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SIGNAL PROCESSING FOR WIRELESS AD HOC COMMUNICATION NETWORKS

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On Coverage and Routing in Wireless Ad Hoc Networks

[IEEE 802.11 versus CDMA technology]

Research in ad hoc networks faces a multitude of challenges from the physical up to the transport and network layers. Because of the scarce wireless resource and tight capacity limitations [1], a number of cross-layer designs have been proposed recently [2], [3] that deal with optimizing all aspects of data communications in the ad hoc scenario, especially routing and TCP (transmission control protocol) over ad hoc networks. However, fundamentally, networking performance such as delay, throughput, and connectivity are determined by the physical layer; unfortunately, the majority of these designs are based on the IEEE 802.11 protocol, which is known to lead to congestion, connectivity loss and increasing delay as the load builds up.

STATEMENT OF THE PROBLEM: IEEE 802.11 VERSUS CDMA TECHNOLOGY IN AD HOC NETWORKS

Ad hoc networks typically use IEEE 802.11 or similar protocols, mostly due to availability and ease of deployment, along with specialized routing protocols such as ad hoc on demand distance vector routing (AODV) [4] and the dynamic source routing (DSR)

protocol for mobile ad hoc networks [5]. Yet IEEE 802.11, in addition to possible throughput degradation as the number of transmissions increases [6], faces issues such as the exposed and hidden node problem, which is especially problematic in multi-hop ad hoc networks. As a solution, the IEEE 802.11 distributed coordination function (DCF) with its four-way handshake of Request-to-Send/Clear-to-Send/DATA/ACK (sometimes simply referred to as RTS/CTS) has been added to the standard. RTS/CTS is used to signal the nodes in the network that a transmitter requires access to the channel; in other words, the RTS/CTS message exchange represents a resource reservation process. Nonetheless, in the ad hoc scenario this very mechanism has been shown not only to be ineffective [7] but may actually cause additional congestion [8]. While it is well known that the RTS/CTS scheme is not efficient, it may in fact cause collision rates as high as 60% at higher loads [9]. Furthermore, because of such high collision probability, back-off times and thus required buffer sizes increase. As a possible solution, delay busy tone multiple access (DBTMA) has been proposed to ease the collision problem. In this method, two narrow-band frequen-

cies are used to communicate the transmission status within the network, and nodes transmit only if they do not hear any busy tones. While DBTMA can help with collisions, it cannot solve the delay problem due to congestion on the channel. In essence, IEEE 802.11 is *protocol limited*. Furthermore, routing protocols for the ad hoc scenario suffer from problems unknown to base station centric “single-hop” networks. Apart from changing connectivity due to node mobility, insufficient performance of the physical layer protocol can also lead to issues such as the *broadcast storm problem* [10], which may cause a tremendous increase in the exchange of routing information, further aggravating congestion problems. Since congestion leads to a loss of connectivity, expanding the ad hoc network’s coverage area necessitates load-balancing mechanisms. Needless to say, the requirements for such algorithms are very demanding and include scalability, distributed operation, robustness, and power efficiency. As a result, load balancing in ad hoc networks has essentially become its own research area; see, for example, [11].

In contrast to IEEE 802.11, code division multiple access (CDMA) technology allows for a multitude of simultaneous packet transmissions, showing the potential to greatly reduce delay, congestion, and the need for load balancing in ad hoc networks [12]. However, unlike “single-user” communication schemes which try to exclusively reserve the channel (either in a random, distributed manner using carrier sense multiple access with collision avoidance (CSMA/CA) as with IEEE 802.11, or through central control) in CDMA networks, the receiver’s ability to suppress multiuser interference becomes a limiting performance parameter. Possibly because of this, in the past, CDMA in ad hoc networks has not received much attention. Only lately, researchers have begun to investigate into the possibilities of this promising technology for the ad hoc setting. Weber et al. [12] investigated the transmission capacity of CDMA ad hoc networks assuming a hypothetical perfect cancellation receiver. Similarly, Xiaocong et al. [13] showed the impact of unresolved multiuser interference on the performance of such systems and conclude that multiuser detection is vital for ad hoc systems. If advanced multiuser detection is to be avoided, another way to reduce the effects of multiuser interference is to assign orthogonal signature sequences to the various nodes within a reception area. Different methods have been proposed for this [9]. However, using code assignment algorithms results in more communication overhead, which leads to scalability problems, as well as a necessary increase in the transmitter’s processing power and memory. Moreover, reducing multiuser interference with orthogonal sequences is only possible if all the nodes within the coverage area of a network segment are synchronous to the chip level. If this cannot be guaranteed, the multiuser interference generated by orthogonal sequences is comparable to the interference generated by random sequences and thus renders the additional effort of code-assignment inconsequential. On a final note, while maintaining “global” synchronization is a costly solution for stationary ad hoc networks, it may be impossible to implement in mobile ad hoc systems. As a result, conventional CDMA medium access control (MAC) protocols such as *cdma one* or 3G schemes are not fit to be used in ad

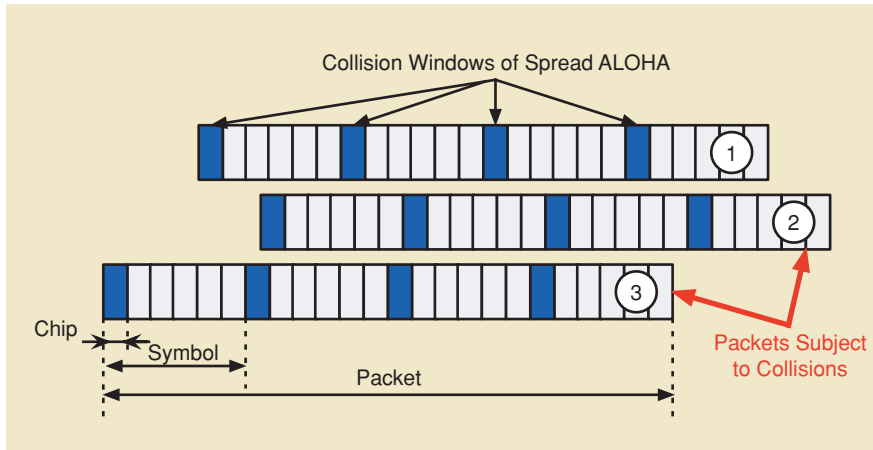
hoc environments and especially for mobile ad hoc networks, a novel, ideally distributed and fully asynchronous random access scheme needs to be found.

As a result of the effectively nonorthogonal nature of the transmissions in CDMA systems, network coverage area becomes a function of the detector capability and typically decreases with traffic load. The effect of a reduction of coverage is well known in base station centric networks and is referred to as *cell shrinking* [14]. Cell shrinking can greatly reduce the maximum distance of a route and thus lead to connection loss. This is especially problematic in ad hoc networks, where recent research has shown that longest hop routing may be beneficial [15]. Another effect which can accelerate detector overload is packet forwarding in multihop ad hoc scenarios. There, nodes also act as relays and thus quickly become highly loaded.

CONTRIBUTION

In this tutorial article, we introduce a promising protocol called RP-CDMA, which is a variety of asynchronous CDMA suited to the ad hoc environment [16]. RP-CDMA is a distributed, fully asynchronous MAC layer protocol that has been designed specifically for a multiuser CDMA setup, where packets are transmitted at random intervals. In contrast to the most popular random accessing scheme for CDMA networks, Spread ALOHA [17], RP-CDMA employs packet-specific random spreading which is conveyed to the receiver by means of an additional header frame. The header is added to every packet to avoid the need for storage of transmitter-specific status information such as spreading sequence assignments at the receiver. While the header adds signaling overhead (respectively, noise) to the channel, which could be avoided through additional handshaking, it is the waiver of the need for the very same which makes RP-CDMA especially suitable for mobile CDMA ad hoc networks.

