Improving the MAC Layer of Multi-Hop Networks

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Abstract. Ad hoc and multi-hop networks will probably be part of the fourth generation of wireless networks, which will integrate networks of several size and capacities with heterogeneous coverage: cellular networks (3G), WLAN hot spots, Wireless Personal Area Networks (WPAN) and Wireless Body Area Networks (WBAN). In this context, MAC protocols play a deciding role for a high utilization of the wireless channel. In this paper, several issues of the MAC layer and concepts for the definition of a new MAC protocol are presented. These concepts include synchronization, multi-user diversity, and multi-packet reception. It is shown that all these techniques can drastically increase the capacity of the MAC layer for multi-hop networks.

Keywords: Ad hoc networks, multi-hop networks, MAC protocols, synchronization, multi-user diversity, multi-user detection, multi-packet reception, slotted protocols, TDMA, mobility.

1. Introduction

In recent years a lot of effort has been spent in the design of protocols for mobile ad hoc networks. Such packet networks are mobile, multi-hop and operate without any fixed infrastructure. This represents a low cost and easily deployable technology to provide high speed Internet access in a wireless environment, to organize networks of sensors, or even to complement the coverage of future cellular networks.

In this paper, a special attention is paid to the Medium Access Control (MAC) sub-layer. It has a lot of impact on the system performance and its design is a very challenging issue. MAC should control access to the medium and share the channel between source-destination pairs and/or flows of data in a dynamic and distributed way. Some desirable features of the access protocol are: to be able to reuse the radio resources as efficiently as possible, to avoid congestion and collisions, to be fair, reliable, and energy efficient.

Many MAC protocols try to address these issues. In the literature, two categories of schemes have been proposed:

1. the contention based schemes

2. the conflict-free schemes

In the contention based protocols, the channel has to be acquired by the nodes for each packet to be transmitted. Examples of contention based schemes are CSMA/CA [32], MACA [29], MACAW [5], FAMA [16], and IEEE 802.11 [1]. The latter seems to be very popular in most of the testbeds because IEEE 802.11 family products are available off the shelf. Although IEEE 802.11 is flexible, robust and simple, a recent paper [41] claims that it may not do very well in a multi-hop environment. According to [41], 802.11 is impacted by the hidden terminal problem, does not handle the exposed terminal problem at all and its backoff strategy leads to severe unfairness in a multi-hop environment.

On the other hand, conflict-free protocols allow the reservation of the channel for a certain amount of time or data, and transmissions are thus conflict-free. TDMA deterministic scheduling may be preferred for networks with heavy load, carrying mixed traffic and realizing sophisticated functions at higher layers. That is the reason why a slot allocation protocol for mobile ad hoc networks, called CROMA (Collision-free Receiver Oriented MAC), is presented in section 2. This protocol illustrates the capacity increase that can be obtained thanks to synchronization.

Two other concepts are presented for the definition of new MAC protocols for multi-hop networks and illustrate the need for a cross-layer interaction. The first one described in section 3 is the multi-user diversity, which is illustrated firstly by the evaluation of the capacity of the channel aware slotted ALOHA and secondly by the use of mobility as a source of diversity.

The third and last concept of this paper is the multi-packet reception. Section 4 shows that the throughput of the multi-hop slotted ALOHA protocol can be greatly increased thanks to multi-packet reception, and in particularly thanks to the multi-user detection.

2. Synchronization

Since the early times of research on ad hoc networks, the node synchronization has been seen as a means to reduce or eliminate the number of collisions and thus to increase the capacity of wireless multi-hop networks. A better spatial reuse of the resource is indeed expected from a smart scheduling of the transmissions.

Unfortunately, most of the scheduling problems are NP-complete. For example, Arikan [3] has shown that constructing an optimal resource assignment in term of throughput is NP-complete for the point-to-point scheduling problem. And this is the same for the broadcast scheduling problem based on throughput optimization, as proved by Ephremides and Truong [14]. Consequently, MAC designers have focussed on sub-optimal, dynamic and decentralized solutions for the slot assignment issue.

A first class of scheduling protocols relies on the allocation of priorities to nodes. A given slot is assigned preferably to the node with the highest priority according to its offered traffic. Slots can be allocated by using a control channel, e.g. in [7]. Priorities of the neighbors are assumed to be known at each node and are allocated in a pseudo-random way as in [4]. Then different strategies can be applied for the allocation of the priorities in order to have a fair and efficient share of the channel (see e.g. in [31]). However, these protocols suffer from a high overhead due to the control channel. Moreover, in some cases, they do not address the problem of the distributed and dynamic assignment of priorities.

On the other hand, time-spread protocols seem to be very attractive because they are topology-independent (see e.g. in [6] or [22]). However, the frame length makes them less scalable and this class of protocols also faces the problem of distributed and dynamic code assignment.

At last, the necessity to address the problem of mobility, topology changes, and scalability, gives rise to a family of protocols where the reservation of the slots is done via a random access, most of the time a handshaking, combined with a carrier sensing mechanism. FPRP [42] proposes a five-phase handshaking supported by a pseudo-Bayesian algorithm to enable a faster convergence of the reservation procedure. CATA [37] uses four mini-slots in each time-slot to enable unicast and multicast transmissions. The protocol presented in this paper, the Collision-free Receiver Oriented MAC (CROMA), comes within this family of protocols. It tries to make use of the advantages of the most popular contention based protocols to a slotted environment in order to increase their efficiency. In particular, the aim of CROMA is to achieve a high slot utilization, i.e., a high capacity, at high input load thanks to an original reservation and polling scheme.

2.1. Protocol Description

CROMA is a medium access protocol for MANET-like networks that dynamically schedules transmissions in a slotted environment. It operates on a single-frequency channel with omni-directional antennas. All nodes are assumed to be synchronized. CROMA is receiver oriented because a slot in the frame is associated to a single receiver. Moreover, any communication between two nodes must be preceded by a preliminary reservation phase.

In CROMA, time is divided into frames, that are in turn divided into a fixed number (L) of slots (see Figure 1). Each slot is further divided in two signaling mini-slots, for request (REQ) and ready-to-receive (RTR), and a information transmission phase (DATA). The REQ-mini-slot is used by requesting nodes during the random access phase to reserve the slot. The RTR-mini-slot is used by their intended receivers to acknowledge requests. After the reservation of the slot, RTR packets are also used in successive frames to acknowledge data packets and to poll different senders. During the data phase, the sender transmits a data packet of fixed length, eventually obtained after segmentation.

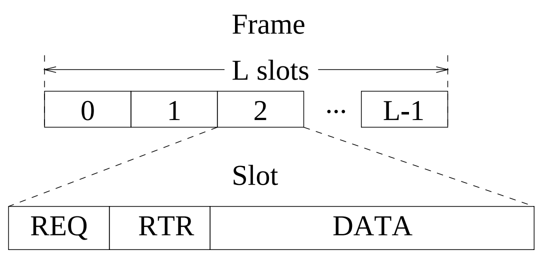

Figure 1. Frame structure of CROMA

The reservation of a free slot is done via a REQ/RTR dialogue similar to the traditional RTS/CTS handshake. Then, the transmission of a data burst is done on the same slot in successive frames. Once the connection is established, the sender is no longer required to send requests. On the other hand, the receiver sends a RTR at each second mini-slot to reserve the channel and to prevent the hidden terminal effect (see [10]). The receiver is said to have got the floor on the slot. The slot is no longer free until the release of the connection.

Now, CROMA allows multiple reservations on the same slot. The receiver indeed maintains a list of senders that managed a successful reservation and will poll them in the successive frames. This feature is illustrated on Figure 2 that shows two successive reservations on the same slot i. In frame j, the REQ/RTR dialogue starts the connection between nodes A and B: A sends a REQ with its address. B sends back a RTR, that contains a field to acknowledge the reservation (ackreq), and a field to poll node A (pol). The RTR is also received by node C that is now aware of a communication on slot i with B as receiver. During the data phase, A, that has just been polled by B, is allowed to transmit a packet with its address A and a sequence number (sn) 0. B is said to have got the floor on slot i. In frame j+1, C establishes a connection with B. With the RTR, node B acknowledges the reservation with the field ackreq, acknowledges the packet transmitted by node A in frame j, and polls node C. In frame j+2, B now polls A. With the RTR, it also acknowledges the data packet of C with sequence number 0. In frame j+3, node B polls node C and acknowledges the data packet of A with sequence number 1.

