A Scheduling Policy for Dense and Highly Mobile Ad hoc Networks

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Abstract: Recent publications in information theory demonstrated that mobility can increase the capacity of wireless ad hoc networks. More precisely, the throughput per source-destination pair can be kept constant as the density of nodes increases. Considering an analytical study as a starting point, in this paper we propose and evaluate a distributed scheduling policy for dense and highly mobile ad hoc networks. This policy takes advantage of mobility in order to reduce the relaying traffic in such a network. Simulation results are provided to show the benefit of mobility on the network throughput and the optimal transmission range is derived from an analytical study.

1 Introduction

In recent years a lot of effort has been spent in the design of routing and medium access protocols for mobile ad hoc networks. These two layers have in fact a lot of impact on the system performance. Their behavior is also highly dependent on the mobility and the traffic pattern (e.g. [Li01]). Thus their study is a very challenging issue.
The role of the routing layer is the establishment of routes through the network and the forwarding of packets along those routes [LNT87]. Because of the nature of mobile ad hoc networks, these tasks must be distributed and dynamic, i.e., the protocol must be able to perform without any centralized unit and to respond to changes. Loop avoidance is also needed. Some desirable features are the minimum hop count, the scalability and the power-awareness. It is also preferable that the control overhead should be minimized. From the literature related to routing schemes, a classification can be the following as a function of system design choices [NLB00]:

1. Proactive vs. reactive vs. hybrid protocols,
2. Protocols for flat or hierarchical architecture,
3. Global position vs. global positionless based protocols.

The role of the MAC layer is to give access to the medium and to share the channel between source-destination pairs and/or flows of data. It has also to be distributed

and dynamic. A medium access protocol will be judged on its ability to reuse the resources as efficiently as possible, to avoid congestion and collisions, to be fair, reliable and energy efficient. From the literature the following classification can be made:

1. Contention based vs. conflict-free schemes,
2. Sender vs. receiver initiated protocols,
3. Multi-channel vs. single-channel protocols.

The proposed scheme combines a receiver-initiated MAC protocol in a slotted environment with a scheduling policy for the packets to be transmitted at each time-slot. In the next section, we explain how this paper is related to recent publications on the capacity of ad hoc networks. Then, the access scheme and the scheduling policy are presented in details. At last, numerical results via simulations and an initial analytical study are provided. The last sections focus on discussion, conclusion and further work.

2 Related Work

In a recent paper [GK00], P. Gupta and P. R. Kumar have opened a new area of research related to the capacity of fixed ad hoc networks. Their main conclusion is that this capacity decreases approximately like $1/\sqrt{n}$, where n is the density of nodes. This is so even with optimal scheduling and routing schemes. For a given node density, the system throughput is limited on the one hand by interference when the number of hops is small, and on the other hand by the amount of relaying traffic if the number of hops is high.
However, M. Grossglauser and D. Tse proved in [GT01] that this limitation can be overcome through node mobility. For that they have used the multi-user diversity concept. This notion is already known in a cellular environment [KH95]: at each time-slot the base-station sends data to the mobile station with the best channel conditions. [GT01] gives an analogy in mobile ad hoc networks: at each time-slot the only packets allowed to be sent are those that are one hop away from their final destination, i.e., with the best "route conditions". This analogy leads to one hop transmissions, i.e., when destination is in the communication range of the source.
In fact it is claimed that mobility brings a substantial increase in system capacity of ad hoc networks, especially if no more than one relay node between each active source and destination pair is considered. As shown in Figure 1, in a dense network, the probability of finding adequatly matched source and destination nodes as well as the same for finding relay nodes as and when required, increases with node mobility.
A centrally controlled scheduling policy described in [GT01] is based on a two phase transmission method, i.e., from source to a waiting queue in a relay node and then from the relay node to destination. Since distributed scheduling policies

are known to be more suitable for implementation in ad hoc networking applications, we demonstrate the usefulness of such a scheme that shows the benefit of node mobility on the network throughput. Moreover, we study the possibility to eliminate the relay node between source and destination by considering only one hop transmissions.