Furthermore, to improve the performance of CDMA in the ad hoc setting, we combine our RP-CDMA MAC layer with a recently proposed parallel joint cancellation-type multistage detection scheme on the physical layer, termed *partitioned spreading* [18]–[20]. To elaborate, as the number of transmissions in a CDMA cell increases, multiuser interference also increases due to the nonzero crosscorrelations between spreading sequences of different users. Unless this multiuser interference can be resolved completely, it leads to the effect that packets are only received successfully if their power level exceeds a certain threshold. This threshold corresponds to the radius of the reduced coverage area and is referred to as the *critical radius* [14]. It is commonly believed that to avoid cell shrinking, during the transmission interval of a remote node, no other node inside the critical radius should be active. However, this requires some form of MAC-layer scheduling, which is counterproductive to the requirement for simplistic, uncoordinated data transmission that is made possible with RP-CDMA. Fortunately, since the degree to which multiuser interference can be resolved is receiver specific, the degree of coverage loss as a function of the offered load also depends on receiver technology and, as we will show, can be greatly reduced with partitioned spreading demodulation.



[FIG1] Collision window of Spread ALOHA. All packets 1–3 face multiuser interference. In addition, packets 2 and 3 are subject to chip-level collisions.

Partitioned spreading has been shown to outperform classical detection methods such as the conventional matched filter, the decorrelator (or zero-forcing filter), the minimum-mean squared error (MMSE) filter, and even other advanced joint detection schemes such as successive cancellation in a base station centric environment [19], making CDMA *near-far resistant*. This aspect of partitioned spreading demodulation is especially important in ad hoc networks without centralized power control and randomly chosen signature sequences. We show via simulation, that since conventional CDMA multiuser detectors can greatly reduce the capacity and connectivity in a subnet (defined as nodes within a transmission area) as the load increases, these nodes should be restricted to the perimeter of the network. Unfortunately, in the case of mobile ad hoc scenarios where nodes may move anywhere in the network, this requirement may effectively rule out conventional multiuser receivers altogether.

While the reader might argue that the benefits of advanced joint detection come at the price of high additional node complexity, we demonstrate that to achieve performance comparable to partitioned spreading demodulation with conventional receivers, a tremendous increase of the processing gain is necessary. (For this article, we assume fixed bit durations. Accordingly, when we increase the processing gain N , the chip size reduces proportional to $1/N$ and the required bandwidth increases proportional to N . Hence, when increasing N , we face a loss of bandwidth efficiency.) This, in turn, leads to an increase in receiver complexity as well as a high loss in bandwidth efficiency. As a result, partitioned spreading with its moderate spreading requirements and therefore higher bandwidth efficiency and increased achievable network capacity [20], actually might not lead to higher ad hoc receiver complexity than a conventional matched filter, decorrelator or MMSE detector.

DISTRIBUTED CODE DIVISION MULTIPLE ACCESS FOR AD HOC NETWORKS: SPREAD ALOHA

The ALOHA random access protocol developed at the University of Hawaii ushered in the era of modern random

access communication systems. Rather than being assigned fixed resources, users transmit data packets whenever they need to, irrespective of others. While ALOHA has the benefit of minimal protocol overhead (no signaling apart from packet acknowledgments is required), data throughput obtained with the original ALOHA system is at most 18% that of full channel access coordination [17]. As we move from “unspread” data transmission, where any packet overlap on the channel leads to data destruction, to an environment with spreading, we are still able to use the original, lightweight ALOHA protocol with only

minor modifications. The resulting protocol is called *Spread Aloha*—a combination of the classical, connectionless ALOHA technique with spread spectrum technology [17]. Since knowledge of the spreading sequence is necessary for successful despreading, Spread ALOHA packets all share a common sequence. This is in contrast to CDMA, where users are separated by different spreading sequences. Effectively, this leads to the two cornerstones of system performance: Spread ALOHA’s interference and collision limitation, which limit its use to small, relatively lightly loaded networks.

MULTIUSER INTERFERENCE IN SPREAD ALOHA

Since packet arrival times are unknown, Spread ALOHA is limited to a matched filter for demodulation at the receiver. Thus, following standard arguments, the received signal-to-noise ratio (SNR) for a packet j is given by

$$\text{SNR}_{\text{S-ALOHA}} = \text{SNR}_{\text{mf}, j} = \frac{P_j}{\sigma^2 + \sum_{k=1, k \neq j}^K \frac{P_k}{N}}, \quad (1)$$

where P_k is the received signal power of packet k and we assume K active packets in the system at the time packet j is transmitted.

CHIP-LEVEL COLLISIONS IN SPREAD ALOHA

In addition to multiuser interference, Spread ALOHA is also subject to collisions that occur when the signals of different packets arrive at the receiver symbol-synchronized within about a chip duration. Due to the common spreading, if these packets overlap, collisions may destroy all information. However, collisions will only affect packets with (in)sufficient power. Otherwise, even if overlaps occur chip-synchronously, some involved packets may be recovered; this effect is known as *multi-packet capture*. Also, it is important to note that the collision window of Spread ALOHA repeats every symbol time (N chips) within a packet duration as illustrated in Figure 1.

As we will see later, because of Spread ALOHA’s collision limitation, multiuser detection techniques cannot be used to

improve its performance [22]. Thus, after despreading, the system throughput S is essentially identical to classical ALOHA, with $S = 1/2e = 18\%$ of a fully access controlled network.

RP-CDMA: A NOVEL PACKET FORMAT FOR CONNECTIONLESS, FULLY ASYNCHRONOUS CDMA NETWORKS

From the above discussion, it is clear that Spread ALOHA as the MAC-layer protocol of a distributed CDMA ad hoc network will waste most of the throughput and capacity benefits that can be gained through CDMA multiuser detection technology. In essence, Spread ALOHA is unable to deliver high performance, wasting in the excess of 80% of the channel resources [17]. Even much worse, Spread ALOHA leads to severe connectivity loss, as we will demonstrate, rendering ad hoc networks inoperable.

To overcome Spread ALOHA's interference and collision limits, a network needs to employ different spreading sequences for all active transmitters; i.e., data detection now requires the recipient of a packet to know the packet specific spreading sequence *before* the packet can be decoded. In current CDMA standards, this effectively translates into a paging process between the sender and the base station receiver [23]. While manageable in metropolitan area networks, in an ad hoc scenario, this requirement is difficult if not impossible to meet—especially in mobile ad hoc networks.

We now review random packet CDMA, a recently proposed random packet multiple access system, which supports a fully connectionless network architecture [16]. A transmission packet of length $L_h + L_d$ consists of header and data frames as illustrated in Figure 2(a). The header frame of length L_h symbols contains the access preamble and code identifier (code-ID). The access preambles are identical for all users using a fixed, predetermined spreading sequence which is known to all nodes in the network. The data portion of the packet is spread by a random spreading sequence, whose identification is contained in the code-ID. The sequence is chosen randomly and independently by the transmitter. The probability that any two active packets employ identical spreading sequences which

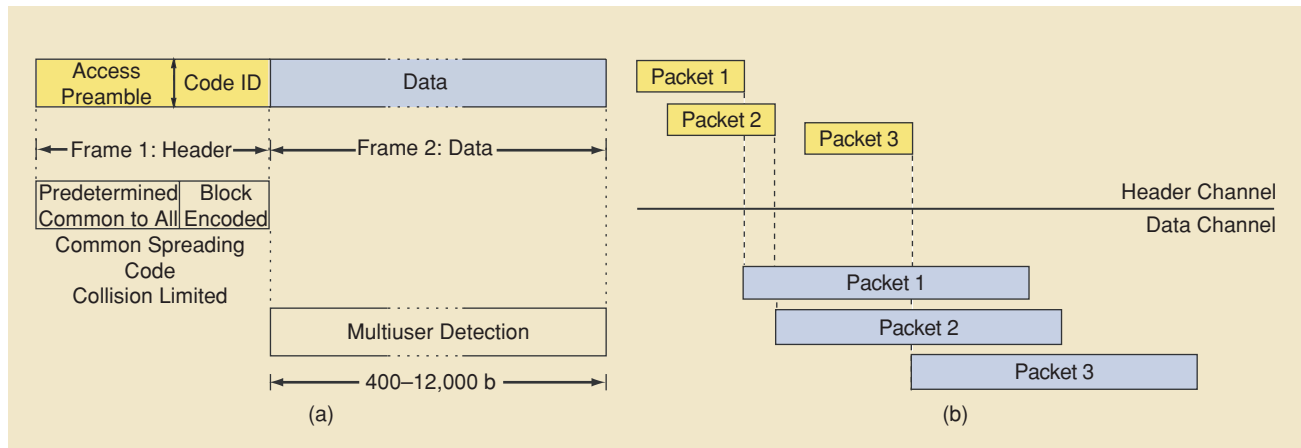
would lead to payload collisions can essentially be made arbitrarily small. Given a spreading sequence of length N , the probability that the data portions of two simultaneously active packets have the same spreading sequence is negligible: typically, a random number generator of length N will deliver $2^N - 1$ different sequences.

