Simulation of a Wireless CDMA Ad Hoc Network

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ABSTRACT
This paper examines the feasibility of CDMA-based communication in wireless ad hoc networks[1]. In particular, it investigates the benefits of canceling out the k strongest interfering connections by multiuser interference reduction techniques. We present simulation results that show that $k = 4$ usually suffices for low bit error rate CDMA communication in presence of reasonable topology constraints.

KEY WORDS
Simulation, ad hoc networks, asynchronous CDMA, wireless, multi-user interference

1 Introduction

We aim to develop a wireline and wireless ad hoc network based on *code division multiple access* (CDMA). While *direct sequence* (DS) CDMA offers advantages in terms of robustness, attack resistance, concurrent channel access, and security, it also poses certain problems like the inherent multiaccess interference. These problems are getting worse if CDMA is used in an ad hoc network. Traditional CDMA-based networks like IS-95 are hence designed to use base stations, allowing, e.g., the use of dedicated pilot channels facilitating synchronous point-to-multipoint CDMA communication. Ad hoc networks, on the other hand, are characterized by their lack of an established infrastructure and their inherent asynchronous multipoint-to-multipoint communication.

In [1], a mathematical model for a comparable but slotted ad hoc network has been introduced to find the optimum transmission range. This work has been continued in [2] and [3]. Multi-user interference of PCS systems is modeled in [4], albeit in a cellular system with base stations.

In order to find out whether completely asynchronous CDMA is feasible in a wireless ad hoc network, we developed a simple simulation based on Matlab that allows us to study the multi-user interference generated in an adhoc network under different system parameters like the node number, minimum distance between nodes, uni- and bidirectional connections, chip length, signal propagation, number of connections per node, and different power management strategies. In particular, we investigate to what extent hardware for multi-user interference reduction at each node improves the performance of the network, and what amount of hardware is required. We use a network model with static connections and analyze its performance in the presence of multi-user interference.

In Section 2, we will outline our network model. Section 3 describes our simulation. Section 4 presents our results and discusses some interesting effects we observed. Section 5 concludes the paper.

2 Network Model

We assume a set $N = \{1, \ldots, n\}$ of n nodes randomly distributed on an area of 100 $\times$100 units, which use wireless DS-CDMA channels for communication.

Each node i has connections with m nodes in its vicinity which form the neighbor set $M_i = \{x | x \in N$ and x has a connection to $i\}$, $|M_i| = m$. Each connection from node i to node j has its own CDMA code $C_l^{(i \to j)}$ with a uniform chip length (code chips per data bit) of l. We assume that connections are used concurrently and continuously.

We postulate that the transmission range is large enough to reach the farthest nodes and we assume that power management adjusts the transmit power so that for all nodes i, the farthest node $j \in M_i$ receives the signal with an amplitude of 1, that is, $A(i,j) = 1$ if $dist(i,j) = max_{k \in M_i} dist(i,k)$, where $A(i,j)$ is the received amplitude from node i at node j and $dist(i,j)$ is the distance between i and j. Any node nearer to the transmitter receives the signal with a higher amplitude, any node further away with a lower amplitude than one.

In most simulations, we assume that the received signal level is proportional to the square of the distance, i.e., $A(i,j) = (dist(i,k)/dist(i,j))^2$, where $dist(i,k) = max_{p \in M_j} dist(i,p)$ and $dist(i,j) > 0$. This is a good approximation for outdoor environments. In indoor environments, however, the attenuation is generally higher and less homogeneous, making it much more difficult to specify. We will investigate this parameter in one of our simulations

[1]This research is part of the W2F-project, which targets a wireline/wireless fieldbus based upon spread-spectrum (CDMA) communications, see http://www.auto.tuwien.ac.at/Projects/W2F/ for details. W2F is supported by the Austrian START program Y41-MAT.

as well.