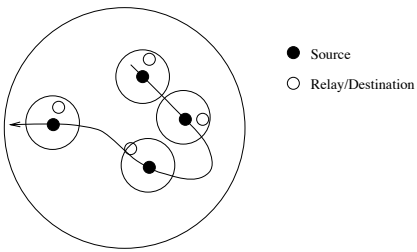

Figure 1: The source disseminates packets along its route

3 Access Scheme

In the proposed scheduling policy, the network is assumed to be perfectly synchronized and the channel is supposed to be slotted. This paper does not address the issue of synchronization. The MAC protocol is similar to MACA-BI [TG97a][TG97b] and is a two-way handshake and receiver-initiated protocol.
During a given time-slot, the receiver sends a RTR message (Ready To Receive). The receiver address is included in the message. A sender that receives an RTR and that has a packet destined to the receiver can transmit data. Packets have a fixed length, so that the two-way handshake is possible within a time-slot (see Figure 2). This protocol is not reliable and there is no collision avoidance mechanism, thus some packets can be lost. We assume that higher layers are responsible for acknowledgment and retransmissions.

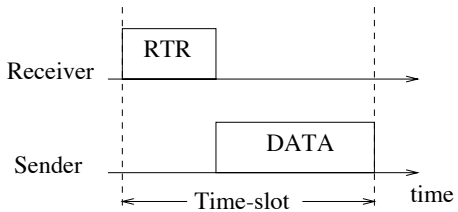

Figure 2: Two-way handshake within a time-slot

4 Scheduling Policy

We will compare two basic strategies. The first one is based on the analytical study of [GT01] and considers at most two hops between source and destination. The second one considers only one hop, i.e., a packet is directly sent from a source to a destination without any relay node.
At each time-slot, θN nodes among N are designated as senders, the remaining nodes are receivers, $\theta \in]0,1[$. This is done in a distributed way by generating a uniform random variable in each node and comparing the result with the predefined parameter θ, called the sender density. All receivers send a RTR message as described in the previous section. The behaviour of senders that receive a RTR depends on the predefined strategy.
In the one-hop strategy, senders transmit only packets whose destination address is included in the received RTR. As a consequence, packets are transmitted only when the destination is in the transmission range of the source. Thus, only one hop is allowed.
In the two-hop strategy, each node manages two packet queues between the MAC layer and the packet generator. One of these, called the source queue, stores packets coming from its own packet generator. The other one, called the relay queue, stores the incoming packets that have to be relayed. A sender receiving a RTR looks in its queues for any packet destined for this receiver. Any such existing packet is transmitted considering the fact that the source queue has priority over the relay queue. Otherwise, a packet is chosen in the source queue to be transmitted to the receiver/relay. This strategy is detailed in pseudo-SDL in Figure 3.

5 Simulation Results

Contrary to the preliminary results of [CBK01], simulations have been performed using the event-driven and widely used network simulator ns2 [NS2] and more realistic models for traffic, mobility and physical parameters. Moreover, an analytical study is provided in the next section. $N = 30$ nodes have been considered moving in a 1000m $\times$ 1000m square field. The sender density is set to $\theta = 0.5$.
The mobility model uses a simplified version of the random waypoint model. For each node, a destination in the field is chosen with an uniform random variable. A predefined speed is chosen at the beginning of the simulation for all nodes. The node goes straight in direction of its destination with the chosen speed. Once the node has reached this point, the simulator computes a new destination and the node resumes its movement. The predefined speed is taken as a metric for mobility.
The traffic generator generates traffic in each node according to an exponential on/off distribution. Packets are sent at a fixed rate during on periods, and no packets are sent during off periods. Both on and off periods are taken from an exponential distribution. Packets and RTR are constant size (resp. 512bytes and 44bytes). The average on-time and off-time are 0.5s. The sending rate during on-times is 64kbits/s. The destination of each packet is uniformely chosen among all nodes but the source. This traffic model could model for example an instant messaging traffic between nodes. Simulations are run for 50 simulated seconds.