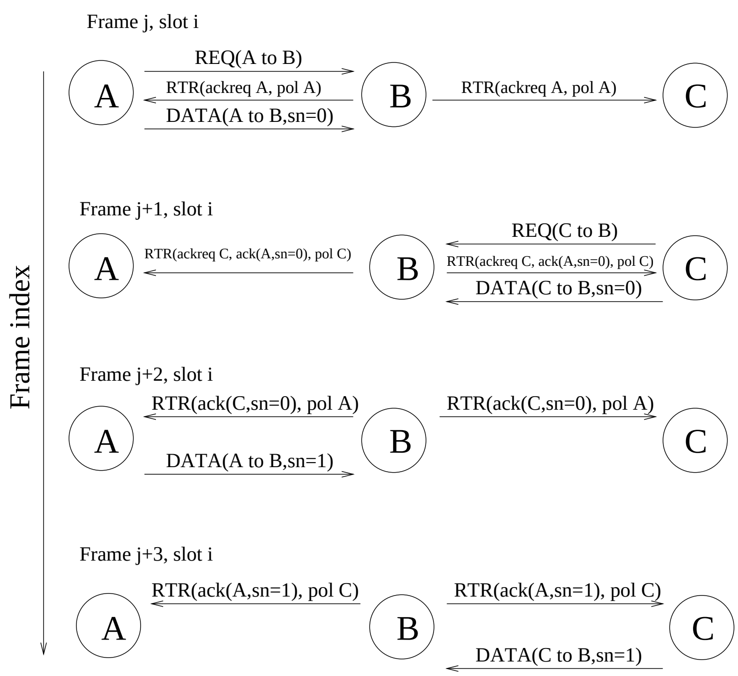

Figure 2. Example of two parallel connections on a slot with CROMA

So, RTRs are used by receivers to acknowledge requests, as well as previous data transmissions, and to poll the senders that managed a successful reservation. It is clear that slots are associated to receivers. In that sense, CROMA is receiver-oriented. This feature favores the spatial reuse of resources since only the zone around the receiver has to be secured with respect to collisions [10]. Moreover, the parallelism of connections reduce the number of collisions of control packets and allows finer flow controls and QoS negociations.

These are the basic principles of CROMA; a precise description of the protocol including packet formats, MAC header, reservation, transmission, and release phases, as well as the correctness analysis are available in [10].

2.2. Performance

In this section, the performance of CROMA is analyzed. In the case of a fully connected network, an analytical model is proposed for the protocol behavior. Then, throughput and delay characteristics are simulated in a challenging multi-hop environment.

2.2.1. *Analysis in a fully connected network*

For the sake of simplicity a simple version of the protocol is analyzed: a receiver can only be associated with a single slot. From this model will be derived the slot utilization of CROMA as a function of the probability p to send a REQ for a given source-destination pair. Let's enumerate the hypothesis of our model (proposed in [9]) for a fully connected network of N synchronized nodes and L slots per frame:

1. The maximum number of connections on a slot is K, i.e., when a receiver is already polling K different senders on a slot, no new REQ is allowed.

2. A receiver can only be associated with a single slot.

3. The traffic between any two communicating nodes s and d is a ON/OFF traffic.

4. The ON periods are modeled by bursts of packets (also called messages) following a geometrical distribution with parameter q.

5. The OFF periods are modeled by a geometrical distribution. If a source s doesn't communicate with a destination d, there is a probability p that s wants to communicate with d at the next frame.

The system is described by the number of parallel connections on the slots at the end of the frame, $(a_0, a_1, ..., a_{L-1})$. This is an aggregated description of the system, which is however sufficient to obtain the slot utilization. Let's consider a slot i occupied by the receiver d. The number of nodes that are likely to send a REQ to d are nodes that are currently not in communication with d, their number is $N-1-a_i$. The probability for such a node s to send a REQ on slot i is p. Thus, the probability of a successful reservation is: The probability of a successful reservation is:

$$\theta_i = \binom{N-1-a_i}{1} p\,(1-p)^{(N-1-a_i)-1} \quad . \tag{1}$$

Now the probability that a message is ending is $1-q$. The transition probabilities for slot i can now be derived:

$$P(a_i \rightarrow a_i+1) = \theta_i q \tag{2}$$

$$P(a_i \rightarrow a_i) = \theta_i(1-q) + q(1-\theta_i) \tag{3}$$

$$P(a_i \rightarrow a_i-1) = (1-\theta_i)(1-q). \tag{4}$$

Let's now consider a free slot i. There are $S = \sum_{i=0}^{L-1} 1_{\{a_i>0\}}$ occupied slots in the frame. The probability that a sender s has n REQ for the $N-S$ possible receivers is

$$p_1(n) = \binom{N-S}{n} p^n (1-p)^{N-S-n} \tag{5}$$

if s also belongs to the S receivers, and

$$p_2(n) = \binom{N-S-1}{n} p^n (1-p)^{N-S-n-1} \tag{6}$$

otherwise. Thus, the probability that s has n requests is:

$$p(n) = p_1(n)\frac{S}{N} + p_2(n)\frac{N-S}{N} \quad . \tag{7}$$

Now, the probability that s sends a REQ on the free slot i is:

$$\beta = \sum_{n=1}^{N-S} min\left(\frac{n}{L-S}, 1\right) p(n) \; . \tag{8}$$

At last, there are N possible senders like s, so the transitions probabilities for i are:

$$P(0 \rightarrow 1) = N\beta(1-\beta)^{N-1} \tag{9}$$

$$P(0 \rightarrow 0) = 1 - P(0 \rightarrow 1). \tag{10}$$

A full slot is now considered. The transition probabilities are:

$$P(K \rightarrow K) = \theta_i(1-q) + q(1-\theta_i) \tag{11}$$

$$P(K \rightarrow K-1) = 1 - P(K \rightarrow K). \tag{12}$$

$$\tag{13}$$

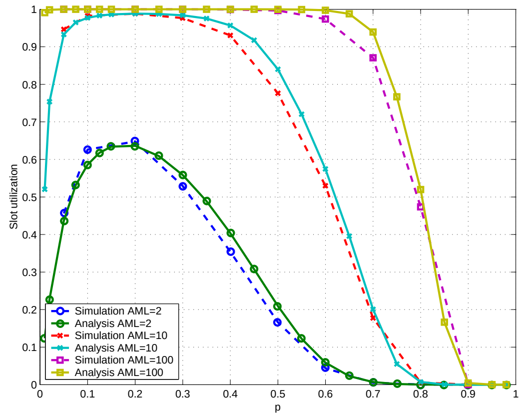

Figure 3. CROMA slot utilization vs. input load, L = 3, N = 5, K = 3

The steady state equations $\vec{\pi} = \vec{\pi}P$, where P is the probability transition matrix, are solved using any numerical method, e.g., the iterative method of Gauss-Seidel [36]. Figure 3 shows the slot utilization of CROMA as a function of p for different Average Message Lengths (AML). Analysis (solid lines) and simulations (dotted lines) are compared and the figure shows a good matching between the two methods. It is also clear that CROMA can achieve a very good channel utilization provided that AML is sufficiently high.

2.2.2. *Simulation Results*

In this section, simulation results are provided and the performance of CROMA and of the standard IEEE 802.11 (DCF mode) are compared.