For reliable header detection, values of $L_h \approx 50$ b its may be necessary [24]. However, the data portion of the packet is typically 400–12,000 b long (50–1,500 B) and hence the header constitutes only a small overhead. Of course, the ratio of header length L_h to data portion length L_d is a crucial parameter for RP-CDMA. As a system effect, the RP-CDMA packet format separates communications into a header and a data channel; see Figure 2(b). While the header channel corresponds to a low-traffic Spread ALOHA channel, the data channel effectively operates the CDMA network with random spreading sequences comparable to what is achievable with the 3G protocols mentioned above. Timing recovery based on matched filtering of an embedded sequence of bits in the header allows an RP-CDMA system to operate fully asynchronously. Since packet specific timing has been established after header detection, advanced multiuser detection techniques become available for the remainder of the packet. Thanks to these properties of RP-CDMA, the ad hoc network can now be optimized for high throughput and high spectral efficiency with low protocol overhead and low latency. The reader is encouraged to refer to [16] for a more detailed discussion on RP-CDMA.

RP-CDMA VERSUS SPREAD ALOHA: RANDOM ACCESS COLLISION LIMITATION

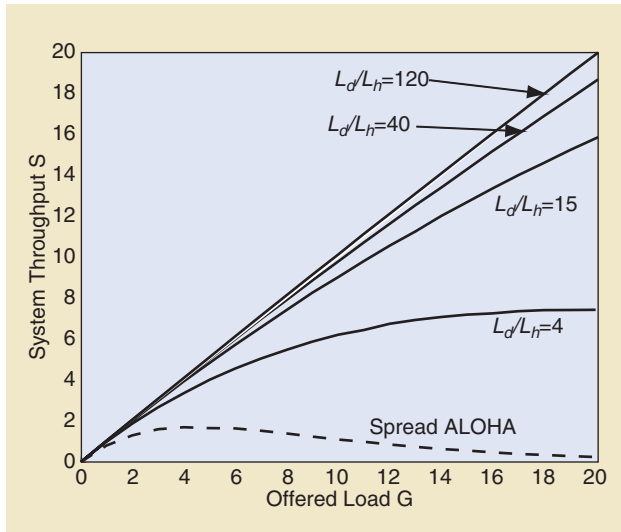
Compared to Spread ALOHA, RP-CDMA offers lower probability of packet collisions and higher throughput. From the RP-CDMA packet structure, because only the headers have a common spreading sequence, the probability of header collisions is the product of the probability of header overlaps, which is a function of L_d/L_h , and the probability for chip-level overlap

$$p_{\text{coll}} = p_{\text{overlap}} p_{\text{chip}}$$



[FIG2] (a) RP-CDMA packet structure. Matched filter detection is used for the header frame and advanced multiuser demodulation techniques may be applied for the data portion (e.g., partitioned spreading). (b) Virtual header and payload channels.

The overall duration of an RP-CDMA packet is $T_{\text{packet}} = (L_h + L_d) b$, and thus the collision vulnerable zone in RP-CDMA compared to Spread ALOHA is reduced by a factor of (L_h/L_d) , assuming that the header and payload portion have the same spreading gains.



[FIG3] Simulated collision limits for Spread ALOHA and RP-CDMA for varying L_d/L_h with header length $L_h = 50$ b and header and payload spreading gains of $N_h = N_{S-\text{ALOHA}} = N_d = 10$.

Figure 3 presents simulation results of the collision limitation of RP-CDMA compared to Spread ALOHA for different values of L_d/L_h with a header size of 50 b and spreading gains for all systems of $N_h = N_d = N_{S-\text{ALOHA}} = 10$. We use N_h , N_d and $N_{S-\text{ALOHA}}$ to denote the spreading gains of the RP-CDMA header, the RP-CDMA data (or payload), and Spread ALOHA, respectively. We see that even for small values of L_d/L_h , RP-CDMA improves the maximum achievable throughput compared to Spread ALOHA considerably. As we further increase the ratio, RP-CDMA system performance approaches the optimal *offered load = system throughput* curve, with close-to-optimal performance up to a load of 20 packets for $L_d/L_h \geq 40$. As an example, Internet2 backbone traffic is trimodally distributed with packet sizes of 50, 500, and 1,500 B and respective probabilities of occurrence of $p_{50} = 0.5$, $p_{500} = 0.4$, $p_{1,500} = 0.1$. With Internet2 traffic and a header length of $L_h = 50$ b, we have $E[L_d/L_h] = 60$. Clearly, from a collision perspective, RP-CDMA promises great improvements over Spread ALOHA, approaching the performance of a fully access controlled system [16].

RP-CDMA VERSUS SPREAD ALOHA: INTERFERENCE LIMITATION

As in Spread ALOHA, header detection in RP-CDMA is subject to interference in addition to the header collision limit. In RP-CDMA, we can identify three distinct sources of multiuser interference: interference from *header/header*, *header/data* and *datadata overlaps*, see Figure 2(b). The parameters which deter-

mine the different levels of interference are L_d/L_h as well as N_h and N_d . These result in the header overlap vulnerable zone η_h

$$\eta_h = \frac{L_h N_h}{L_d N_d}.$$

Headers of different packets may only overlap in this zone—and obviously, reducing L_h reduces η_h and thus the probability of *header/header* overlaps. This leads to one major advantage of RP-CDMA over Spread ALOHA, since out of all sources of interference, only *header/header* interference cannot be reduced by optional means of advanced signal cancellation. To address this type of interference, increasing the header processing gain N_h or the header transmit power $P_{\text{TX},h}$ are possible. However, choosing a higher N_h than N_d changes η_h which will negatively affect the collision performance of RP-CDMA. On the other hand, as we increase the header power, mutual interference also increases. This may not be a limiting problem in RP-CDMA, where the header only constitutes a small fraction of the packet. Obviously, optimal values of N_d , N_h and $P_{\text{TX},h}$ depend on system-specific parameters. In contrast, Spread ALOHA interference is always directly determined by the system load.

After discussing the motivation and necessity for a new distributed MAC-layer protocol for CDMA ad hoc networks, we now address the issue of multiuser detection on the physical layer. As we will show in the upcoming sections, classical “single-shot” multiuser detection such as matched filtering, zero-forcing (i.e., decorrelation) and MMSE filtering may not be suitable for the ad hoc setting. As a consequence, in the following section we introduce partitioned spreading that has shown superior performance in the base station scenario to ad hoc networks.