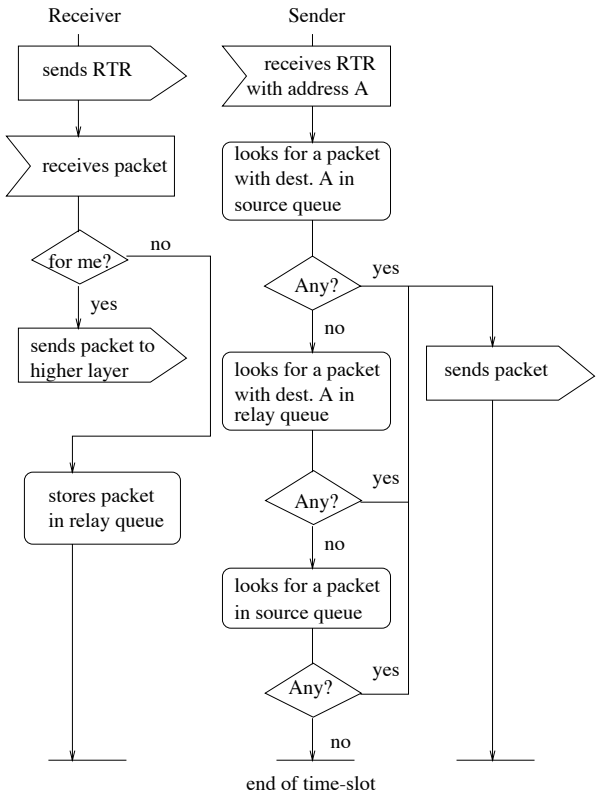

Figure 3: Two-hop strategy

Thus the total input load is in average $l = 30 \times 0.5 \times 64 = 960$kbits/s. We also assume that queues could have an infinite length.
Propagation delay and receive-to-transmit transition time are assumed to be negligible. The received power is computed using the free space propagation model with omni-directional antennas. For the sake of simplicity, the physical parameters of the Lucent's WaveLAN card have been chosen: The considered frequency is 914MHz and the bandwidth 2Mbps. This card was made before the IEEE 802.11 standard but its characteristics are widely used in literature for the sake of comparison (e.g. in [Pe01]). The effects of interference and capture are not taken into account, i.e., receive and carrier sense thresholds have the same value and the C/I ratio is not considered. Moreover, problems related to high mobility w.r.t the channel model, e.g. Doppler effect, are not taken into account.
Figure 4 shows the benefit of mobility on the network throughput as a function of the transmission range. In a multi-hop network, long range communications ensure a very good connectivity of the network and reduce the mean number of hops (and thus, routing overhead). However, network throughput is fundamentally limited because of the high level of interference induced by high transmitted power. The number of collisions is also high because of the number of nodes contending for the channel. As a consequence, this design choice increases significantly the MAC overhead and limites spatial reuse of the resources. On the other hand, communications between nearest neighbours increases the mean number of hops and thus routing overhead. In this case, most of the packets carried by the network are relayed packets.
In the scheduling policy proposed by [GT01] and the presented design choice for it, both the maximum number of hops and the transmitted power are kept small provided that an adequate transmission range is found. Figure 4 shows that an optimal range is achieved at about 150m in the simulation conditions, and that this range is constant as mobility pattern varies. The benefit of mobility is also shown

