MAC for Networks with Multipacket Reception Capability and Spatially Distributed Nodes

Guner D. Celik
CNRG
MIT
gcelik@mit.edu

Gil Zussman
Dept. of Electrical Engineering
Columbia University
gil@ee.columbia.edu

Wajahat F. Khan and Eytan Modiano
CNRG
MIT
{wajahat, modiano}@mit.edu

Abstract—The physical layer of future wireless networks will be based on novel radio technologies such as UWB and MIMO. One of the important capabilities of such technologies is the ability to capture a few packets simultaneously. This capability has the potential to improve the performance of the MAC layer. However, we show that in networks with spatially distributed nodes, reusing backoff mechanisms originally designed for narrow-band systems (e.g. CSMA/CA) is inefficient. It is well known that when networks with spatially distributed nodes operate with such MAC protocols, the channel may be captured by nodes that are near the destination, leading to unfairness. We show that when the physical layer enables multipacket reception, the negative implications of reusing the legacy protocols include not only such unfairness but also a significant throughput reduction. We present alternative backoff mechanisms and evaluate their performance via Markovian analysis and simulation. We show that our alternative backoff mechanisms can improve both overall throughput and fairness.

Index Terms—Multipacket Reception, Capture, Medium Access Control (MAC), Performance Evaluation.

I. INTRODUCTION

Future wireless communications technologies, such as Ultra-Wideband (UWB), have several characteristics that set them apart from other wireless communications technologies. One of these characteristics is the ability to capture a few packets simultaneously [25], [26]. A Multipacket Reception (MPR) capability at the physical layer calls for the design of new Medium Access Control (MAC) protocols, that are tailored for this capability [25]. The combination of MPR at the physical layer and a tailored MAC layer has the potential to significantly improve the network’s performance [8]. Yet, recent proposals for MAC protocols for UWB networks (e.g. [7]) do not specifically address the potential MPR capability. Moreover, although a number of previous works provided important insights regarding the effects of MPR, some of the important characteristics of the physical layer and the need for distributed operation have not been fully considered yet. Therefore, in this paper we focus on studying the design considerations of distributed MAC protocols for wireless networks with spatially distributed nodes and MPR capability.

The design of MAC protocols for wireless networks has received tremendous attention in the last four decades [4], [23]. A basic underlying assumption in the design and evaluation of legacy MAC protocols (e.g. Aloha) was that any concurrent transmission of two or more packets results in a collision and failure of all packets. This assumption does not reflect the actual situation in many wireless communications systems in which the packet with the strongest power level can be received successfully (captured) in the presence of contending transmissions. This capture effect has been extensively studied in the past. In particular, [1], [13]–[15], [17], [27] studied the effect of capture on Aloha systems and [12], [18], [21] studied the issue of capture in IEEE 802.11 (CSMA/CA) systems (a review of previous work can be found in [5]).

Some systems are capable of capturing more than a single packet. Such a capability is known as Multipacket Reception capability. Previous research regarding MPR includes the works of Ghez et al. [10] who studied the stability properties of slotted aloha with MPR; Tong et al. [19], [25], [26] who proposed MAC protocols that take into account MPR; and Nguyen et al. [20] who considered the SINR capture model of [27] in the context of MPR systems. Finally, a number of algorithms that control the transmission attempts were proposed in [6], [16], [22]. Despite the recent interest in the area of MPR, numerous research challenges still exist [8]. In particular, little has been done toward the design of distributed algorithms that work effectively with spatially distributed nodes.

Under existing backoff mechanisms (e.g. CSMA/CA, used in IEEE 802.11), once a node transmits and senses a collision, it increases its contention window (i.e. decreases the transmission probability). On the other hand, following a successful transmission, it decreases the contention window. We refer to such an operation model as the Standard Model. It is well-known that the Standard Model may be unfair and can cause starvation to some of the nodes [2], [9]. The unfairness phenomenon is more pronounced in networks with spatially distributed nodes, since the received signals from the distant nodes are usually weaker than the signals from the nearby nodes. This may lead to starvation of distant nodes because once a nearby node captures the channel, it increases its transmission probability hence continuing to capture the channel. On the other hand, the distant nodes that failed to capture the channel, will decrease their transmission probability further reducing their chances to succeed. Moreover, under most spatial distributions the number of distant nodes is usually considerably larger than that of nearby nodes. Hence, a single “powerful” nearby node can block a number of distant nodes which with the MPR capability have the potential to be captured simultaneously. Therefore, the
Standard Model results not only in unfairness but also in a significant throughput reduction.