PARTITIONED SPREADING

Partitioned spreading is a recently proposed technique that utilizes the benefits of interleaving and iterative receiver processing [18]–[20]. In partitioned spreading, the original spreading sequences are separated into several chunks called partitions, and partitions are transmitted separately after passing through an interleaver. The partitions of each data symbol are understood as symbols of a repetition code and are iteratively decoded at the receiver using message passing or a multistage receiver. Figure 4 presents an RP-CDMA packet with partitioned spreading applied to its payload portion where M denotes the number of partitions per symbol. (We want to emphasize that partitioned spreading is only applied to the payload frame.) The gaps in the figure are filled by the partitions from other symbols. The interleaving function $\pi(m)$ is the permutation list to which these partitions are spread out such that overlapping partitions belong to statistically independent symbols and no correlation can build up. The function of this interleaver is analogous to that used for turbo codes, and the receiver operates with a number of stages (or iterations) where the first stage is a conventional matched filter receiver. In subsequent demodulation iterations, soft bits from the previous step are used to cancel part of the signal interference for each user k . By means of signal reconstruction, such decoders can

be implemented even for asynchronous systems. Furthermore, since the partitions in partitioned spreading are understood as symbols of a repetition code, adjusting M allows to adjust the code rate anywhere from full rate, $R = M = 1$, to low rate when $R = 1/N$, which is the case when $M = N$. Therefore, in combination with the RP-CDMA packet format where partitioning-information can be included in the header frame, partitioned spreading supports very flexible network operation with even dynamically changing data rates. High rate transmission, $M = 1$, may be favorable in an environment with only a small number of interferers. On the contrary, when the number of interferers is high (such as in a fully loaded system), increasing M and therefore decreasing the data rate to allow for reliable detection, can be the preferred modus operandi. Interestingly, as has been shown elsewhere [20], partitioning values of $M = N$ are mostly unnecessary and performance does not improve significantly above $M = N/2$. In addition to increasing M , the bit error rate (BER) performance of partitioned spreading can also be improved by using advanced multiuser detectors (MUD) such as MMSE-filtering in the iterative detection stage at the receiver with a reasonable increase in complexity [25].

At this point we wish to acknowledge the contribution made by Li et al. [26], [27] prior to the development of partitioned spreading. The method developed by these authors is a low rate forward error correction (FEC) channel coding scheme called interleave division multiple access (IDMA). According to [26] and [27], in IDMA, all users in the system use the same FEC and the only means of differentiating them from each other is through interleavers which are chosen *differently* for different users. For the FEC, any code may be used, ranging from simple repetition coding as in partitioned spreading, to advanced turbo detection schemes [27]. Partitioned spreading is similar to IDMA in its basic transmitter structure that employs some form

of coding together with interleaving. However, in contrast to partitioned spreading, in IDMA, any bandwidth expansion is achieved by means of an FEC code. In essence, IDMA has been developed as a consequence of the fact that to approach the capacity of the multiple access channel, all bandwidth expansion should be devoted to coding and it has been shown that IDMA does accomplish this promise [27], [28]. A variant of IDMA

which has been mentioned implicitly in [26] and [27] uses an FEC code which is a concatenation of a repetition code, as *outer* code, followed by a much higher rate channel code, such as a convolutional code, as

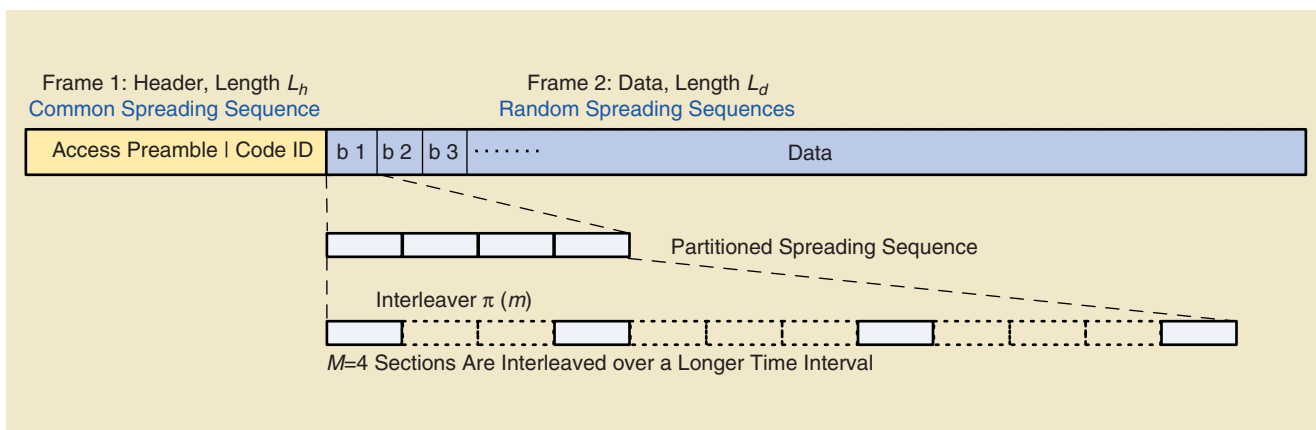
inner code. Compared to this variant of IDMA, in partitioned spreading, the order of the inner and outer codes are reversed. This modification, as shown by Shi et al. [20], does not incur any performance loss when $M = N$. More importantly, this trivial change allows for the performance versus complexity tradeoff as explained above, since now, we are free to choose partitioning values of $M < N$. To elaborate, while in IDMA soft decoding and cancellation can only be performed at the chip level, partitioned spreading provides the option of multichip front-end processing prior to the soft decoding and cancellation stage. In other words, IDMA is limited to an interleaver size equal to the number of information symbols multiplied by the inverse of the code rate. Partitioned spreading, on the other hand, allows for a reduction of interleaver length, i.e., receiver complexity, at only a minor loss of performance.

To illustrate the behavior of a partitioned spreading multi-stage receiver, we consider a system with $K = 54$ uniformly distributed users in a cell. Path loss is computed according to

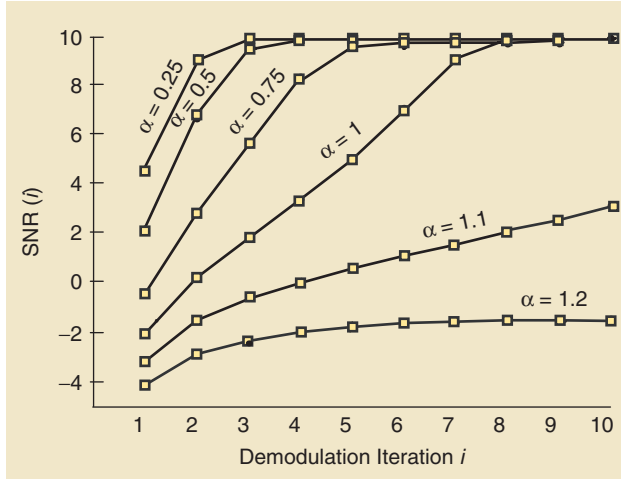
$$P_{RX} = \frac{P_{TX}}{(1 + d)^2} \quad (2)$$

Figure 5 shows the average SNRs for this system at each stage i . As can be seen, the average SNRs approach the interference-free

WE INTRODUCE A PROMISING PROTOCOL CALLED RP-CDMA, WHICH IS A VARIETY OF ASYNCHRONOUS CDMA SUITED TO THE AD HOC ENVIRONMENT.



[FIG4] RP-CDMA packet format with partitioned spreading applied to the data portion. Note that partition spreading is *not* applied to the headers. In this example, there are $M = 4$ partitions for each data symbol.



[FIG5] Demodulation performance of partitioned spreading in an unequal power system with $K = 54$, $\alpha = K/N$. Path loss according to (2). We illustrate that in this example, as long as $\alpha \leq 1$, partitioned spreading can achieve the interference-free SNR = 10 dB very quickly [18].

values within only a few iterations, resolving virtually *all* multi-user interference up to a fully loaded system, i.e., for $\alpha = K/N \leq 1$. This shows the near-far resistance of partitioned spreading [18]–[20].