As a reference, a challenging topology (see Figure 4), used in the literature [16], is considered. Four end-to-end communications are running in parallel:0-1-2-3, 0-5-2-7, 7-6-5-4, and 3-6-1-4. Simulations have been carried out using the ns2 tool [27] with an ON/OFF traffic (Tab.I). In Figure 5, the throughput of CROMA as a function of the input load

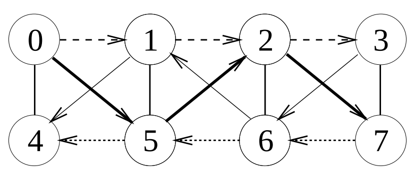

Figure 4. A multihop topology, the "squares topology"

for different values of L is shown. CROMA clearly outperforms IEEE 802.11 in all cases. However, CROMA suffers from higher delays at low

Table I. Simulation parameter values

Parameter	**Value**
DATA Packet size	512 bytes
K	3
PHY Data Rate	2 Mbps
ON distribution	Exponential
OFF distribution	Exponential
Peak Rate	256 Kbps
Mean OFF time	0.5 s

input load, as shown on Figure 6. This is mainly due to the minimum delay of one frame between two successive packet transmissions and to the reservation phase. Let's now define the fairness index f, as

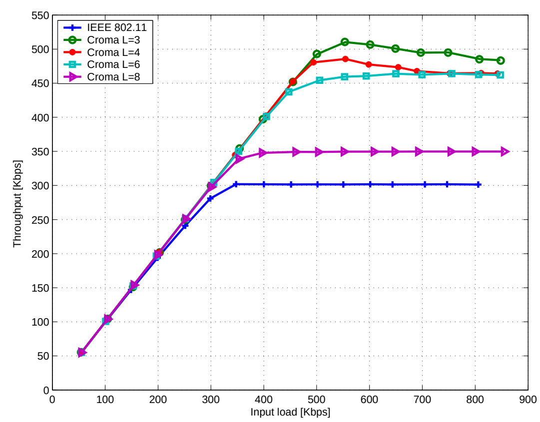

Figure 5. Throughput vs. input load, squares topology

proposed in [21]. If a system allocates resources to n contending entities, such that the i^{th} entity receives an allocation x_i, then:

$$f(x) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2}. \tag{14}$$

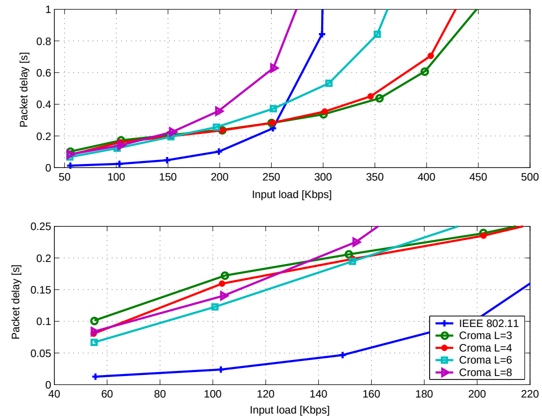

Figure 6. Packet Delay vs. input load, squares topology

If all entities get the same amount, i.e., x_i's are all equal, then the fairness index is 1 and the system is 100% fair. The choice of the metric depends upon the application. In our case, entities are the flows of data between source-destination pairs (i, j) and the metric is their throughput, $T_{i,j}$. On Figure 7, the fairness index of CROMA and IEEE 802.11 are compared. While the index of the standard decreases at the saturation point, CROMA fairness is always above 0.98. An optional

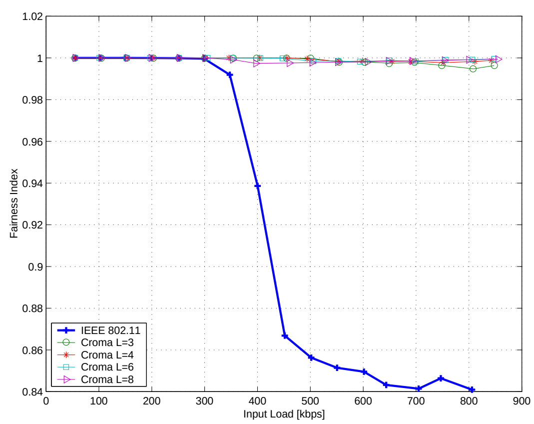

Figure 7. Fairness index vs. input load, squares topology

multi-slot communication feature can be added to CROMA in order to reduce the dependence of the performance on the frame length. When it is activated, a communication can be split over several slots. This allows a better utilization of all the slots of the frame.

Each data packet includes a *buffer status* field that indicates whether the sender's buffer exceeds a pre-defined threshold value, MS_THRESH. In this case, the receiver is requested for finding a free slot in the frame in order to split the communication. Thus, two or several slots in the frame can be attributed to a single sender-receiver pair.

For a new slot, the receiver has not priority. Indeed, if it has chosen a free slot and receives or senses a packet during the REQ phase of this slot, it refrains from sending a RTR. With this algorithm, new communications that are initiated by REQ have priority on already running communications that request a new slot.

Figure 8 shows an example of splitting. On the left hand side, a reservation is done by the sender on slot i, the buffer status field is set to 0. On the right hand side, the buffer exceeds the threshold, "buffer status" is set to 1. Slot j is attributed to the receiver until the end of the communication on this slot.

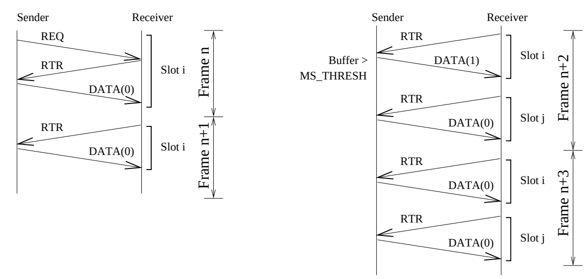

Figure 8. Example of multi-slot communication with CROMA.

Figure 9 shows that allowing multi-slot communications reduces the influence of the frame length. Performance is similar for $L = 3, 4, 6$ and 8.

3. Multi-User Diversity

Multi-user diversity is a method firstly introduced by Knopp and Humblet in [23] that aims at improving the capacity of multi-user communications over fading channels. They considered uplink communications in a single cell and showed that the policy that schedules at any given time the user with the best channel conditions maximizes the capacity. The probability to find a user with very good channel quality, and the capacity of the system, increases with the number of users. Hence, this number appears to be a source of diversity.

Multi-user diversity is used in the High Data Rate (HDR) system of Qualcomm [28]. The principle of favouring the user with the best

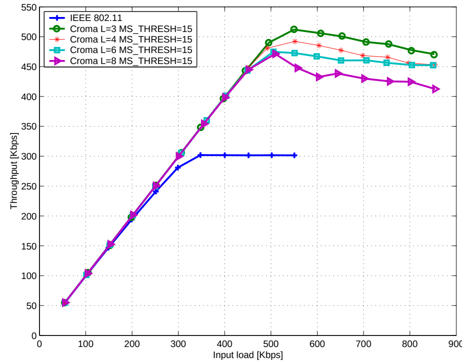

Figure 9. Throughput vs. input load, influence of L, squares topology, $MS\_THRESH = 15$

"channel" quality has been also adapted in the context of ad hoc networks [19] and in multi-antenna systems [40].

3.1. Channel Aware Slotted ALOHA

In this section, we focus on a new application of the notion of multi-user diversity for random access. Qin and Berry have proposed in [30] a new medium access control protocol based on slotted ALOHA and called channel aware slotted ALOHA.

In the considered topology, there is a central station, e.g., a receiver node in CROMA terminology, and users attempting to send information to this central point, e.g., REQ packets for a slot reservation. Thus, only uplink distributed and random access is considered. This protocol is based on the traditional slotted ALOHA: time is divided in equal time-slots, where terminals are allowed to transmit with a probability p. If several users take the same decision of transmitting during a given time-slot, a collision occurs at the central station and all packets are lost. In our study, the possibility of capture is excluded. Now, let T be the event of a successfull transmission on a time-slot. All users are assumed to be backlogged. If there are n users:

$$P[T] = np(1-p)^{n-1} \; . \qquad (15)$$

In the slotted ALOHA protocol, the decision of transmission is not correlated to the channel conditions experienced by the user. In the channel aware slotted ALOHA protocol, users are allowed to transmit only if their channel quality is good enough, i.e., if their Signal-to-Noise Ratio (SNR), γ, is above a given threshold, γ_0. γ_0 is chosen in order to match with the probability p of transmission. Let $F(\gamma)$ be the complementary distribution function (cdf) and $p_\gamma(\gamma)$ the probability distribution function (pdf) of the SNR. $F(\gamma)$ and γ_0 are given by:

$$F(\gamma) = \int_{\gamma}^{+\infty} p_\gamma(\gamma) d\gamma \quad (16)$$

$$\gamma_0 = F^{-1}(p) . \quad (17)$$

The channel aware slotted ALOHA protocol assumes that each user is aware of its own channel conditions and that all users experience the same SNR distribution. The former assumption can be achieved if we consider that the central station periodically sends a beacon frame on the same channel, e.g., a RTR control packet. The latter assumption is realistic if users are in the same environment and have short range communications, so that they have approximatly the same mean SNR. Otherwise, the system is expected to be unfair.