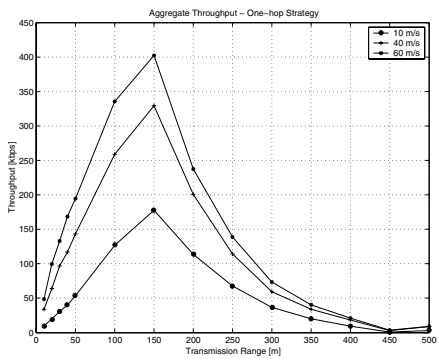

Figure 4: Aggregate Throughput - one-hop Strategy

for the two-hop strategy in Figure 5. We also note from the figures below that the

relaying scheme (two-hop strategy) does not bring additional diversity. Instead, the relaying traffic degrades the performances of the system. This result seems to contradict the conclusion of [GT01] that claims that better performances are achieved with relaying. This is probably due to the different chosen transmission model. In this paper, only collisions are taken into account, whereas [GT01] allows reception according to the signal-to-interference ratio. [GT01] also considers that each sender node transmits packets to its nearest neighbour among all nodes. That is not necessarily the case with the proposed scheduling policy. Figure 6 shows the

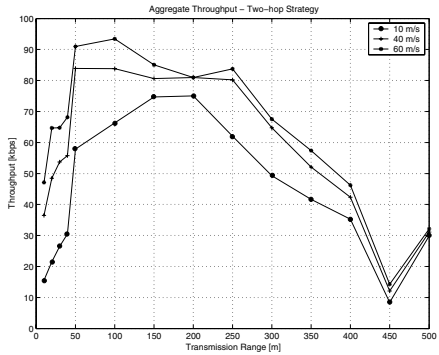

Figure 5: Aggregate Throughput - two-hop Strategy

deciding influence of the traffic model. In the so-called "single destination traffic model" (see [GT01] and [GK00]), a given source generates packets for only one well determined destination, whereas in the "multi-destination traffic model" destinations are randomly chosen for each packet. With the latter traffic model, the system exhibits better performances. This is due to the fact that the distribution of the packets for a given destination among all node queues is a key factor for the throughput of the network. The more these packets are disseminated in the network, the higher is the probability that the destination has a neighbor with a packet for it. In the multi-destination traffic model, packets for a given destination are disseminated in the network thanks to the traffic generators.
Again Figure 7 shows for a higher number of nodes that the one-hop strategy outperforms the two-hop strategy in the simulation conditions and with the single-destination traffic model.

6 Optimal Transmission Range

In this section, we try to derive from a simplified one-hop strategy the optimum transmission range for a given sender density. For that, we consider that at a given time-slot the positions of senders and receivers are two independent Poisson point processes with density resp. $\theta\lambda$ and $(1-\theta)\lambda$. This is one snapshot of the simulation. In order to simplify the problem, we also assume that a sender has

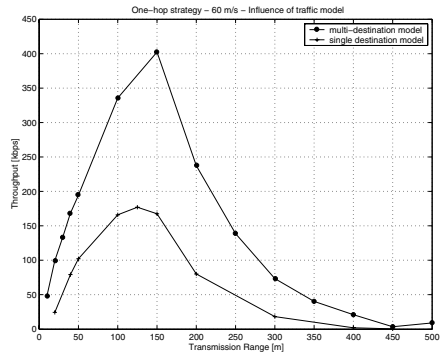

Figure 6: One-hop strategy - Single vs. multi-destination traffic - 60 m/s

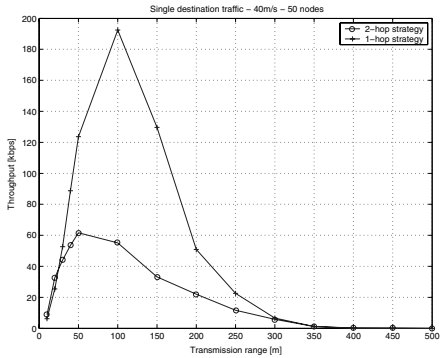

Figure 7: Single-destination traffic - One-hop vs. two-hop strategy - 40 m/s

always something to transmit to the receiver from which it received an RTR. This assumption is not realistic w.r.t the previous simulations. However, infinite queues combined with a multi-destination traffic generator makes this assumption quite reasonable at the stationary state of the simulation. We don't take into account the edge effects either.
Then, the probability of finding k senders in a region of area A is

$$Pr[k \text{ in } A] = \frac{(\theta\lambda A)^k}{k!} e^{-\theta\lambda A}. \tag{1}$$