CDMA MULTIUSER DETECTION TECHNOLOGY

Before we dive into our simulation results, let us first review the performance equations on which our investigations are based. The results for the conventional multiuser receivers, the matched filter, the zero-forcing or decorrelation receiver as well as the MMSE filter, are derived from large-system analysis in CDMA networks with random spreading [29].

MATCHED FILTER

In a matched filter receiver, each signal is despread with a filter matched to its own waveform. The SNR at the output of the detector depends on the number and powers of other active users. For a packet j to be received successfully, its power P_j must satisfy

$$P_j > \gamma \left(\sigma^2 + \sum_{k=1, k \neq j}^K \frac{P_k}{N} \right), \quad (3)$$

where γ is the detection threshold, K is the number of active users and N is the spreading gain.

DECORRELATOR (ZERO FORCING RECEIVER)

The decorrelating receiver inverts the channel to completely eliminate interference. This results in a loss of energy for each user, depending on the user population. Interference no longer depends on the power of other users, and a packet j will go through if its power P_j meets

$$P_j > \gamma \left(\sigma^2 \frac{N}{N - K + 1} \right). \quad (4)$$

MINIMUM MEAN SQUARE ERROR FILTER

The minimum mean square error (MMSE) establishes a filter to minimize the mean square error caused by noise and the multi-user interference. For the MMSE receiver, a given packet j will be received successfully if P_j satisfies

$$P_j > \gamma \left(\sigma^2 + \frac{1}{N} \sum_{k=1, k \neq j}^K \frac{P_j P_k}{\gamma P_k + P_j} \right) \quad (5)$$

through application of the results in [29].

SUCCESSIVE INTERFERENCE CANCELLATION

Here, joint detectors are viewed as layered detectors that typically consist of two stages: interference detection/cancellation and a bank of parallel decoders/detectors. We assume such a successive cancellation decoder employing a powerful code which requires a minimal code signal-to-noise threshold γ . A packet j out of K packets will only be successfully decoded if P_j obeys the following condition

$$P_j > \gamma \left(\sum_{k=1}^{j-1} \frac{1}{N} P_k + \sigma^2 \right). \quad (6)$$

This assumes that all packets $j+1, \dots, K$ with higher power levels have been decoded and cancelled, and decoding commences with the strongest packet, arbitrarily labeled K . For a successive interference cancellation receiver to work well, the received powers have to be sorted in ascending order ($P_1 \leq P_2 \leq \dots \leq P_K$), which we assume here.

PARTITIONED SPREADING

Partitioned spreading can be viewed as a multiuser signal detector that is able to achieve the interference-free, single-user SNR by iteratively canceling the interference from other users. From [18]–[20], the variance evolution at iteration i can be bounded by

$$\sigma_i^2 \leq \sum_{k=1}^K \frac{P_k}{N} \min \left(\frac{1}{1 + \frac{M-1}{M} \frac{P_k}{\sigma_{i-1}^2}}, \pi Q \left(\sqrt{\frac{M-1}{M} \frac{P_k}{\sigma_{i-1}^2}} \right) \right) + \sigma^2, \quad (7)$$

where M denotes the number of partitions and $Q(x) = (1/\sqrt{2\pi}) \int_0^x e^{-(t^2/2)} dt$. Hence, packet j will be successfully decoded if after iteration i its SNR satisfies

$$\text{SNR}_{\text{ps},j} = \frac{P_j}{\sigma_i^2} > \gamma.$$

SIMULATION RESULTS: SERVICE

AREAS FOR DIFFERENT RECEIVER TECHNOLOGIES

In this section, we investigate the effect of coverage loss in a random ad hoc network as well as in a system based on the FLUX mobile robot testbed [21] for the various detectors mentioned above. Our simulations assume a CDMA packet network

with random spreading and, in the case of the FLUX Mobile robot testbed, an ad hoc network with an RP-CDMA MAC layer. For our simulations, we developed a network simulator based on MATLAB. In general, the detection of a packet j will be successful if the signal-to-noise ratio after the detector exceeds a certain threshold; $\text{SNR}_j > \gamma$.

For the remainder of this article, we assume that no power control is exercised. In fact, different power levels may beneficially be used to enable optimization strategies on rate/power/connectivity for different nodes. We note that the power control problem in wireless ad hoc networks to date has no satisfactory solution [30] and likely would lead to control protocols that are difficult if not impossible to implement. At first, to differentiate between the limits of the detectors and the impact of RP-CDMA on system performance, we assume a conventional CDMA, i.e., the codes are known at the receivers. (This effectively translates into synchronous CDMA protocols with resource reservation message exchange as for example in *cdma one* or 3G protocols. While these protocols are hardly usable in ad hoc networks, we need to investigate into “raw” detector performance first in order to differentiate later between negative effects due to insufficient multiuser detection capabilities and losses caused by the RP-CDMA MAC layer protocol.) This initial detector comparison is performed in a randomly generated ad hoc network, where nodes are placed with uniform probability over a unit area. We will later combine the RP-CDMA packet format with the various receiver technologies to evaluate system performance in a realistic ad hoc network based on the FLUX mobile robot testbed [21].

RECEIVER PERFORMANCE IN RANDOM AD HOC NETWORKS

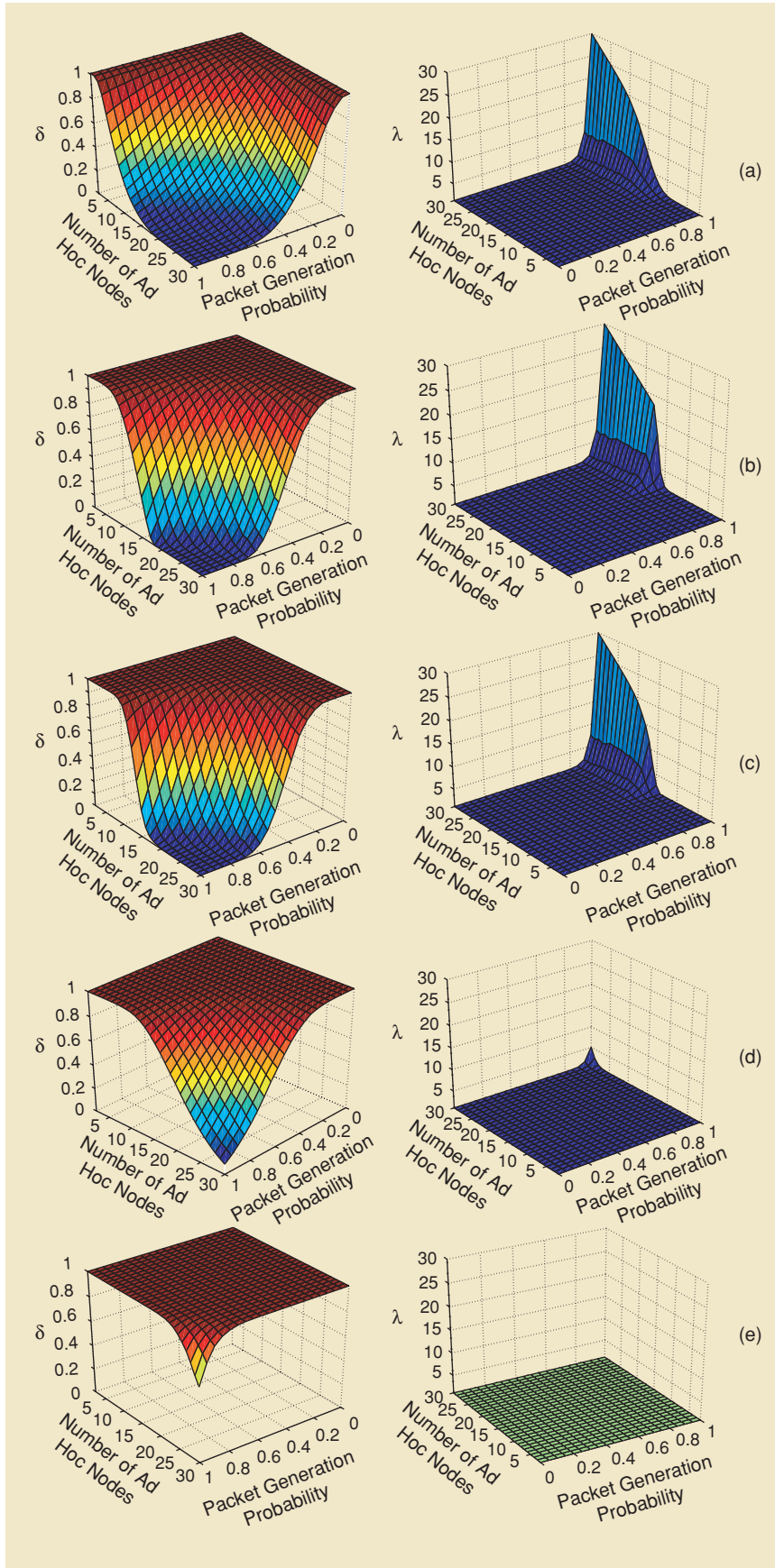
In our random scenario, between 2–30 ad hoc nodes are placed with uniform probability over a unit-area and path loss is assumed according to (2). In our simulations, for all detectors, we chose spreading gains of $N = 20$, an SNR of $P_{\text{TX}}/\sigma^2 = 11$ dB with detection and code thresholds of $\gamma = 3$ dB, leading to an *originally* fully interconnected (fully meshed) single hop network. Note that as the load increases, the ad hoc network may be transformed into a (still fully interconnected) multihop environment. In an initial route discovery phase, the nodes exchange routing information with all other nodes whose packets satisfy the detection threshold. As soon as the discovery phase is completed, nodes generate packets according to a Bernoulli process with probability p . Varying p , $0 < p < 1$, allows us to study the effect of cell shrinking as a function of the network load for the different receivers. Depending on node connectivity, nodes may act as relays in addition to transmitting locally generated packets. As we will demonstrate, this effect can greatly increase the load of multihop ad hoc networks since the probability of packet transmission p_{trans} is composed of the two components $p_{\text{trans}} = p_{\text{packet generation}} + p_{\text{packet forwarding}}$. Of course, at any time, a node can at most transmit one packet; thus, the natural limit on the transmission probability is $p_{\text{trans}} = 1$. The destina-