The channel is now assumed to change at a rate much slower than the data rate, so the uplink is a block fading channel. The general theory for the capacity of such fading channels has been developed in [17]. It has been shown that the fading channel capacity with channel side information at both the transmitter and receiver is achieved when the transmitter adapts its power, data rate, and coding scheme to the channel variations. In our case, the normalized capacity is in bits/Hz/second:

$$C_{opra} = \int_{\gamma \geq \gamma_0} \log_2(1+\gamma) p_\gamma(\gamma) d\gamma . \quad (18)$$

If users are further assumed to transmit with power $S(\gamma)$ subject to an average power constraint S

$$\int_{\gamma \geq \gamma_0} S(\gamma) p_\gamma(\gamma) d\gamma \leq S , \quad (19)$$

the Lagrange multipliers provide:

$$C_{opra} = \int_{\max(\gamma_0,\lambda)}^{+\infty} \log_2\left(\frac{\gamma}{\lambda}\right) p_\gamma(\gamma) d\gamma , \quad (20)$$

where λ must satisfy:

$$\int_{\max(\gamma_0,\lambda)}^{+\infty} \left(\frac{1}{\gamma} - \frac{1}{\lambda}\right) p_\gamma(\gamma) d\gamma = 1 . \quad (21)$$

Now, the capacity of the protocol is given by:

$$\begin{aligned} C &= E\left[\log_2(\gamma/\lambda)\right] \quad (22) \\ &= P[T] E\left[\log_2(\gamma/\lambda) | T\right] \\ &= np(1-p)^{n-1} E\left[\log_2(\gamma/\lambda) | \gamma \geq \max(\lambda, \gamma_0)\right] . \end{aligned}$$

From this expression, the spectral efficiency of the channel aware slotted ALOHA protocol in case of optimal power and rate adaptation with average transmit power constraint is deduced in bits/Hz/second:

$$C = np(1-p)^{n-1} \frac{\int_{\max(\gamma_0,\lambda)}^{+\infty} \log_2\left(\frac{\gamma}{\lambda}\right) p_\gamma(\gamma) d\gamma}{\int_{\max(\gamma_0,\lambda)}^{+\infty} p_\gamma(\gamma) d\gamma} . \tag{23}$$

Note that if $\gamma_0 \geq \lambda$, $\int_{\max(\gamma_0,\lambda)}^{+\infty} p_\gamma(\gamma)d\gamma = p$ and C can be written:

$$C = n(1-p)^{n-1} \int_{\gamma_0}^{+\infty} \log_2\left(\frac{\gamma}{\lambda}\right) p_\gamma(\gamma) d\gamma . \tag{24}$$

In this paper, the uplink is assumed to be a Rayleigh fading channel. So the pdf of the SNR is given by the exponential distribution:

$$p_\gamma(\gamma) = \frac{e^{-\gamma/\bar{\gamma}}}{\bar{\gamma}} , \tag{25}$$

where $\bar{\gamma}$ is the average received SNR.

From Equation 16, the SNR threshold is given by:

$$\gamma_0 = -\bar{\gamma} \ln(p). \tag{26}$$

Let assume that $\lambda \leq \gamma_0$ and so $\max(\lambda, \gamma_0) = \gamma_0$. By substituting Equation 25 in Equation 21, the power constraint is:

$$\int_{\gamma_0}^{+\infty} \left(\frac{1}{\lambda} - \frac{1}{\gamma}\right) \frac{e^{-\gamma/\bar{\gamma}}}{\bar{\gamma}} d\gamma = 1 . \tag{27}$$

After some manipulations λ can be written:

$$\lambda = \frac{\gamma_0 E_0(\gamma_0/\bar{\gamma})}{\bar{\gamma} + E_1(\gamma_0/\bar{\gamma})} , \tag{28}$$

where $E_n(x)$ is the exponential integral of order n defined by:

$$E_n(x) = \int_1^{+\infty} t^{-n} e^{-xt} dt \ , x \geq 0 . \tag{29}$$

If $\gamma_0 \leq \lambda$, the power constraint is:

$$\int_{\lambda}^{+\infty} \left(\frac{1}{\lambda} - \frac{1}{\gamma}\right) \frac{e^{-\gamma/\bar{\gamma}}}{\bar{\gamma}} d\gamma = 1 , \tag{30}$$

and λ is the solution of the following equation:

$$E_0\left(\frac{\lambda}{\bar{\gamma}}\right) - E_1\left(\frac{\lambda}{\bar{\gamma}}\right) = \bar{\gamma} . \tag{31}$$

It is straightforward to show by derivation that this equation has a unique solution (see [2] for a similar demonstration).

This paper focuses on the dependency of the capacity on p. So, let $g(p)$ be the expression of λ when $\lambda \leq \gamma_0$, i.e., $g(p) = \frac{\bar{\gamma} p}{\bar{\gamma}+E_1(-\ln p)}$. Equation 28 is valid only for $g \leq \gamma_0$. Hence, the sign of $f(p) = p + \ln p(\bar{\gamma} + E_1(-\ln p))$, which has the same sign than $g(p) - \gamma_0(p)$ has to be studied. The derivative of f,

$$f'(p) = \frac{\bar{\gamma} + E_1(-\ln p)}{p} , \tag{32}$$

is clearly positive for p between 0 and 1. Moreover, $\lim_{p\to 0} f(p) = -\infty$.

On the other hand, when p tends towards 1, $x = -\ln(p)$ tends toward 0. Moreover, an asymptotic expression of E_1 (see p. 927 of [18], $E_1(x) = -E_1(-x)$) provides:

$$E_1(x) = -C - \ln(x) - \sum_{k=1}^{\infty} \frac{(-1)^k x^k}{k.k!} \tag{33}$$

$$xE_1(x) = -xC - x\ln(x) - \sum_{k=1}^{\infty} \frac{(-1)^k x^{k+1}}{k.k!} \tag{34}$$

$$\lim_{x\to 0} xE_1(x) = 0, \tag{35}$$

where C is the Euler constant.

Now, it is straightforward that $\lim_{p\to 1} f(p) = 1$

Hence, let p^* be the unique solution of $f(p) = 0$. For $p \leq p^*$, λ is given by Equation 28 and for $p \geq p^*$, λ verifies Equation 31.

However, the case $p \geq p^*$ is not the most interesting one. Indeed, Figure 10 shows p^* as a function of $\bar{\gamma}$ and Figure 11 shows the capacity of the protocol for a small number of users, $n = 5$, as a function of p. It is clear that for $p \geq p^*$, the capacity is very low and the protocol parameter is not well dimensionned. It is also expected that the most interesting part for p is where the capacity reaches its maximum, i.e., in the neighborhood of $1/n$. In the following steps, this case will be neglected and next steps will focus on situations where $\lambda \leq \gamma_0$.