The probability of finding k receivers in a region of area A is

$$Pr[k \text{ in } A] = \frac{((1-\theta)\lambda A)^k}{k!} e^{-(1-\theta)\lambda A}. \tag{2}$$

If interference and capture are not taken into account, a sender receives a RTR iff there is only one receiver in its transmission range r. Thus, according to Equation 2, the probability for a sender to receive a RTR is the following:

$$p_1 = (1-\theta)\lambda\pi r^2 e^{-(1-\theta)\lambda\pi r^2}. \tag{3}$$

Now, a receiver receives data iff there is a single sender that received a RTR in its transmission range r. Given k the number of senders in the communication disk, this probability is

$$k p_1 (1-p_1)^{k-1}. \tag{4}$$

Thus, according to Equation 1 and Equation 4, the probability for a receiver to receive a data packet is

$$\begin{aligned}
P &= \sum_{k=1}^{\infty} Pr[\text{1 RTR received} | k \text{ senders}] Pr[k \text{ senders}] \qquad (5)\\
&= \sum_{k=1}^{\infty} k p_1 (1-p_1)^{k-1} \frac{(\theta\lambda\pi r^2)^k}{k!} e^{-\theta\lambda\pi r^2}\\
&= p_1\theta\lambda\pi r^2 e^{-\theta\lambda\pi r^2} \sum_{k=1}^{\infty} (1-p_1)^{k-1} \frac{(\theta\lambda\pi r^2)^{k-1}}{(k-1)!}\\
&= p_1\theta\lambda\pi r^2 e^{-\theta\lambda\pi r^2} e^{\theta\lambda\pi r^2(1-p_1)}\\
&= p_1\theta\lambda\pi r^2 e^{-\theta\lambda\pi r^2 p_1}\\
&= \theta(1-\theta)(\lambda\pi r^2)^2 \times\\
&\quad exp\left[-(1-\theta)\lambda\pi r^2(\theta\lambda\pi r^2 e^{-(1-\theta)\lambda\pi r^2} + 1)\right] .
\end{aligned}$$

In Figure 8, $P(r)$ is plotted with the parameters of the simulations, $\theta = 0.5$ and $\lambda = 3.10^{-5}$ nodes/m^2. Looking at the performances of the one-hop strategy in Figures 4 and 6, we see that the chosen assumptions for the analytical study were reasonable to find the optimal transmission range. The difference is due to edge

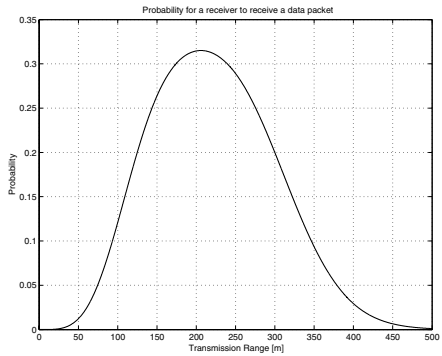

Figure 8: Probability for a receiver to receive a data packet

effects, espacially for long transmission ranges.
Note that for $\theta = 1/2$, $P(r) = 1/2p_1\lambda\pi r^2 e^{-1/2p_1\lambda\pi r^2}$. It can be written as follows: $P(r) = y(r)e^{-y(r)}$ with $y(r) = 1/2p_1\lambda\pi r^2$. The function ye^{-y} is increasing for $y \geq 0$ until a maximum at $y = 1$. Now:

$$\forall r,\ y(r) = \left(\frac{1}{2}\lambda\pi r^2\right)^2 e^{-\frac{1}{2}\lambda\pi r^2} \leq 1 \tag{6}$$

because $\forall x,\ x^2e^{-x} \leq 1$. As a consequence, the optimal transmission range maximizes $y(r)$ and

$$r_{opt} = \frac{2}{\sqrt{\lambda\pi}} \ . \tag{7}$$

For $\theta \in]0, 1[$,

$$y(r) = \theta(1-\theta)(\lambda\pi r^2)^2 e^{-(1-\theta)\lambda\pi r^2} \ . \tag{8}$$