tion of a packet is chosen randomly by the source node and shortest path routing is performed for each hop.

We define δ as the ratio of the maximum distance of the operational routes to the maximum distance of the possible routes discovered during the initial route discovery phase. We denote the number of network partitions, respectively the number of isolated subnets, by λ . Clearly, δ , λ are both functions of the detector type and the network load. The optimal detector, the one that is able to maintain original network coverage and connectivity irrespective of the load, leads to $\delta = \lambda = 1$. In other words, the ad hoc system remains fully connected with a single cohesive network. Note that in the random scenario, due to the initial fully meshed character of the network, the effect of additional packet forwarding is not as pronounced as in the FLUX setup presented later, and in most cases $p_{\text{trans}} \approx p_{\text{gen}}$.

Figure 6 presents simulation results for this random scenario in the form of three-dimensional plots. The following observations are made.

- **Matched Filter Detector:** As the packet generation probability increases, matched filter detector performance degrades rapidly. Similarly, the number of network partitions increases quickly, eventually equalling the number of nodes in the network. In essence, the matched filter receiver may not be able to sustain original coverage even at relatively low network loads.
- **Decorrelation Detection:** In the case of the decorrelator, network coverage can only be sustained up to marginally higher loads before fragmentation renders it inoperable. Since zero forcing cannot invert the channel when the number of active users exceeds the spreading gain, its basic behavior can best be observed when the number of transmissions in the network is smaller than N . Restricting ourselves to the curvature of the surface representing the maximum distance of the intact routes, we see that fundamentally, decorrelation detection is very similar to matched filtering and also cannot sustain original network coverage as the load increases.
- **Successive Cancellation Detector:** In the case of exponentially distributed powers, successive cancellation can achieve the capacity of the multiuser channel by means of onion-peeling decoding. However, in our scenario with square path loss, the performance of the successive canceller is very similar to the matched filter and the decorrelation receiver. In essence, if decoding of one user group fails, successive cancellation cannot proceed and is only able to suppress multiuser interference through the spreading gain. In this case, receiver performance is lower bounded by the interference suppression capabilities of the matched filter detector. Basically, the performance of a successive cancellation receiver depends greatly on the experienced path loss, making successive cancellation somewhat unpredictable—especially in a mobile ad hoc network scenario where the channel environment may change constantly.
- **MMSE Detector:** In contrast to the matched filter, the decorrelator and the successive canceller, the MMSE filter is able to maintain the original size of the cell up to an almost fully active network where all nodes would be transmitting



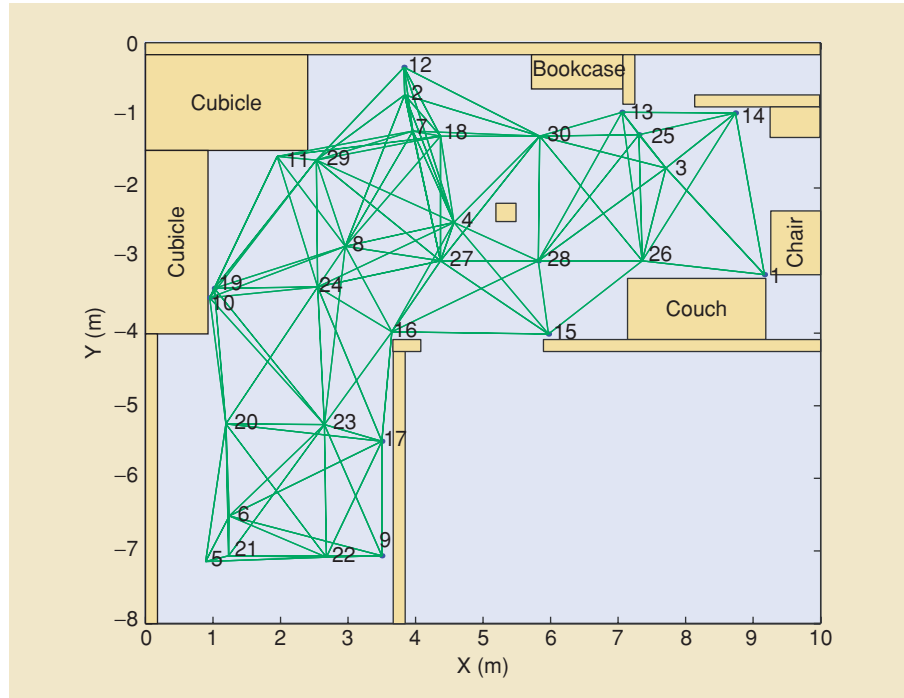
[FIG6] Receiver performance in randomly generated ad hoc networks, $P_{RX} = P_{TX}/(d+1)^2$ over a unit area. For all receivers, spreading gain $N = 20$, $P_{TX}/\sigma^2 = 11$ dB and detection thresholds $\gamma = 3$ dB. Partitioning factor for partitioned spreading demodulation $M = 5 = N/4$. δ denotes the ratio of the maximum distance of the operational routes to the maximum distance of the routes during the initial route discovery phase. λ represents the number of network partitions. (a) Matched filter, (b) decorrelation receiver, (c) successive canceler, (d) MMSE, and (e) partitioned spreading, $M = N/4 = 5$.

with probability $p_{trans} = 1$. However, with the chosen values of N and P_{TX} , in the limit, MMSE detection also leads to a loss of coverage and an increase in the number of network fragments.

■ **Partitioned Spreading Detection:** In the case of partitioned spreading, original cell sizes can be maintained. This translates into no network fragmentation and leaves the network fully operational at all loads. In our specific examples, only partitioned spreading detection is able to resolve multiuser interference reliably.