Equation 25 can now be substituted in Equation 24:

$$C = n(1-p)^{n-1} \int_{\gamma_0}^{+\infty} \log_2\left(\frac{\gamma}{\lambda}\right) \frac{e^{-\gamma/\bar{\gamma}}}{\bar{\gamma}} d\gamma , \tag{36}$$

that can be reduced to:

$$C = n(1-p)^{n-1} \log_2(e) \times \left(\ln\left(\frac{\gamma_0}{\lambda}\right) e^{-\gamma_0/\bar{\gamma}} + \frac{\gamma_0}{\bar{\gamma}} J_1(\gamma_0/\bar{\gamma})\right) , \tag{37}$$

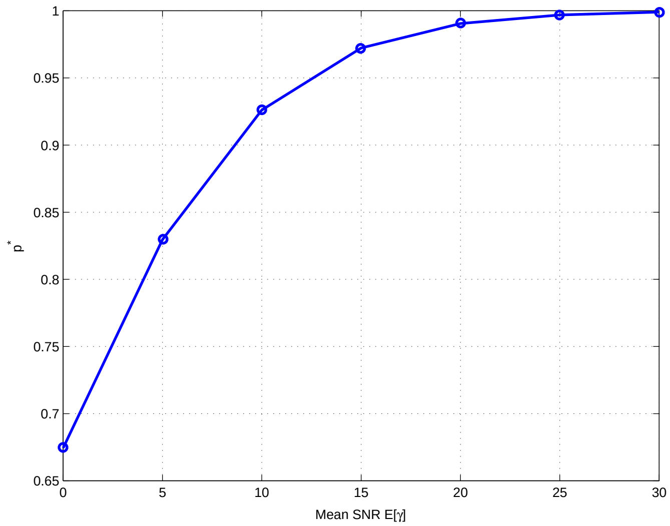

Figure 10. p^* as a function of the mean SNR $\bar{\gamma} = E[\gamma]$.

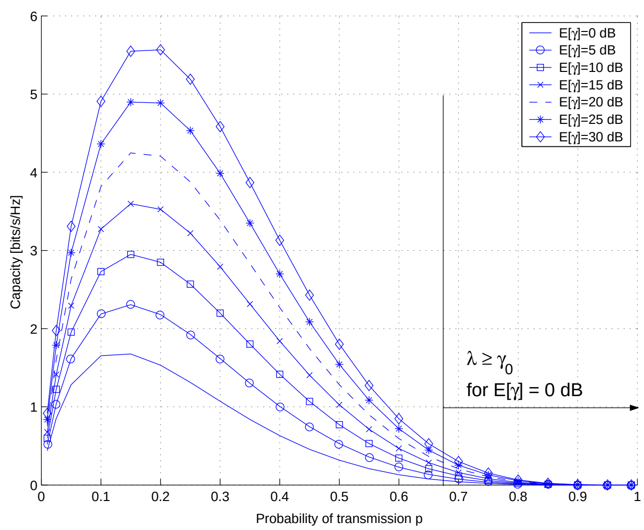

Figure 11. Capacity as a function of the mean SNR $\bar{\gamma} = E[\gamma]$ for n=5 users.

where the integral $J_n(\mu)$ are defined by:

$$J_n(\mu) = \int_1^{+\infty} t^{n-1} \ln(t) e^{-\mu t} dt, \quad \mu > 0; \; n = 1, 2, \ldots . \tag{38}$$

The integration by parts of $J_1(\mu)$ yields: $J_1(\mu) = E_1(\mu)/\mu$. The capacity in bits/Hz/second is given by:

$$C = n(1-p)^{n-1} \log_2(e) \times \left(\ln\left(\frac{\gamma_0}{\lambda}\right) e^{-\gamma_0/\bar{\gamma}} + E_1(\gamma_0/\bar{\gamma}) \right) . \quad (39)$$

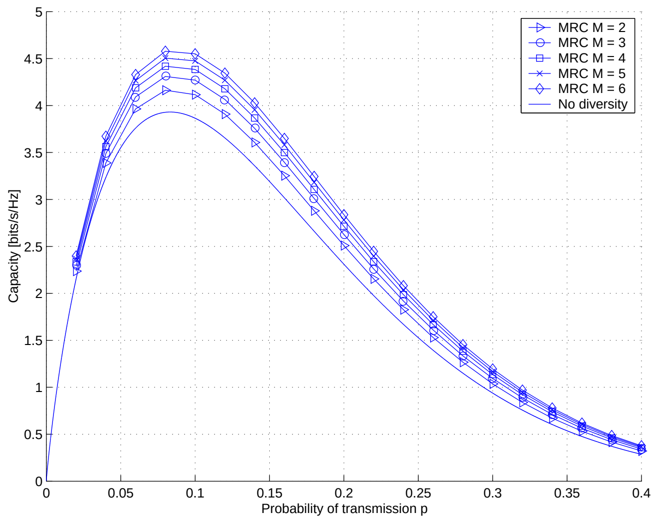

Figure 12. Capacity over a Rayleigh channel with MRC and without diversity scheme for $\bar{\gamma} = 15dB$ and $n = 10$.

[12] also provides closed-form formula for the capacity of the protocol with the Maximum Ratio Combining (MRC) technique. In Figure 12, the capacity of the protocol with MRC over a Rayleigh channel is provided for $\bar{\gamma} = 15dB$ and $n = 10$ as a function of p, several orders of diversity are also shown. We note that the optimum probability of transmission, p_{opt}, is independent on the order of diversity and is different from $1/n$, which is the classical optimum for the slotted ALOHA protocol.

Figure 13 shows the classical result of multi-user diversity: the capacity of the channel-aware slotted ALOHA increases with the number of users.

3.2. Mobility as a Source of Diversity

In [20], P. Gupta and P. R. Kumar have drawn quite pessimistic observations regarding 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

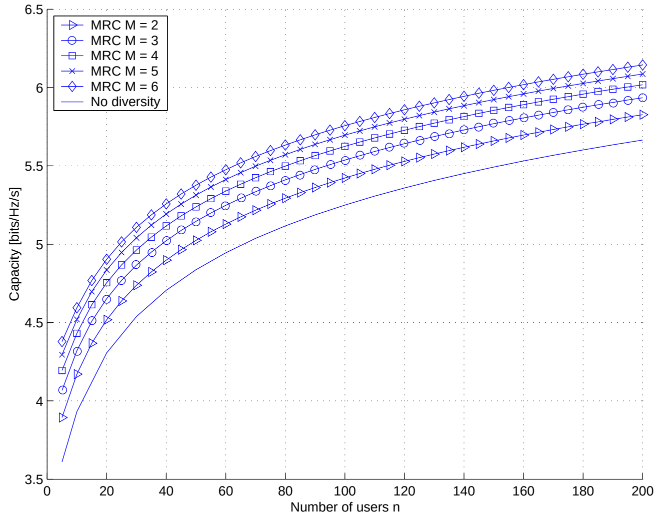

Figure 13. Influence of the number of users on the capacity at $p = 1/n$ for $\bar{\gamma} = 15dB$, with MRC and without diversity scheme.

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 [19] that this limitation can be overcome through node mobility. For that they use an analogy of multi-user diversity 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. 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 [19] 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, this section demonstrates the usefulness of such a scheme that shows the benefit of node mobility on the network throughput.

In the proposed scheduling policy [11], the network is assumed to be perfectly synchronized and the channel is supposed to be slotted. The MAC protocol is a two-way handshake and receiver-initiated protocol. During a given time-slot, the receiver sends a RTR. 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 (see Figure 14). This is a simplified version of CROMA.

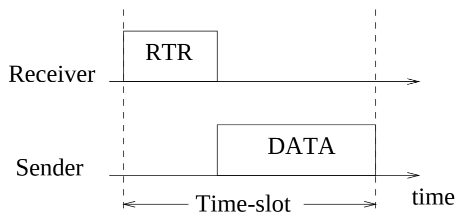

Figure 14. Two-way handshake within a time-slot

At each time-slot, θN nodes among N are designated as senders, the remaining nodes are receivers, $\theta \in]0,1[$ is the sender density. All receivers send a RTR as described before. Each sender manages two packet queues. 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 policy is called the “two-hop strategy” because packets are transported through at most two hops. An alternative is the “one-hop” strategy, where packets are not relayed, but directly sent from the source to the destination.