Without any interference, the receiver correlator value of node i for the connection to node j is calculated as $R_{\text{perfect}}(i,j) = l * A(i,j)$. A negative value of $R(i,j)$ indicates a logical 1, whereas a positive value translates to a logical 0. Due to our ad hoc requirement, we have no pilot channel available and cannot rely on a common time base, hence we have to use fully asynchronous CDMA. Unfortunately, there are no perfect codes for asynchronous CDMA and each connection $(x \rightarrow y)$ causes an interference for a connection $(i \rightarrow j)$ with the respective cross-correlation $X_{(x\rightarrow y)}^{(i\rightarrow j)}$. The interference produced by a connection $(x \rightarrow y)$ on another connection $(i \rightarrow j)$ is the cross-correlation $X_{(x\rightarrow y)}^{(i\rightarrow j)}$ times the received amplitude $A(i,j)$, which can get rather large due to the arbitrary node distances (near-far problem).

The receiver correlator value with multi-user interference from all other connections is therefore calculated as

$$R_{\text{interf.}}(i,j) = l * A(i,j) + \sum_{(x,y)\neq(i,j)} X_{(x\rightarrow y)}^{(i\rightarrow j)} * A(x,j)\,.$$

Since a node employs a correlator for each incoming connection, the corresponding signal is known. Obviously, the signal produced by outgoing connections is also known. Therefore, it is possible to eliminate these components from the received signal via a process called multi-user interference reduction (MUIR) [5]. We assume MUIR to be perfect, so incoming and outgoing connections of a node do not interfere with each other at all. Therefore, our $R_{\text{interf.}}$ is computed as

$$R_{\text{interf.}}(i,j) = l * A(i,j) + \sum_{\{(x,y)|x\in N\setminus\{j\} \text{ and } y\in M_x\setminus\{j\}\}} X_{(x\rightarrow y)}^{(i\rightarrow j)} * A(x,j)\,.$$

3 Simulation

Our simulation has been built on Matlab. We can vary the number of nodes n, the number of connections per node m, the minimum distance d between them, the signal propagation, and the chip length l. We can also choose between unidirectional and bidirectional connections.

As CDMA codes we use Gold codes, which are suitable for asynchronous CDMA and have a trivalent cross-correlation function [6]. For these codes we calculate X with the stochastic function

$$X = \begin{cases} -1 & \text{with the probability of } 49.\overline{49}\%, \\ -\varphi(l) & \text{with the probability of } 25.\overline{25}\%, \\ \varphi(l)-2 & \text{with the probability of } 25.\overline{25}\% \end{cases}$$

where

$$\varphi(l) = \begin{cases} 2^{\frac{ld(l+1)+1}{2}}+1 & \text{if } ld(l+1) \text{ is odd}, \\ 2^{\frac{ld(l+1)+2}{2}}+1 & \text{if } ld(l+1) \text{ is even}\,. \end{cases}$$

Here, l is the chip length, which also determines the size of the code set: For a chip length of l, the size of the code set of Gold codes is $l+2$.

If the data bit of the transmitter i, which determines the sign of the code, corresponds to the sign of $R_{\text{interf.}}(i,j)$ at node j, then no error has occurred. If the signs are different, we have experienced a bit error. For each connection, we send 100 random data bits and count the number of bit errors at the receiver. The resulting *bit error rate* (BER) is our measure of quality for a connection. In our network model, we do not use a global code allocation service; instead, each node has the whole code set and probes until an unused code is found.

In W2F, the graph formed by the connections of each node to its m neighbors should be a node- and therefore path-redundant spanner [7] which has good properties with respect to, e.g., power consumption and fault tolerance. To simplify matters, we do not use any spanner algorithm in our simulation. Instead, each node chooses the nearest m nodes as its neighbors in the unidirectional case. For the bidirectional case, which means that for each connection from node i to node j there is also a connection from j to i, the nodes are iterated in a random order, and each node j selects the corresponding outgoing connection (j,i) for each incoming connection (i,j) and fills up the remaining connections with its nearest nodes which have currently less than m connections. The error introduced by this simplification does not have any significant influence on the simulation results.

External interference from sources other than the network nodes (e.g. external noise) is not taken into account.