To overcome this phenomenon, we define an Alternative Model in which a node decreases its transmission probability following success and increases it following failure. In order to evaluate the Standard and Alternative Models, we define a simple MAC protocol, referred to as the Generic Distributed Probabilistic (GDP) protocol. Under this protocol, each node selects between two transmission probabilities according to its success history. We study the performance of the GDP protocol through analysis and simulations. Our model considers a single receiver (e.g., a base station) and multiple transmitters.

We note that in this setting a distributed solution is not strictly necessary. However, we focus on the design of randomized (and hence distributed) access mechanisms that can ultimately be of use in a multihop setting where a centralized solution is less appealing. We also note that although we focus on controlling the transmission probability, other mechanisms, such as power control, can also be utilized in an MPR setting. However, power control mechanisms require sophisticated feedback and complex transmitters that can adjust the transmit power level dynamically on a per-packet basis. Although such mechanisms are appropriate for cellular networks, they may be more difficult to adapt to wireless (ad hoc and sensor) networks. Moreover, in a multihop setting in which a transmitter may interfere with transmissions destined to a number of receivers, the distributed power control problem is a challenging open problem even for the single packet reception case.

The main contribution of this work is the thorough performance evaluation of simple generic MAC protocols in a way that enables us to gain important insights regarding the correct operating point when the network is capable of MPR. While the idea of using feedback from the channel to tune a backoff algorithm is not new, our work exploits this idea in the context of networks with spatially distributed nodes capable of MPR and shows that the tuning has to be done differently than in legacy systems capable of single-packet reception. In particular, we provide extensive numerical results that demonstrate that the Alternative Model outperforms the Standard Model both in terms of throughput and fairness in a wide range of network scenarios. This implies that one cannot directly reuse backoff mechanisms (e.g., CSMA/CA) designed for narrowband networks in networks with MPR capability.

This paper is organized as follows. In Section II we describe the system model and the generic protocol. In Section III we present an analysis of the GDP protocol in a fading-free environment, and in Section IV we extend our analysis to a fading environment. We use the GDP protocol to demonstrate the basic need to redesign the backoff mechanisms for networks with MPR capabilities. However, the GDP protocol is rather simplistic. Hence, in Section V we briefly discuss a more practical implementation using a simple contention window backoff mechanism similar to that used in IEEE 802.11 systems. We present numerical results in Section VI.

1We note that our objective is to gain understanding of the effects of MPR. Therefore, this protocol does not deal with many practical problems.

II. MODEL AND PROTOCOL

Consider \( n \) spatially distributed nodes that transmit to a single receiver (e.g., a base station or an access point) over a slotted channel. We assume that the packets are one-slot long, that the transmit power is constant (denoted by \( P_T \)), and that the propagation model includes path loss and Rayleigh fading (i.e., there exist independent and identically distributed Rayleigh fading channels between the nodes and the receiver). The received power of a transmission from node \( i \), located at distance \( r_i \) from the receiver, is given by [13], [27]:

\[
P_R(i) = R^2 K r_i^{-\beta} P_T,
\]

where \( R \) is a Rayleigh distributed random variable with unit power \( (R^2 \sim \text{Exponential}(1)) \), \( \beta \) is the power loss exponent (typically between 2 and 6), and \( K \) is the attenuation constant. When we analyze systems without fading, we set \( R = 1 \).

We use the SINR capture model [15], [17], [20], [27], defined below (also known as the Physical Model [11] and the power capture model [13]).

Definition 1 (SINR Capture Model): Given \( k \) simultaneous transmissions, the packet of user \( i \) is captured (successfully decoded) at the receiver if

\[
SINR(i) = \frac{P_R(i)}{N + \sum_{j=1,j\neq i}^{k} P_R(j)} > z,
\]

where \( z \) is the capture threshold ratio and \( N \) is the background noise.