$N = 30$ nodes have been considered moving in a 1000u $\times$ 1000u square field, where u is a unit of length. The mobility model uses the random waypoint model with a fixed speed, which is taken as a metric for mobility. The simulations parameters are given in Tab.II. Note that the destination of each new packet is uniformly chosen among all nodes but the source. The effects of interference and capture are not taken into account, i.e., only collisions of packets are considered and nodes have a fixed transmission range. Moreover, problems related to high mobility w.r.t the channel model, e.g., Doppler effect, are not taken into account.

Table II. Scheduling policy simulation parameter values

Parameter	Value
N	30
θ	0.5
DATA size	512 bytes
RTR size	44 bytes
ON distribution	Exponential
Mean ON time	0,5s
ON data rate	64 Kbps
OFF distribution	Exponential
Mean OFF time	0.5 s
PHY data rate	2 Mbps

Figures 15 and 16 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. However, network throughput is fundamentally limited because of the high level of interference induced by high transmitted power. On the other hand, communications between nearest neighbours increases the mean number of hops and thus routing overhead. Above all, most of the packets carried by the network are relayed packets. In the scheduling policy proposed by [19] 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.

We now derive the optimum transmission range applicable to the one-hop strategy for a given sender density. For that, we consider that during a given time-slot the positions of senders and receivers are two independent Poisson point processes with density resp. $\theta\lambda$ and $(1-\theta)\lambda$. We also assume that a sender has always something to transmit to the receiver from which it received an RTR. If the edge effects are neglected, and interference and capture are not taken into account, a sender receives a RTR if and only if there is a single receiver in its transmission range r. Thus, the probability for a sender to receive a

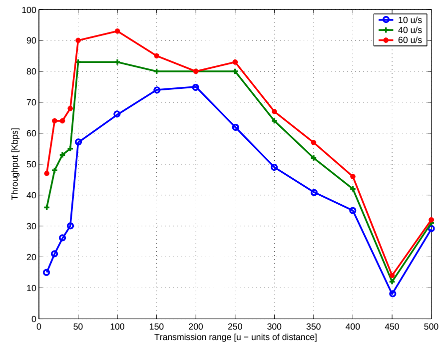

Figure 15. Aggregate throughput - two-hop strategy

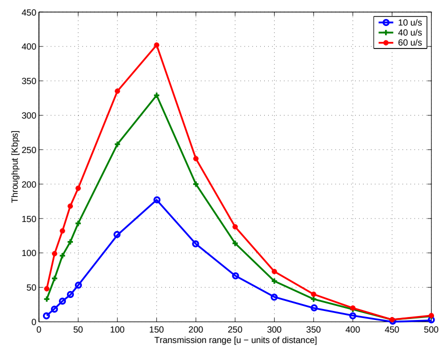

Figure 16. Aggregate throughput - one-hop strategy

RTR is the following:

$$p_1 = (1-\theta)\lambda\pi r^2 e^{-(1-\theta)\lambda\pi r^2}. \tag{40}$$

Now, a receiver decodes a data packet if and only if 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:

$$kp_1(1-p_1)^{k-1}. \tag{41}$$

Thus, the probability for a receiver to receive a data packet is:

$$\begin{aligned} P &= \sum_{k=1}^{\infty} Pr[\text{1 RTR received} | k \text{ senders}] Pr[k \text{ senders}] \\ &= \sum_{k=1}^{\infty} kp_1(1-p_1)^{k-1} \frac{(\theta\lambda\pi r^2)^k}{k!} e^{-\theta\lambda\pi r^2} \\ &= p_1\theta\lambda\pi r^2 e^{-\theta\lambda\pi r^2 p_1} \end{aligned} \tag{42}$$

$$= \theta(1-\theta)(\lambda\pi r^2)^2 exp\left[-(1-\theta)\lambda\pi r^2(\theta\lambda\pi r^2 e^{-(1-\theta)\lambda\pi r^2}+1)\right] .$$

$P(r)$ can be written $P(r) = y(r)e^{-y(r)}$ with

$$y(r) = \theta(1-\theta)(\lambda\pi r^2)^2 e^{-(1-\theta)\lambda\pi r^2} . \qquad (43)$$

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

$$r_{opt} = \sqrt{\frac{2}{(1-\theta)\lambda\pi}} . \qquad (44)$$

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

$$\theta(1-\theta)(\lambda\pi r^2)^2 e^{-(1-\theta)\lambda\pi r^2} = 1 . \qquad (45)$$

This equation has two solutions:

$$r_{opt1} = \sqrt{\frac{2W_0\left(-\sqrt{\frac{1-\theta}{4\theta}}\right)}{\lambda\pi(\theta-1)}} \qquad (46)$$

$$r_{opt2} = \sqrt{\frac{2W_{-1}\left(-\sqrt{\frac{1-\theta}{4\theta}}\right)}{\lambda\pi(\theta-1)}} , \qquad (47)$$

where W_0 is the principal branch of the Lambert W-function, and W_{-1} is the second value [8].

4. Multi-Packet Reception

The spatial capacity of the slotted ALOHA protocol has been studied in [26], where the effect of capture is detailed. This capacity has been obtained with the assumption that receivers devices are able to decode at most a single packet per slot. However, research performed since the early 80's in the domain of multi-user detection in CDMA systems [39] shows that this condition can be overcome. Indeed, receivers using multi-user detection schemes can decode the packets from several simultaneous transmitters. In particular, the near-far resistance of the multi-user detectors [25] makes this technique very attractive for ad hoc networks, where power control schemes are much more difficult to implement than in traditional single-hop systems.

In this paper, the result of [26] is extended in the case of multi-packet reception and a closed-form formula is provided for the throughput of the slotted ALOHA as a function of the probability, $r_{n,k}$, for a receiver to decode k packets given that n have been sent in its neighborhood.

Throughout this section, a packet radio network of nodes is considered, spatially distributed in the plane according to a Poisson process with parameter λ. That means that the probability to find k nodes in any region, A, of area $S(A)$ is:

$$P[k \text{ in } A] = \frac{(\lambda S(A))^k}{k!} e^{-\lambda S(A)} . \quad (48)$$

The considered network is large and the edge effects will be neglected.

All nodes are assumed to operate with a half-duplex radio device. This means that a collision of the second order can occur if a node receives a packet, while it is itself transmitting during the same slot. In this case, the packet is lost. The transmit power is constant and equals P_0.

As assumed in the introduction, nodes access the channel by using the slotted ALOHA protocol, i.e., time is divided in equal time-slots. At a given slot, a node sends a packet with a fixed probability p. Otherwise, it is able to receive one or several packets coming from the transmitters. Let R_0 be the reception radius of a receiver. R_0 is the maximum distance from which can come a packet destined to this receiver. If there are n transmitters within R_0 from the receiver, the probability to decode k packets is $r_{n,k}$.

It is assumed that packets destined towards a particular node in the network are routed with equal probability towards one of the neighboring nodes that lies in the direction of the destination. All these assumptions are taken from [26].

We are interested in the local throughput of the system, i.e., the expected number of packet received per slot.

Before looking at the local throughput, let's recall two preliminary results already given in [26]. A particular node a is considered and let the random variable X be the number of correctly decoded packets destined to a in a given slot. The definition of four important events is also needed:

- (A) the event that a does not transmit.
- (T) the event that a particular sender t sends a packet to a.
- (T_n) the event that there are n senders in the neighborhood of a.
- (D_k) the event that a decodes exactly k packets in the given time-slot.

The two basic results are:

$$P[A] = 1 - p \,, \tag{49}$$

$$P[T] = \frac{1 - e^{-\lambda\pi R_0^2/2}}{\lambda\pi R_0^2} \,, \tag{50}$$

where p is the probability of transmission, λ is the density of the nodes, and R_0 is the transmission range. Note that if nodes are spatially distributed according to a Poisson process with density λ, senders, at a given time-slot, are spatially distributed according to a Poisson process with density λp (see e.g. in [15]).