$y(r)$ reaches its maximum for $r_0 = \sqrt{2/((1-\theta)\lambda\pi)}$ and $y(r_0) = 4\theta e^{-2}/(1-\theta)$. For $\theta \leq 1/(4e^{-2}+1)$, $y(r_0) \leq 1$ and

$$r_{opt} = \sqrt{\frac{2}{(1-\theta)\lambda\pi}} \ . \tag{9}$$

For $\theta \geq 1/(4e^{-2}+1)$, there are two optimum transmission ranges that are solutions of the following equation:

$$\theta(1-\theta)\lambda\pi r_{opt}^2 e^{-(1-\theta)\lambda\pi r_{opt}^2} = 1 \ . \tag{10}$$

With the parameters values of the simulations, $r_{opt} \approx 206.0$m, and $P(r_{opt}) \approx 0.31$. If the optimum transmission range is chosen at the beginning of the simulation, the probability that a receiver receives a data packet is approximatly 0.31 in a

given time-slot. Thus, with 15 receivers in average at each time-slot, we get the average number of simultaneous transmissions during a given time-slot: $0.31 \times 15 = 4.65$. Unfortunately, this spatial reuse of the channel is not observed in simulations because senders have not always a packet to send to their nearest receiver.

In Figure 9, $P(\theta)$ is plotted for $r = 206$m. Similar considerations show that

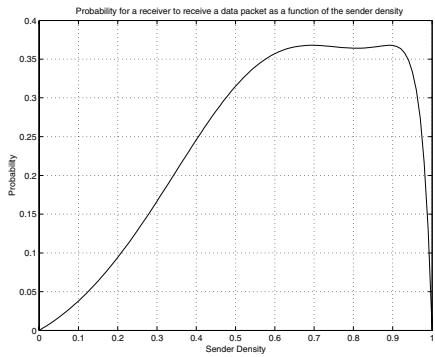

Figure 9: Probability for a receiver to receive a data packet as a function of the sender density, $r = 206$m

the optimal sender density for a given transmission range is given by the equation $p_1 \theta \lambda \pi r^2 = 1$. With the parameters values of the simulations, $\theta_{opt1} \approx 0.7$ and $\theta_{opt2} \approx 0.9$.

7 Discussion

The proposed distributed scheduling policy is a practical way of showing that mobility can increase the aggregate throughput in mobile ad hoc networks. The transmission model that have been used could be improved in future simulations by considering the C/I ratio. We can also note that the influence of queues can be studied in order to improve the accuracy of the analytical results. Indeed, results show an increasing length of nodes along the simulations. Moreover, as explained in [GT01] and [KH95], multi-user diversity can not be used for time-sensitive application because the delay of packets is not garanteed. In certain cases the excessive delays suggest that the system might not be stable. At last, the issue of synchronization has not been studied. The possibility to be in an un-slotted environment could be considered.

8 Conclusion

In this paper, we have proposed and studied a scheduling policy for dense and highly mobile ad hoc networks. This policy is using mobility as a source of diversity in order to increase the network throughput. Simulation results with a MACA-BI-

like access scheme show that the more mobile the nodes are, the higher is the network throughput. Two strategies (one-hop and two-hop) are compared with two different traffic patterns. The one-hop strategy provides a higher throughput and for both strategies, a better performance is achieved with the multi-destination traffic model. An analytical study gives the optimal transmission range for the proposed scheduling policy.

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