The background noise power level is usually much lower than the power level of the interference, and therefore, it will be neglected. For single packet reception narrow-band systems \( 1 \leq z \leq 10 \), whereas for wideband Multipacket Reception systems (e.g., CDMA and UWB) \( z < 1 \) [13], [20]. Since we focus on the MPR capability, we assume that \( z < 1 \). The maximum number of simultaneously successful transmissions is denoted by \( c \). From (2), it can be seen that the maximum number of packets will be captured, if there are \( c \) equal received-power packets at the receiver. Hence, \( c = \lceil 1/z \rceil \).

We analyze the performance of the system in various scenarios. In particular, we consider the node distribution models, defined below.3 We note that Fig. 1 illustrates an example of nodes deployed according to the rings model.

Definition 2 (Rings Model): \( n_1, n_2, \ldots, n_L \) nodes are located on \( L \) rings around the receiver \((\sum_{i=1}^{L} n_i = n) \). The radii of these rings are denoted by \( r_1, r_2, \ldots, r_L \) respectively.

Definition 3 (Disk Model [15], [17], [27]): \( n \) nodes are randomly distributed in a disk of radius \( r_d \) and the Probability Density Function (PDF) of a node’s distance from the receiver \( r \) is denoted by \( f(r) \).

2In [13], the capture equation (2) is defined with an equality, and therefore, there: \( c = 1 + \lceil 1/z \rceil \).

3Since nodes cannot get arbitrarily close to the receiver, when considering the SINR model, we assume that nodes are distributed such that \( \min(r) \geq 1 \). Specifically, in the disk model, we consider a punctured disk [14], [15].
In Section II-A we will present a generic protocol in which the transmission attempts are random. When analyzing this protocol, we denote the failure probability of a packet transmitted by a node located at distance $r$ from the receiver by $p_f(r)$ and the probability of transmission by $\tau(r)$. The throughput of a node at distance $r$ is denoted by $S(r)$ and is defined as the expected number of successfully received packets per slot for that node. The overall throughput is the expected number of successfully received packets per slot throughout the system and is denoted by $S$.

In order to enable analytic performance evaluation, we make two assumptions that have been extensively used in the past (see [4], [23]): (i) there exists a simple immediate and reliable feedback mechanism that provides the node an acknowledgement if its attempt succeeded and (ii) the nodes are saturated (i.e. at each node, there is always a packet to send).

A. Generic Distributed Probabilistic (GDP) Protocol

We now define the Generic Distributed Probabilistic (GDP) protocol. The analysis and performance evaluation of this protocol is later used to demonstrate the need to redesign MAC protocols for networks with MPR capability. Since we focus on the effects of MPR, the protocol does not deal with many practical problems and is far from providing a complete MAC solution (such as provided, for instance, by IEEE 802.11).

The operation of a node under the GDP protocol is described in the state diagram in Fig. 2. A node can be in two states: AS - After Success and AF - After Failure. Transitions may take place after a transmission attempt. A node moves into the AS (AF) state following a successful (failed) transmission of a packet by that node. Since transitions take place after an attempt, a node does not change its state following an idle slot.

The GDP protocol can be viewed as a two-state Aloha system that dynamically adjusts the transmission probability of each node according to its success history. When a node is in the AS (AF) state, it transmits with probability $p_h$ ($p_f$) at each slot, disregarding the status of the channel. The protocol is generic in the sense that it can be evaluated under any combination of $p_h$ and $p_f$. A high $p_h$ value corresponds to maintaining a small contention window following a successful attempt in the traditional backoff mechanisms such as the one used in IEEE 802.11. Similarly, a low $p_f$ value corresponds to maintaining a large contention window following a failure. Hence, for a large value of $p_h$ and a small value of $p_f$, the protocol captures, in a very simplistic sense, the dynamic and adaptive operation of traditional backoff mechanisms. Accordingly, we refer to the operation of the GDP protocol with $p_h > p_f$ as the Standard Model and to the operation with $p_f > p_h$ as the Alternative Model. We will show that although the Standard Model may achieve good throughput in networks with single packet reception, in networks with MPR capability and spatially distributed nodes, the Alternative Model usually yields higher throughput than the Standard Model.4

III. Rings Model without Fading - Analysis

In this section we analyze the GDP protocol under the rings model in a system without fading. We provide exact and approximate results. We have used the exact results in order to check the accuracy of the approximation method and of our simulation model (described in Section VI).