Now, the probability that a receives x packets given (A), (T_n), and (D_k) is:

$$P[X = x|A, T_n, D_k] = \binom{k}{x} P[T]^x (1 - P[T])^{k-x} \,, k \geq x \,, \tag{51}$$

because among the k packets decoded, x are destined to a. This probability is zero if $k < x$. This relation is now successively marginalized:

$$P[X = x|A, T_n] = \sum_{k=0}^{n} P[X = x|A, T_n, D_k] P[D_k|A, T_n] \tag{52}$$

$$= \sum_{k=0}^{n} P[X = x|A, T_n, D_k] r_{n,k} \tag{53}$$

$$= \sum_{k=x}^{n} \binom{k}{x} P[T]^x (1 - P[T])^{k-x} r_{n,k} \,. \tag{54}$$

The second line is justified by the fact that the events (D_k) and (A) are independent. The third line takes into account Equation 51. Now, assuming that the considered node a does not transmit:

$$P[X = x|A] = \sum_{n=0}^{\infty} P[X = x|A, T_n] P[T_n|A] \tag{55}$$

$$= \sum_{n=0}^{\infty} P[X = x|A, T_n] \frac{(\lambda p\pi R_0^2)^n}{n!} e^{-\lambda p\pi R_0^2} \tag{56}$$

$$= \sum_{n=0}^{\infty} \sum_{k=x}^{n} \binom{k}{x} P[T]^x (1 - P[T])^{k-x} r_{n,k} \frac{(\lambda p\pi R_0^2)^n}{n!} e^{-\lambda p\pi R_0^2} \tag{57}$$

The second equation results from the fact that (T_n) and (A) are independent and that the density of the senders is λp as explained before. Note that if a is a sender at the considered slot, a cannot receive any packet because of the half- duplex nature of its radio device. So, for $x \neq 0$:

$$\begin{aligned} P[X = x] &= P[X = x|A]P[A] \\ &= P[X = x|A](1 - p) , \end{aligned} \tag{58}$$

according to Equation 49. The pdf of X, the number of packets received by a, is obtained:

$$P[X = x] = \sum_{n=0}^{\infty} \sum_{k=x}^{n} \binom{k}{x} P[T]^x (1-P[T])^{k-x} r_{n,k} \frac{(\lambda p \pi R_0^2)^n}{n!} e^{-\lambda p \pi R_0^2} (1-p) . \tag{59}$$

The throughput in a is immediatly obtained by taking the expectation of X:

$$E[X] = \sum_{x=1}^{\infty} x P[X = x] . \tag{60}$$

If there are N nodes in the network, the local throughput of the network, S, i.e., the throughput at the MAC layer is:

$$S = NE[X] . \tag{61}$$

Note that the single-packet detection without capture is a special case of the aboves formulas. Indeed, by taking $r_{1,1} = 1$, $r_{n,0} = 1$ for $n \neq 1$, and $r_{n,k} = 0$ otherwise, the throughput is given by:

$$\begin{aligned} E[X] &= P[X = 1] \\ &= P[T](\lambda p \pi R_0^2) e^{-\lambda p \pi R_0^2} (1 - p) \\ &= p(1 - p)(1 - e^{-\lambda \pi R_0^2/2}) e^{-\lambda p \pi R_0^2} , \end{aligned} \tag{62}$$

which is in accordance with the results of [26].

The previously considered ALOHA protocol is now assumed to be a spread slotted ALOHA. At a given time-slot, all senders are supposed to choose randomly a pseudo-noise (PN) sequence among a large book of low cross-correlated PN codes with a large spreading factor L. All potential receivers, i.e., all nodes have the knowledge of this book and are able to perform multi-packet reception. The probability that two neighboring senders choose the same code is neglected in order to simplify the calculations. From the presented models, values for the $r_{n,k}$ are derived.

The first model is a simple one, used in the literature, e.g. in [24]. It states that all of the simultaneous transmissions can be successfully received if no more than K users are transmitting at the same time.

If there are more than K users transmitting at the same time, the multi-user receiver is overhelmed and a collision occurs. Thus:

$$r_{n,k} = \begin{cases} 1, & \text{if } k = n \text{ and } n \leq K \\ 1, & \text{if } k = 0 \text{ and } n > K \\ 0, & \text{otherwise} \end{cases} \tag{63}$$

The second model supposes that radio receivers devices are made of a bank of Matched Filters (MF) that are able to decode each spreading code individually. If P_0 is the transmit power, the received power at a distance r is assumed to be $P(r) = P_0/r^\gamma$, where $\gamma > 2$ is the path loss exponent. This expression is a far-field approximation that doesn't hold for small values of r. A packet is considered to be decoded if the Signal-to-Interference plus Noise Ratio (SINR), β, of a signal at the output of the MF reaches a SINR target β_0, i.e., if:

$$\beta = \frac{P(r)}{\sigma^2 + \frac{1}{L}\sum_{i=0}^{n-1} \frac{P_0}{r_i^\gamma}} \geq \beta_0 \ , \tag{64}$$

where σ^2 is the power of the noise, n is the number of interferers, and L is the spreading length.

In order to analitycaly evaluate the $r_{n,k}$ parameters, the cdf of the SINR is needed in the case of a Poisson field of interferers. This problem has been treated in [35] and in [34], where the characteristic function of the interference $Y = \sum_{i=0}^{n-1} P_0/r_i^\gamma$ has been obtained. This expression leads to the exact cdf of β and thus to the $r_{n,k}$ in the MF case. However, this is not the case for the Multi-User Detection (MUD) receiver. That is the reason why the $r_{n,k}$ probabilities are evaluated thanks to Monte Carlo simulations in order to allow a fair comparison with the MMSE detector.

A Poisson field of interferers with density λp is generated on a two dimensional squared network $[-Xmax; Xmax] \times [-Ymax; Ymax]$. The considered receiver, a, is placed at $(0; 0)$. R_0 is fixed as the maximum distance from which can come packets for the receiver. In the abscence of interferer, R_0 verifies the following expression: $\beta_0 = P_0/(R_0^\gamma \sigma^2)$. n is the number of senders inside the disk of radius R_0 with center a. For each of these senders, the SINR is computed after summing the interference from the whole network. If the SINR reaches the SINR target, the packet from this sender is assumed to be decoded. A snapshot of the simulation is shown on Figure 4. Tab.III shows the parameter values used for the simulations.

Figure 4 shows the plot of the matrix $r_{n,k}$ for $n \leq 14$ and $p = 0.2$. The mean number of senders in the disk of radius R_0 is $\lambda p \pi R_0^2 \simeq 5$, so the probability that $n > 14$ is very low. This figure shows that for

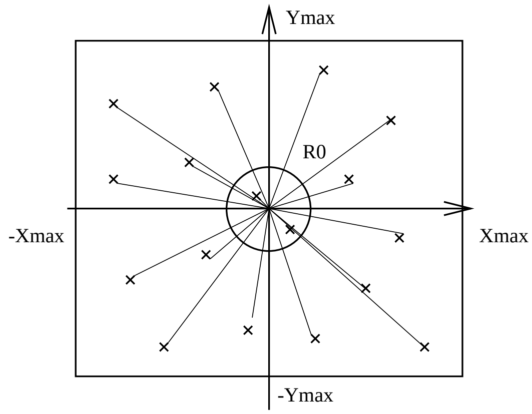

Figure 17. Snapshot of the Monte Carlo simulation: the power of all the interferers are sumed at the receiver.

Table III. Parameter values used for the Monte Carlo simulations

Parameter	**Value**
$Xmax$	50
$Ymax$	50
λ	0.25
p	0.2
L	32
P_0	5
β_0	0.025
σ^2	0.2
γ	4

small values of n, all packets are decoded. Then, when n increases, the number of decoded packets decreases.

The third model assumes that receivers are able to perform multi-user detection thanks to a MMSE detector. While the traditional MF or Rake receiver treats interference from other users as additive noise, the MUD scheme jointly decodes all users.