MULTIUSER COMMUNICATIONS IN THE FLUX MOBILE ROBOT TESTBED

So far, we have investigated the performance of various detectors in a *randomly generated*, initially fully meshed CDMA network. While these simulations may not reflect a realistic multihop ad hoc system, we gained an understanding of the capabilities and limitations of the different detection methods. We did not investigate the effect of the RP-CDMA packet format on network performance. In this section, we apply RP-CDMA to an *existing* ad hoc network based on a snapshot of the FLUX mobile robot testbed [21] shown in Figure 7. As its name suggests, the FLUX mobile robot testbed is a mobile network open to researchers and is accessible via the Internet. In its current stage, it contains 30 nodes, of which a number are mobile robots with Mica2 motes as well as IEEE 802.11 cards. To show the possible benefits achievable with CDMA technology, for our simulations we assume that the nodes are



[FIG7] Snapshot of the FLUX mobile robot testbed [21], green links indicate connectivity with a transmission radius of 2.5 m.

equipped with CDMA-enabled detectors. Based on their spatial coordinates, we evaluate the performance of a hypothetical RP-CDMA communication system using the various detection methodologies. Also, we compare Spread ALOHA to RP-CDMA to emphasize the negative effect of network fragmentation of Spread ALOHA.

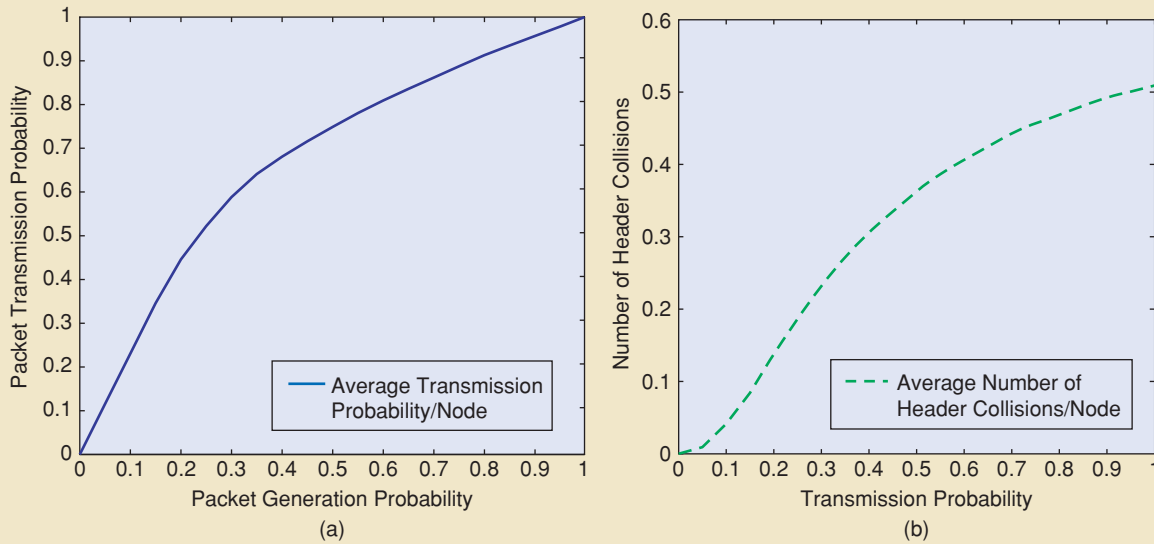
In the previous section, we were only interested in basic detector behavior and we did not try to map system performance to a realistic scenario, so the assumption of square path loss over a unit-disc was sufficient. However, to realize a multihop ad hoc network based on the FLUX mobile robot testbed, we decided that the maximum transmission radii should be less than approximately 2.5 meters. Consequently, (2) is not a good approximation for the powers at the receivers. Nevertheless, for such dense scenarios, a more realistic channel model based on measurements is available [15], which suggests a path loss of

$$P_{RX} = P_{TX} \min(1, 10d^{-3}). \quad (8)$$

In our simulations, we chose a header size of 50 b and a constant payload-to-header ratio of $L_d/L_h = 40$. This translates into a data portion of 250 B that seems adequate, for example, for a network of mobile ad hoc surveillance robots. As before, we assume an SNR for data transmission of $P_{TX,d}/\sigma^2 = 11$ dB and a higher ratio for header transmission of $P_{TX,h}/\sigma^2 = P_{TX,S-ALOHA}/\sigma^2 = 14$ dB to combat header/data interference. Note that Spread ALOHA is granted higher transmission power compared to the RP-CDMA payload portion to improve its performance in this specific scenario. Our desired maximum transmission radius of 2.5 m is achieved in the fol-

lowing way. As the result of a hypothetically high data rate, we assume that the payload frames of the RP-CDMA packet require an SNR of 9 dB for successful reception. This is reflected in the threshold for data/payload detection of $\gamma_d = 9$ dB which results directly from (8) when $P_{TX,d}/\sigma^2 = 11$ dB and $d = 2.5$ m. While we would technically have to assume the same threshold for Spread ALOHA, we have reduced the imaginary data rate such that we can realize a lower threshold of $\gamma_{S-ALOHA} = 3$ dB to improve its performance. This became necessary after initial simulation results indicated that with the higher threshold, Spread ALOHA shows disastrous performance under all loads.

As far as header detection in RP-CDMA is concerned, it was shown in [16] that reliable header and timing recovery can be performed at SNRs of 3 dB (and possibly even lower). Therefore, for our simulations we assume a header detection threshold of $\gamma_h = 3$ dB. (Effectively, the maximum transmission radii of 2.5 m are realized only by means of the data detection threshold γ_d . Even if a header j can be acquired, the following data detection will fail unless the SNR of the data portion of packet j after the detector front end fulfills $SNR_{d,j} \geq \gamma_d = 9$ dB.) With these chosen parameters, all 30 active packets may contribute to interference and header collisions. We now need to determine the *minimally required* processing gains which translates into *maximum spectral efficiency* for the FLUX scenario with up to $K = 30$ active transmitters. We know that partitioned spreading is able to maintain original coverage if we assume spreading gains of $N_d = 20$. To maintain the original $L_d/L_h = 40$, we also choose header spreading gains of $N_h = N_d = N_{S-ALOHA} = 20$. During the initial route discovery phase, each node establishes an average of eight routing entries and the resulting initial connectivity of the



[FIG8] (a) Resulting average packet transmission probability P_{trans} as a function of the packet generation probability p_{gen} . As p_{trans} increases, network connectivity decreases due to failures of header detection and less nodes are used as intermediate hops. This effect decelerates the slope of p_{trans} for $p_{\text{gen}} > 0.4$. (b) Average number of header collisions per node in the FLUX mobile robot ad hoc scenario. $N_h = N_d = 20$, $L_d/L_h = 40$, header detector threshold is 3 dB such that from a perspective of sufficient power, the headers of all transmissions may overlap destructively on the channel, resulting in the worst case RP-CDMA performance in this scenario.

network is shown in Figure 7. Figure 8 shows the average number of failures of RP-CDMA header detection as a function of the packet generation probability. Even though *all* active headers may contribute to collisions/interference on the channel as outlined previously, on average only 0.5 headers are lost per node, resulting in an average number of $8 - 0.5 = 7.5$ *intact* routing entries. We want to recall at this point that RP-CDMA does not suffer from the hidden node problem that—especially in our multihop scenario with the chosen detector thresholds—could easily cause more than an average of 0.5 packet collisions [8]. Also shown in Figure 8, because of the multihop character of the FLUX scenario, the impact of additional packet forwarding on the average probability of packet transmission is significant. For values of the packet generation probability p_{gen} , $0 < p_{\text{gen}} < 0.25$, additional packet forwarding effectively doubles the load of the network. For even larger values of p_{gen} , average node connectivity is slightly reduced due to failures of header detection, and source nodes choose more well interconnected nodes as intermediate hops. However, as shown below, header collisions alone do not increase the number of network fragments.