A. Two Rings - Exact Analysis

Consider $n_1$ and $n_2$ nodes distributed on two rings whose radii are $r_1$ and $r_2$. Using (1) and (2), it can be seen that if $r_1^{-\beta} > z((c-1)\tau_1^{-\beta} + n_2 r_2^{-\beta})$, the $n_2$ nodes on the ring at $r_2$ cannot generate enough interference to cause failure to a transmission from a node on the ring at $r_1$ (even if there are $c-1$ other transmissions from $r_1$). A simplification yields the following observation.

Observation 1: If $n_2 < (r_2/r_1)^{\beta}(z^{-1} - c + 1)$, then transmissions from the nodes on the ring at $r_2$ cannot cause failures to packets transmitted from nodes on the ring at $r_1$. The following can also be obtained from (1) and (2).

Observation 2: If $(r_1/r_2)^{\beta} < z$, a transmission from a node at $r_2$ can be captured only when all the nodes at $r_1$ are silent. For example, for $z = 0.2$, $\beta = 4$, $r_1 = 1$, and $r_2 = 2$, the condition in Observation 1 implies that $n_2 < 16$. In order to facilitate the exact analysis, we assume that the conditions presented in the observations above hold.

We describe the evolution of the system under the GDP protocol by a two dimensional Markov chain whose states are denoted by $(i,j)$. $i$ and $j$ denote the number of nodes on the rings at $r_1$ and at $r_2$ (respectively) that are in the AF state. Accordingly, the number of states in the chain is $(n_1 + 1)(n_2 + 1)$. An example of part of such a Markov chain is illustrated in Fig. 3. Each arrow represents a possible transition between states $(i,j)$ and $(k,l)$ that has some transition probability associated with it. We group the transition probabilities according to the type of change (positive, negative, or none) in each of the two dimensions. For example, one group includes

4There are some cases in which the Standard Model outperforms the Alternative Model. For example, when there is a single node in the network the Standard Model is preferable.
the transition probabilities for which \( k > i \) and \( l > j \), while another group includes the probabilities for which \( k < i \) and \( l = j \). All the possible combinations of changes results in 9 groups.

Due to space constraints, we omit the equations describing the transition probabilities (they can be found in [5, Chapter 5]). Given the transition probabilities, the steady state probabilities (denoted by \( p(i, j) \)) can be obtained by solving a set of linear equations. Once the steady state probabilities are obtained, the throughput of these nodes can be computed as if there is a single ring.

\[ \text{Definition 4 (Inter-ring Independence Assumption): For a node on a ring at } r_j, \text{ the probability that a node on the ring at } r_i (i \neq j) \text{ transmits } (\tau(r_i)), \text{ is constant and is independent of the states of the nodes on the rings at } r_h (h \neq i). \]

In general, the probability that a node transmits depends on its success history and the actions of the other nodes. Yet, similar independence assumptions have been made in the analyses of IEEE 802.11 (while taking into account the dependence on \( r_i \) [18] or ignoring it [3]). We note that since we assume that there is dependence between the nodes on each ring, the assumption is weaker than the assumptions made in the past.

We wish to limit the possible interactions between the different rings, and thereby, between the different Markov chains. Namely, we want that for a ring at \( r_i \), the effective \( \tau(r_j) \) \( \forall r_j > r_i \) will be zero. For example, if the condition in Observation 1 holds, the nodes at \( r_1 \) are not affected by transmissions at \( r_2 \). Therefore, in the derivation of the Markov chain of the ring at \( r_1 \), we can assume that \( \tau(r_2) = 0 \). In order to limit the interactions, the conditions at observations 1 and 2 have to hold in addition to a number of other conditions. In the following observations, we demonstrate the conditions for the case of 3 rings. We then outline the results for this case.

