of the network border, we use a special *scope*, $\mathcal{E}^* \subset \mathcal{E}$, to compute precision and recall. The scope we use includes all edges where one or both nodes are located within a circle with radius $4/10$ of the network length, and with its origin at the center of the network area.

B. Recall/Precision Trade-off

Figure 4a shows the reservation recall and precision for different values of k. As can be observed, there is a clear trade-off between reservation recall and precision. Maximizing for recall (by choosing a bigger value for k) reduces the precision of the reservation. The result is disappointing since it says that in a network where nodes are deployed randomly, a good reservation quality can only be achieved with an extensive distributed reservation which entails an enormous waste of bandwidth. Figure 4b shows the traditional recall precision scatter-plot for the same network setting as we used in Figure 4a. The scatter-plot includes a point for every one of the 1000 samples taken. The x and y coordinates of the dots refer to the corresponding recall and precision values of the sample. The plot includes samples for values of k from 1 to 8. The scatter-plot illustrates the trade-off between reservation recall and precision: a high precision implies a low recall and viceversa. Why it is unfeasible to choose a value for k that maximizes both reservation recall and reservation precision is shown in Figure 4c. The Figure shows the average distribution of the interfering nodes with respect to their hop distance measured from the node they interfere with. As can be seen, the distribution's peak is around 3 hops. Choosing a value of 3 for k, however, does not take the tail of the distribution into account. Since the tail is not negligible, a large set of interferers is not covered. Choosing a value of 10 or 11 covers the nodes at the tail of the distribution, but at the same time, includes many nodes which are not interfering at all.

C. Impact of network density

We now explore how recall and precision are affected by the network density. We look at a network of size $2000m \times 2000m$ while deploying an increasing number of nodes. As can be inferred from Figure 4d, reservation recall drops with an increasing network density if k is smaller than 3, but increases with the network density if k is greater than 3. This behavior is a direct consequence of the fact that the number of nodes in a disc grows with the square of the radius of the disc. Imagine a simplified view where the k-neighborhood is represented by all nodes located in a disc d_k with radius r_k and all interfering nodes to be the nodes located in another disc d_I with radius r_I. If the network density grows, obviously the number of nodes within d_I grow faster than the number of nodes in d_k, if $r_I > r_k$. This is what happens in Figure 4d when k is smaller or equal than 3. Since with increasing node density the number of interfering nodes increases faster than the number of nodes within the set k-NH, the reservation recall drops. If, on the other hand, k is greater than 3, then r_k becomes larger than r_I and the opposite happens: with increasing node density, the number of nodes in k-NH increases faster than the number of interfering nodes, which improves the reservation recall.



(a) Reservation Recall and Precision as a function of k

(b) Recall Precision Curve

(c) Distribution of interfering nodes

(d) Impact of network density on reservation recall

(e) Impact of network density on reservation precision

(f) Impact of the path loss coefficient ρ on reservation recall

(g) Impact of the path loss coefficient ρ on reservation precision

(h) Impact of shadowing on reservation recall

(i) Impact of shadowing on reservation precision

Fig. 4. Recall and Precision

While the influence of the network density on reservation recall very much depends on the value of k, its effect on reservation precision is more consistent and also more modest. From Figure 4e we see that the reservation precision slightly improves as the network density increases. The reason is that the set of interfering nodes grows a little faster than the k-neighborhood for an increasing network density.

D. Impact of radio propagation

So far, we fixed the path loss and the shadowing deviation of the radio propagation (Equation 1) to be 4 and 0 respectively. However, it is clear that both path loss and shadowing deviation must have an impact on the interference perceived at a given node. Figure 4f-g illustrate the effect of the path loss coefficient on recall and precision. It is shown that the bigger the path loss coefficient, the higher the recall (at the expense of a lower precision). The reason is that a high path loss coefficient makes the signal drop below the interference threshold very quickly and thus makes the set of interfering nodes approach the 1-hop neighborhood. That's why – already for a k of 1 – the recall for a path loss coefficient of 8 becomes bigger than 0.8. On the other hand, the precision drops very quickly for high path loss values (Figure 4g). This is because most nodes outside the 1-hop neighborhood no longer interfere. In both Figures 4f and 4g no fading effects are considered ($\sigma = 0$). However, such a setting refers to an ideal transmission range (circle) which is rarely the case in practice. Much more realistic values for σ are values in the range of 2–10, depending on the network environment [11]. Figure 4h shows how reservation recall evolves when the radio propagation becomes irregular. From the Figure, we observe that for a given value of k, the reservation recall improves as σ increases. Why this is the case can easily be seen when looking at the received signal strength under fading. The expected received signal power in the log-normal shadowing radio propagation model (Equation 1) computes to $p_r = p_t \left(\frac{r}{d_0}\right)^{-\rho} \exp\left(\frac{\log(10)^2}{200}\sigma^2\right)$, which increases with σ. It follows that the set of decoders $\mathcal{D}_n$ increases and therefore so does the set of of k-neighbors, which improves the overall reservation recall. How the reservation precision is affected by irregular radio propagation is illustrated in Figure 4i. It can be observed that the reservation precision drops as σ increases. This is what we would expect since the higher the values for σ the more randomness is induced into the signal. As the randomness increases, the correlation between the number of hops of a source destination pair and its euclidian distance is reduced.

VI. Conclusions

In this paper we use Monte-Carlo methods to study the performance of existing bandwidth reservation schemas in MANETs. In particular, we have shown that there exists a clear trade-off between reservation recall and precision since optimizing recall is done at the cost of precision. This says that in a network where nodes are deployed randomly, a good reservation quality can only be achieved with an extensive distributed reservation which entails an enormous waste of bandwidth. In the paper, we have also shown that irregular radio propagation diminishes the reservation precision but improves the recall. One reason for this is that the set of nodes in a k-neighborhood grows under fading, which then increases the interference coverage. In this work, we considered only static networks. One could imagine that the situation deteriorates even more in mobile scenarios, where nodes occupying a reservation leave the interfering area at some point in time. The conclusion is that distributed bandwidth reservations are inadequate to provide QoS in MANETs and that other techniques have to be considered, e.g., priority based approaches.

Acknowledgement

The work presented in this paper was supported (in part) by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS), a center supported by the Swiss National Science Foundation under grant number 5005-67322.

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