Figure 9(a) presents simulation results for the percentage of intact routes over the packet generation probability p_{gen} . Spread ALOHA is heavily interference and collision limited and in the best case can only sustain 3% of all available routes. Similarly, the matched filter and successive cancellation receivers suffer from the characteristics of the channel model and only 30% of the initial routes remain operational. In con-

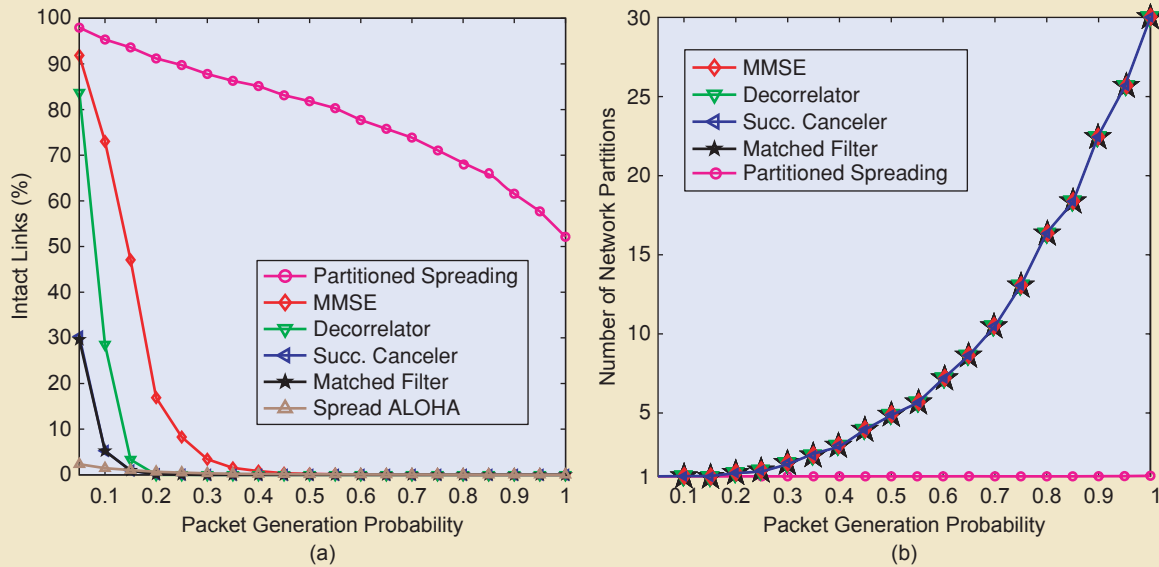
trast to this, at least at very low loads, the decorrelator as well as the MMSE filter are able to sustain a large percentage of intact routes. However, as soon as $p_{\text{gen}} \approx 0.10$ and $p_{\text{gen}} \approx 0.15$, respectively, both detectors degrade rapidly with the percentage of intact routes going to zero. In the case of partitioned spreading, detector performance degrades gracefully from a maximum of 100% of working routes to a minimum of $\approx 50\%$ at maximum system load ($p_{\text{gen}} = 1$). As shown on

**COMPARED TO SPREAD ALOHA,
RP-CDMA OFFERS LOWER PROBABILITY
OF PACKET COLLISIONS
AND HIGHER THROUGHPUT.**

the right-hand side of Figure 9, for partitioned spreading, this translates into a constantly fully connected multihop network, whereas in the case of *all other detectors* starting from a packet generation probability of $p_{\text{gen}} \approx 0.20$, the number of

network fragments is monotonically increasing, eventually equalling the number of nodes in the network. Interestingly, as far as the number of network fragments is concerned, at high loads, *no* benefit can be gained by upgrading from matched filtering to complex MMSE detection.

At first glance, this does not seem to lead into a dilemma, since given a certain number of active transmitters, it is always possible to improve the multiuser interference suppression techniques of all multiuser detectors by increasing the spreading gain N . To find the required increase in spreading gain for the different receivers to achieve performance identical to that of partitioned spreading with $N = 20$, we resimulated the FLUX-scenario, successively and individually increasing N . We found that, to maintain full coverage with the MMSE at all load points, the spreading gain N would have to be increased to $N \approx 50$. In



[FIG9] (a) Percentage of intact links and (b) number of network partitions, $N_h = N_{S\text{-Aloha}} = N_p = 20$, partitioning factor $M = N/2 = 10$. Header SNR = $P_{\text{Tx,h}}/\sigma^2 = 14$ dB, payload SNR = $P_{\text{Tx,d}}/\sigma^2 = 11$ dB. Payload detection thresholds for max. transmission range of 2.5 m: $\gamma_p = 9$ dB. Header and Spread ALOHA detection thresholds $\gamma_{h,S\text{-ALOHA}} = 3$ dB. Path loss model $L_{\text{path}} = \min(1, 10d^{-3})$ according to [15].

the case of the decorrelator, a spreading gain of $N \approx 80$ is required and for the matched filter and successive cancellation, N has to be increased to $N \approx 250$. Obviously, if spectral efficiency is a concern, with the exception of partitioned spreading *all other detectors are strongly wasteful*. Furthermore, since such dramatic increases in the length of the spreading sequence come at the cost of additional receiver complexity, at this point it is hard to compare implementation complexity of partitioned spreading with its minimal spreading requirement versus conventional multiuser detectors.

As far as the effect of RP-CDMA on network performance is concerned, even in the case of highly spectrally efficient partitioned spreading payload detection, the RP-CDMA header format typically does *not* pose a performance limitation. In the case when other conventional detectors are used, the necessary increase in N further reduces the probability of header collisions, matching the performance of RP-CDMA to a fully access controlled CDMA system. (Remember that we require $N_d = N_h$ to maintain maximum L_d/L_h .)

As a last note, we recall that a single “weak” ad hoc node can greatly reduce the capacity and connectivity area of a network segment. From this perspective, it is clear that in an heterogeneous ad hoc network, nodes with matched filter, decorrelation, MMSE or successive cancellation receivers should be restricted to the network periphery and more capable partitioned spreading detectors have to be used at its core. In the case of mobile ad hoc networks, where nodes may move anywhere in the network, conventional detection may need to be avoided completely.

CONCLUSIONS

In this article, we discussed problems of IEEE 802.11 in (mobile) ad hoc networks. We also note that while CDMA

offers higher throughput and does not suffer from IEEE 802.11’s hidden terminal problems, it requires knowledge of the spreading sequences, which, in turn, necessitates additional handshaking. However, additional paging is hard if not impossible to implement. As a possible solution to this problem, we presented RP-CDMA, a packet format for uncoordinated, connectionless data transfer.

Furthermore, we discussed various advanced CDMA detection methods, including a recently proposed CDMA transmission scheme based on iterative detection with sequence partitioning called partitioned spreading. We showed that partitioned spreading is near-far resistant and compared the performance of this detector to the matched filter, decorrelator, MMSE as well as successive cancellation detection methods. The comparison was performed in randomly generated, initially fully connected ad hoc networks as well as in a multihop ad hoc network based on a snapshot of the FLUX mobile robot testbed [21], developed at the University of Utah.

We demonstrated that as the load increases, partitioned spreading detection is able to maintain a sizeable advantage and assures original network coverage and connectivity. To achieve comparable performance with other conventional detectors, the processing gain N needs to be increased considerably, which increases computational complexity and lowers spectral efficiency.

We also showed that receiver overload results in network fragmentation, and thus needs to be avoided. Since conventional detectors can greatly reduce the capacity and connectivity of a subnet, these detectors should be restricted to the periphery of a CDMA ad hoc network. In the case of mobile ad hoc networks, where nodes may move anywhere in the network, conventional detection may need to be avoided completely. We thus conclude

that in ad hoc networks, advanced joint detection may be a necessity—not primarily to achieve higher transmission rates, but mainly to maintain network connectivity.

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