The following observation is derived from (1) and (2) in a very similar way to the derivation of Observation 1.

\[ \text{Observation 3: If } n_3 < (r_3/r_2)^3(z^{-1} - c + 1), \text{ then transmissions from the nodes on the ring at } r_3 \text{ cannot cause failures to packets transmitted from the nodes on the ring at } r_2. \]

Using (1) and (2), it can be seen that if \( r_1^{-\beta} > z((c-1)r_1^{-\beta} + n_2 r_2^{-\beta} + n_3 r_3^{-\beta}) \) holds, the \( n_2 \) and \( n_3 \) nodes on the rings at \( r_2 \) and \( r_3 \) cannot generate enough interference to cause failure to a transmission from a node on the ring at \( r_1 \) (even if there are \( c - 1 \) other transmissions from \( r_1 \)). A simplification yields the following observation.

\[ \text{Observation 4: If } n_2 < (r_2/r_3)^3(z^{-1} - c + 1) - n_3(r_2/r_3)^3, \text{ then transmissions from the nodes on the rings at } r_2 \text{ and } r_3 \text{ cannot cause failures to packets transmitted from the nodes on the ring at } r_1. \]

The following observation can be obtained in a similar way to Observation 2.

\[ \text{Observation 5: If } (r_2/r_3)^3 < z, \text{ then a transmission from a node at } r_3 \text{ can be captured only when all the nodes at } r_2 \text{ and at } r_1 \text{ are silent.} \]

For example, for \( z = 0.2 \) and \( \beta = 4 \), \( r_1 = 1, r_2 = 2, r_3 = 4, n_3 \leq 15 \) and \( n_2 \leq 15 \) satisfy the conditions in
observations 1-5. Assuming that the conditions in observations 1-5 are satisfied, we obtain the transition probabilities of the Markov chains as follows. For a Markov chain of a given ring, there are 3 possible transitions in every time slot: the number of nodes in the AF state can increase, decrease, or stay the same. We associate a transition probability with each of these events. Due to space constraints we provide two demonstrative cases (the complete description can be found in [5]).

The first case is a transition probability for the Markov chain of the nodes at \( r_1 \). Recall that due to our assumptions, nodes on the ring at \( r_1 \) are not affected by nodes on other rings. Specifically, we denote by \( P_{i \rightarrow i-s} \), the probability that the number of nodes in the AF state decreases from \( i \) to \( i-s \). In this case, there are \( s \leq i \) successful transmissions from the \( i \) nodes that are in the AF state (i.e. nodes transmitting with probability \( p_h \)). Since the maximum number of simultaneously successful transmissions is \( c \), for \( s \geq c+1 \), \( P_{i \rightarrow i-s} = 0 \). If \( s \leq c \), then there should be \( s \) transmissions from the \( i \) nodes at the AF state and up to \( c-s \) transmissions from the \( n_1-i \) nodes at the AS state. Accordingly, for \( s \leq c \):

\[
P_{i \rightarrow i-s} = \sum_{v=0}^{\min(c-s,n_1-i)} \binom{n_1-i}{v} p_h^v (1-p_h)^{n_1-i-v}.
\]

The second case, appearing in (5), is a transition probability for the Markov chain of the ring at \( r_2 \). It is the probability that the number of nodes in the AF state increases from \( j \) to \( m \). This can happen due to \( k \) failures from \( j \) to \( m \) failed transmissions from the \( n_2-j \) nodes that are at the AS state. If \( m \leq c \), nodes at \( r_2 \) fail only if there is at least one transmission from the ring at \( r_1 \). Under the Inter-ring Independence Assumption this happens with probability \( (1-(1-\tau(r_1))^{n_1}) \), where \( \tau(r_1) \) is the expected transmission probability of a node on the ring at \( r_1 \) computed using the Markov chain of that ring. When \( m \geq c+1 \), in addition to the failures due to the transmissions from the ring at \( r_1 \), nodes on the ring at \( r_2 \) can fail if there are more than \( c \) transmissions from that ring. This second contribution occurs when there is no transmission from the ring at \( r_1 \), \( k \) transmissions from the \( n_1-i \) nodes on the ring at \( r_2 \) that are in the AS state, and at least \( c+1-k \) transmissions from the \( i \) nodes at \( r_2 \) that are in the AF state. If \( k \geq c+1 \), all the transmissions from the ring at \( r_2 \) will fail. In this case, the transition probability is the probability that \( k \) nodes in the AS state will transmit.