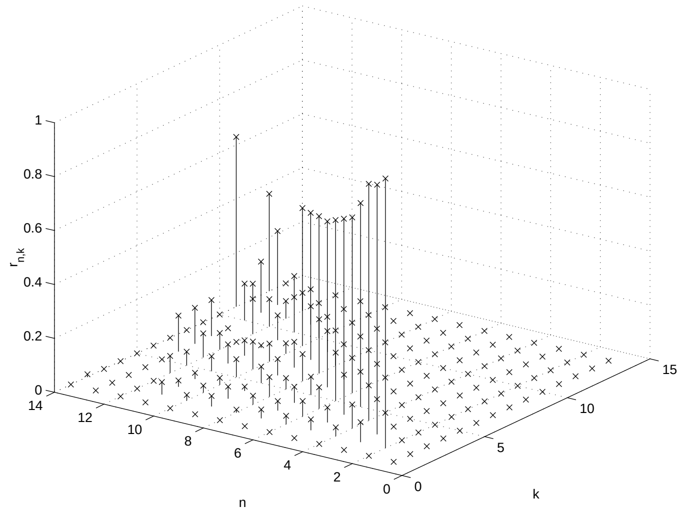

Figure 18. Probabilities, $r_{n,k}$, for a receiver to decode k packets given that n have been sent in the case of a MF bank.

The condition of decoding a packet is still based on the SINR at the output of the signal detector. According to [38], to check if the target for a given sender's SINR, β_0, can be met for a given system of senders, it suffices to check the following condition:

$$\frac{P}{\sigma^2 + \frac{1}{L}\sum_{i=0}^{n-1} I(P_i, P, \beta_0)} \geq \beta_0 \ , \tag{65}$$

where $P = P_0/r^\gamma$ is the received power of the given sender, P_i is the received power from the interferer i and $I(P_i, P, \beta_0)$ is the effective interference of sender i on the considered sender at the target SINR β_0:

$$I(P_i, P, \beta_0) = \frac{P P_i}{P + P_i \beta_0} \ . \tag{66}$$

Equation 65, also used in [33] in the context of call admission control, is an approximation since it is true for large systems, when $L \to \infty$, $n \to \infty$ and $L/n = \alpha$, and for random spreading sequences.

It can be shown that the characteristic function of the interference for a given sender and a given SINR target, β_0 is:

$$\phi_Y(\omega) = exp\left(i\lambda p \pi \omega \int_0^{P/\beta_0} \left(\frac{P_0}{t} - \frac{P_0 \beta_0}{P} \right)^{2/\gamma} e^{i\omega t} dt \right) \ . \tag{67}$$

While in the MF case $\phi_Y(\omega)$ is the characteristic function of a stable law, Equation 67 seems to be un-tractable for further computations.

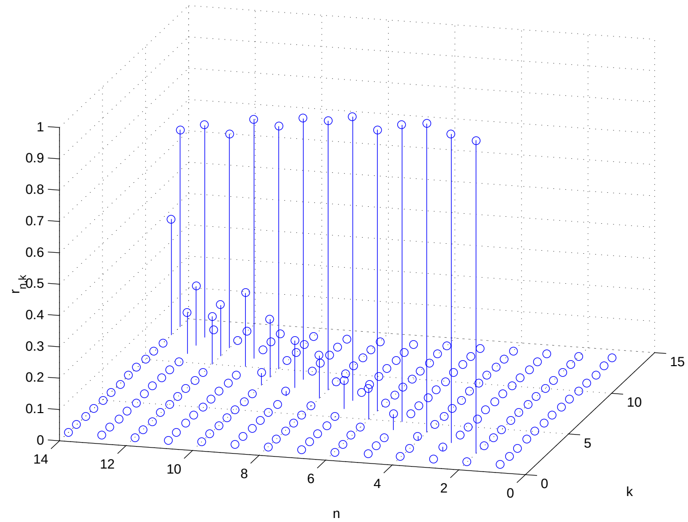

Figure 19. Probabilities, $r_{n,k}$, for a receiver to decode k packets given that n have been sent in the case of MMSE MUD.

That is the reason why results rely on Monte Carlo simulations. Parameter values are given in Tab.III and the condition of packet decoding is given by Equation 65. Figure 4 shows the graph of the matrix $r_{n,k}$ for $n \leq 14$. It is clear that the MUD scheme offers a much better performance than the MF decoding. Note also that the simple model is an approximation of the MMSE performance if K is chosen appropriately.

On Figure 4, the local throughput is presented for the first simple model with different values of K. In all cases, curves have the characteristic shape of the throughput of the ALOHA protocol as a function of the input load. As expected, the multi-packet reception feature improves the maximum achievable throughput.

Figure 4 compares the local throughput of the MF receiver with this of the MMSE receiver. The MUD scheme has a great advantage over the conventional receiver (approximatly 30% in our scenario). Indeed, the joint detection of all users makes the MUD receiver very robust to near-far effects. This near-far resistance is of great interest in ad hoc networks because power control schemes are difficult to implement in such decentralized networks. Further results can be found in [13].

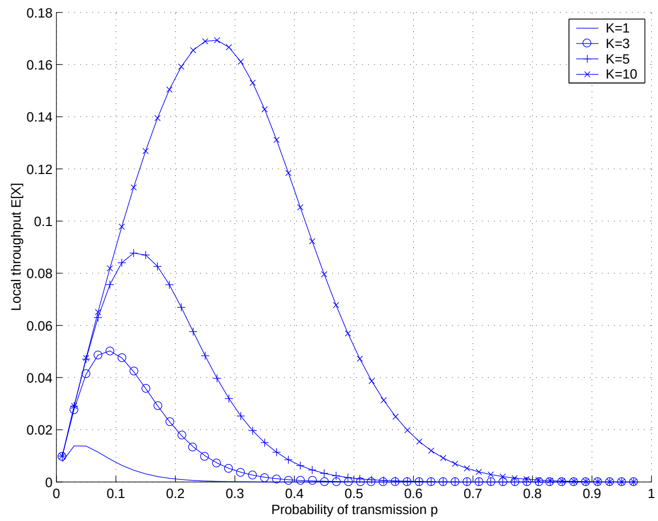

Figure 20. Local throughput in packets/time-slot for the simple model of multi-packet reception for different values of K, the maximum number of packets that can be decoded by the receiver.

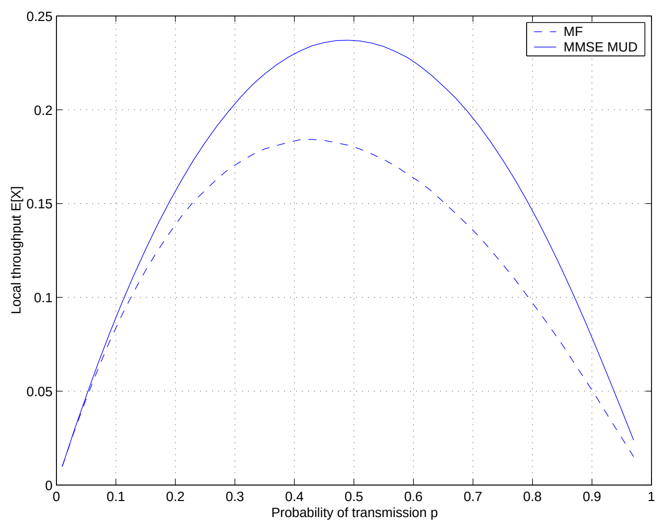

Figure 21. Local throughput in packets/time-slot for the MF receiver and the MMSE receiver.

5. Conclusion

Ad hoc networks, and in particular mobile multi-hop networks, are a very challenging environment for MAC designers. They don't only face inherent problems related to the varying wireless channel, but they also have to take into account the lack of infrastructure, the distributed and moving nature of the network, or the limited features of the radio devices. Some answers have been provided by the IEEE 802.11 standards. However, specific MAC have to be designed in order to solve all issues of ad hoc networks. This paper proposes three examples of improvement using cross-layer interactions. The first one is a new protocol, called CROMA, based on a slotted structure, which shows the benefit of synchronization for improving the throughput and the fairness of the system. The second presented concept is multi-user diversity applied to random access and to routing in ad hoc networks. The advantage of such a method is highlighted by two examples of schemes, and new analytical results are provided. At last, the capacity increase achieved thanks to multi-packet reception allows to conclude that MUD technology is a very good candidate for the physical layer of next generations of ad hoc networks.

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