Due to the decoupling between the Markov chains, the approximation method is easier to formulate than the exact method presented in Section III-A. Particularly, the derivations of the transition probabilities in the Markov chains of the different rings are very similar to each other. Given the transition probabilities, the steady state probabilities of each of these Markov chains \((p_1(i), p_2(j), \text{and} p_3(h))\) can be obtained by solving a set of linear equations. Once they are obtained, the throughput of the system can be obtained in a similar way to the derivation of (4) and by using \( S_{r_g}(m,i) \) (defined in (3)). It is given by the following expression

\[
S = \sum_{i=0}^{n_1} \sum_{j=0}^{n_2} \sum_{h=0}^{n_3} p_1(i)p_2(j)p_3(h)(S_{r_g}(n_1,i) + (1-p_h)^{n_1-i}(1-p_h)S_{r_g}(n_2,j) + (1-p_h)^{n_1+n_2-i-j}(1-p_h)^{i+j}S_{r_g}(n_3,h)).
\]

Due to the Inter-ring Independence Assumption, the probability of having \( i, j, \) and \( h \) nodes in the AF states on the rings at \( r_1, r_2, \) and \( r_3 \) (respectively) is \( p_1(i)p_2(j)p_3(h) \). Due to our assumptions, the nodes on the ring at \( r_1 \) are not affected by the nodes on other rings, and therefore, their throughput can be computed using \( S_{r_g}(m,i) \) as if there is a single ring. Nodes on the ring at \( r_2 \) succeed only if the nodes at \( r_1 \) are silent (the probability of this event is \( (1-p_h)^{n_1-i}(1-p_h) \)). Similarly, the nodes at \( r_3 \) succeed only if the nodes on the rings at \( r_1 \) and \( r_2 \) are silent (i.e. with probability \( (1-p_h)^{n_1+n_2-i-j}(1-p_h)^{i+j} \)).

We verified the accuracy of the approximation by comparing its results for the 2 rings case with the exact results. While the results for the \( n_1 = 1, n_2 = 5 \) and \( n_1 = 2, n_2 = 10 \) cases were same up to three decimal places, the results for the \( n_1 = 6, n_2 = 10 \) case were within 1.6% of the exact results. We also compared the approximate results for the 3 rings case to results obtained by the simulation model described in Section VI. In all the considered cases, the approximate results were within 2.2% of the simulation results.

IV. RINGS MODEL WITH FADING

We continue to study the performance of the GDP protocol under the rings model. Unlike in the previous section, we now assume that the propagation model includes Rayleigh fading. This assumption allows us to obtain approximate results for a large number of rings without using Markov chains.

We also introduce the following independence assumption.

Definition 5 (Independence Assumption): The probability that a packet transmitted by a node on the ring at distance \( r_i \)
is lost, \( p_l(r_i) \), is constant and is independent of the number of retransmissions suffered.

In general, when a node transmits a packet, the probability that it is lost (due to collisions) depends on other transmissions during that slot. Yet, as mentioned above, similar independence assumptions have been made in the analyses of IEEE 802.11 [3], [18]. When the number of nodes is large, the independence assumption is likely to hold. Indeed, in [5, Chapter 5], we have shown via exact analysis and simulation that results based on this assumption provide a good approximation.

According to Fig. 2, a node changes its state from AS to AF, if it attempts to transmit and fails. Under the independence assumption is likely to hold. Indeed, in [5, Chapter 5], we have shown via exact analysis and simulation that results based on this assumption provide a good approximation.

Using (8) and combining the terms with the same distance, we obtain:

\[
p_{c,j}(r_1, r_2, \ldots, r_L; k_1, k_2, \ldots, k_L) = \prod_{m=1}^{L} \left( \frac{1}{1 + z \left( \frac{r_m}{\tau_m} \right)^{\beta}} \right)^{k_m}.
\]

Eq. (9) can now be used within (7). Then, (6) along with (7) can be solved numerically. Using the numerical solutions, one can obtain the overall throughput \( S = \sum_{i=1}^{L} n_i \tau(r_i)(1 - p_l(r_i)) \).

We used Matlab to solve the equations and obtain numerical results. We verified their accuracy using the simulation model described in Section VI. While in almost all the cases, the approximate results were within 2.6% of the simulation results, a few cases were within 4.6%.

V. GENERIC DISTRIBUTED CONTENTION WINDOW (GDCW) PROTOCOL

We now present the Generic Distributed Contention Window (GDCW) protocol, which is potentially easier to implement compared to the GDP protocol and can be operated according to the Standard and Alternative Models. Unlike the GDP protocol, the GDCW protocol does not easily lend itself to analysis. Hence, we evaluate its performance via simulation.

Similarly to the GDP protocol, nodes operate according to the state machine in Fig. 2. Namely, nodes are assigned contention windows of different sizes according to their success or failure in the previous attempt. When a node enters an AS state, it is assigned a contention window of size \( w_s \) slots. It then selects a backoff interval \( B \) uniformly in \([0, w_s]\) and retransmits after waiting for \( B \) slots, disregarding the status of the channel. Similarly, when a node enters the AF state, it selects a backoff interval uniformly in \([0, w_f]\) and retransmits at the end of this interval.

The GDCW protocol is generic in the sense that it can be evaluated under any combination of \( w_t \) and \( w_s \). For a large value of \( w_t \) and a small value of \( w_s \), the protocol captures, in a very simplistic sense, the operation of backoff mechanisms such as the one used in IEEE 802.11. Hence, we refer to the operation with \( w_t > w_s \) as the Standard Model. When \( w_t > w_s \), we refer to the scheme as the Alternative Model.

VI. PERFORMANCE EVALUATION

We used the analytic methods, described in sections III and IV along with extensive simulation experiments to evaluate the performance of the GDP and GDCW protocols under the Standard Model and the Alternative Model. Analytic results can be obtained for the GDP protocol under the rings model, and therefore, we present analytic results for that case. We also present simulation results for both protocols for the more realistic disk model. Extensive additional numerical results can
be found in [5]. All the reported results are obtained under the SINR model with the assumption that $N = 0, \beta = 4,$ and $z = 0.2$ (i.e. $c = 5$ - at most 5 packets can be captured simultaneously). We verified that the results are not very sensitive to changes in $z$. As mentioned in Section II, when considering the disk model, we assume that nodes are distributed in a punctured disk and that the nodes’ distribution is Uniform. Namely, $f(r) = 2r/(r_d^2 - r_0^2)$, $r_0 \leq r \leq r_d$. In particular, in the reported experiments $r_0 = 1$ and $r_d = 10$.

A. Simulation Model

The simulation model was developed in C. It allows operating the system in different scenarios (e.g. rings model, disk model, with and without fading, etc.) and according to the different protocols. We verified the correctness of the simulation model in a number of ways. For example, we compared results obtained via simulation for the GDP protocol with the rings model to exact results obtained by the method described in Section III-A. In all the cases, the simulation results were within 1.5% of the exact results. We also compared simulation results obtained for the GDP protocol with the disk model and fading to numerical results presented in [14, Figures 4–6] for the special case of $p_d = p_t$. Our simulation results were within 2% of the results in [14]. As mentioned in sections III-B and IV, once the performance of the simulation model had been verified, we also used it in order to check the accuracy of the approximation methods.

In the reported simulation results, for each data point the simulation length was 100,000 slots. Since in the disk model nodes are randomly placed, results presented for that model are averaged over 40 different experiments. In each of these experiments nodes are placed differently.

B. Rings Model without Fading

We now present exact and approximate results regarding the performance of the GDP protocol and simulation results regarding the performance of the GDCW protocol.

Fig. 4(a) presents the overall throughput under the GDP protocol with nodes on two rings. The maximum throughput of 2.195 is obtained for $p_{th} = 0.55$ and $p_t = 1$. At that point, $p_t$ is larger than $p_{th}$, implying that the Alternative Model outperforms the Standard Model. Fig. 4(b) shows the total throughput obtained in this case by the nodes at distance $r_2 = 2$. While the distant nodes achieve very low throughput in the Standard Model, they manage to achieve high throughput in the Alternative Model. At the operating point in which the overall system throughput is maximized, the throughput obtained by a distant node is $0.33$ while the throughput obtained by a nearby node is $0.55$. Hence, the Alternative Model not only improves the performance in terms of overall throughput but also provides some degree of fairness.

The overall throughput under the GDP protocol with nodes on 3 rings is presented in Fig. 5(a). The maximum throughput is obtained for $p_{th} = 0.35$ and $p_t = 1$. This again demonstrates that the Alternative Model outperforms the Standard Model. Furthermore, at this maximum point, the nodes at different distances are not starved ($S(1) = 0.350, S(2) = 0.295, S(3) = 0.154$). Fig. 5(b) shows the total throughput of the $n_3$ nodes at $r_3$. It can be seen that these distant nodes benefit from low values of $p_{th}$, which reduce the chances of nearby nodes to
capture the channel, and high values of $p_{th}$, which increase the number of their retransmission attempts.

Up to now we reported analytic results regarding the GDP protocol. We also evaluated the performance of the GDCW protocol via simulation. Such results are shown in Fig. 6. The figure demonstrates that the throughput is maximized when $w_f < w_s$. Namely, the Alternative Model is beneficial for the GDCW protocol as well.

C. Rings Model with Fading

We used the approximation method described in Section IV to obtain numerical results regarding the performance of the GDP protocol in a system with fading in which the nodes are distributed according to the rings model. For example, Fig. 7 shows the overall throughput for a system with 3 rings. As before, the throughput is maximized by large values of $p_{th}$ and small values of $p_{ts}$. Once fading is considered, the received power of a transmission from a nearby node is not necessarily stronger than the power of a transmission from a distant node. However, this does not significantly change the fact that the Alternative Model still outperforms the Standard Model.

D. Disk Model

We used the simulation model to obtain numerical results for the case in which nodes are distributed according to the disk model and there is no fading. Figures 8(a) and 8(b) show the throughput under the GDP and GDCW protocols. In both figures there are two local optimums. One of them represents the Alternative model and the other the Standard Model. However, as before, under the Standard model, distant nodes are usually starved. Therefore, the Alternative Model is preferable. It can be seen that the results obtained for the disk model are similar to results obtained for the rings model. Hence, the rings model provides a good approximation, while lending itself to analytic performance evaluation.

In Fig. 9 we present simulation results for a system with fading in which nodes are distributed according to the disk model. The results are similar to the results for the non-fading case. Since the fading effect somehow averages the transmission powers, the nearby nodes do not always succeed and distant nodes may succeed despite transmissions of nearby nodes. Hence, the local optimums are not as strict as in the fading-free case. Moreover, unlike in the fading-free case, there is no local optimum corresponding to the Standard Model.

VII. Conclusions

The Multipacket Reception capability has the potential to significantly improve the performance of wireless networks. In this paper, we focused on the design considerations of MAC protocols for networks of spatially distributed nodes with such capability. It is known that standard backoff mechanisms can lead to unfairness when nodes are spatially distributed. We demonstrated that with MPR capability these mechanisms can also lead to significant throughput loss. To deal with this effect, we presented and analyzed an alternative backoff mechanism whereby nodes increase their transmission probability after a failed transmission and decrease it after a success. Our analysis shows that in most cases the Alternative Model outperforms the Standard Model in terms of both throughput and fairness.
Hence, new MAC protocols have to be designed for MPR networks and these protocols have to diver from the traditional backoff mechanisms.

This work is the first approach towards the design of distributed MAC protocols for networks with MPR capability. Hence, there are still many open problems to deal with. As mentioned above, since the objective of this work is mainly to provide insight regarding MAC for networks with MPR capability, the studied protocols do not provide a complete solution. We intend to develop more elaborate backoff mechanisms that will utilize feedback from the receiver more effectively. These mechanisms should deal with issues such as power and congestion control that have been ignored in this work. For example, we intend to develop distributed mechanism that would tune the values of the protocol’s parameters (e.g. $p_b, p_d, w_s, w_f$). Furthermore, estimating the number of contenting nodes (e.g. the work of [24] for the IEEE 802.11 case) is a possible future direction as it could provide important input to the algorithm. Finally, designing an efficient MPR MAC protocol for a multihop setting is a challenging open problem.

ACKNOWLEDGMENTS

This work was supported by NSF ITR grant CCR-0325401, ONR grant number N000140610064, a grant from Draper laboratory, a Marie Curie International Fellowship within the 6th European Community Framework Programme, and the MAGNET/ISRC Consortium.

REFERENCES