Our simulation places n nodes randomly on the plane, ensuring that the minimum distance requirement is obeyed. This is done by repeatedly choosing a random position for the node until the minimum distance requirement to all already placed nodes is fulfilled. It then establishes the connections with the algorithm described above. After setting up the connections, the simulation assigns random codes to them, and for each connection, a random data bit is transmitted and the receiver correlator value with multi-user interference is computed. The bit error rate of a connection is determined from 100 iterations of assigning random codes and computing the receiver value. It is divided into three classes: BER$\leq$ 10%, 10% <BER< 25%, and BER$\geq$ 25%.

As an example for a network, consider the simulation of Figure 1. Here, we assumed $n = 100$ nodes with $m = 4$ unidirectional connections each, and chose a code length of $l = 1023$. The minimum distance between the nodes was $d > 3$ units in a 100×100 plane.

We obtain a typical network with several interesting features, which we will explore in more depth in Section 4. Note that even though we did not enforce it, the network does not have any partitions. We also observe that most connections have a low bit error rate, and that connections

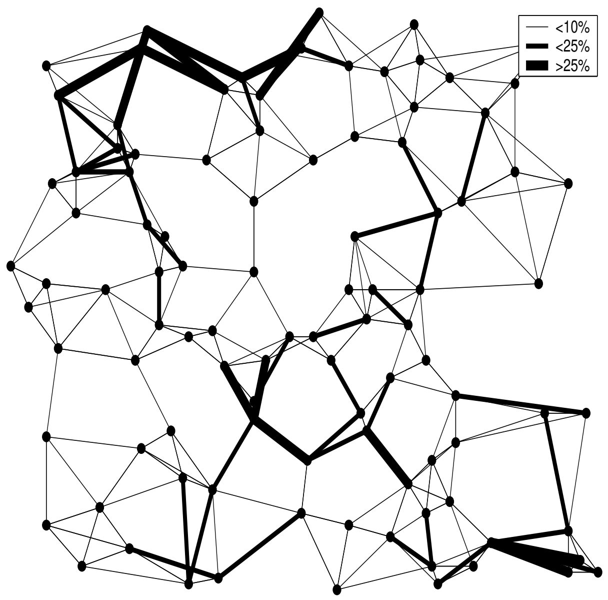

Figure 1. Network with neighbor connections

	unidirectional	bidirectional
BER$\leq 10\%$	372.28	279.28
10% <BER$< 25\%$	19.56	65.48
BER$\geq 25\%$	8.16	55.24
average BER	2.2122%	8.9330%

Table 1. Comparison of uni- and bidirectional connections

with high BER tend to be close together. An interesting aspect is the fact that most connections with high BER are at the circumference of the graph. This is most probably due to the higher transmission power used by nodes at the border: In areas with lower node density, the average distance to a node's m neighbors increases accordingly, which in turn increases the overall transmission power a node needs to use to maintain its connections. Since each node's transmissions constitute interference for all other nodes but the receiver, this increase in transmission power deteriorates the BER in the vicinity.

In the following section, we will vary the system parameters to determine their influence on the bit error rate.

4 Results

Unless used as a parameter for a plot, all simulation runs presented in this section use $n = 100$, $m = 4$, $l = 1023$, and $d > 3$ on a 100×100 plane with unidirectional connections. Each plot is an average over 100 runs of randomly generated networks for that particular setting.

Before we start with our simulations, let us consider the difference between unidirectional and bidirectional connections and their influence on the bit error rate. Intuitively, we would expect the bidirectional network to perform much worse than the unidirectional one, probably even rendering CDMA communication infeasible. Surprisingly, this is not the case. Table 1 compares the average number of connections in the three BER classes and the average BER for unidirectional and bidirectional networks.

We see that although the unidirectional case performs better and the increase in connections with BER ≥ 25 is considerable, the difference in the average BERs is not too bad. Nevertheless, the unidirectional network ensures a significantly lower BER and is therefore our network of choice for W2F. Bidirectional networks or hybrid networks using both uni- and bidirectional connections are possible though, as long as we can avoid connections with high BER, e.g., by assigning well-chosen codes in areas of high BER or randomly trying codes until a suitable one is found [8].

Our first simulation in Figure 2 is concerned with the influence of the minimum distance between nodes. The left plot shows its influence on the average BER. The right plot depicts its effect on the high BER classes.

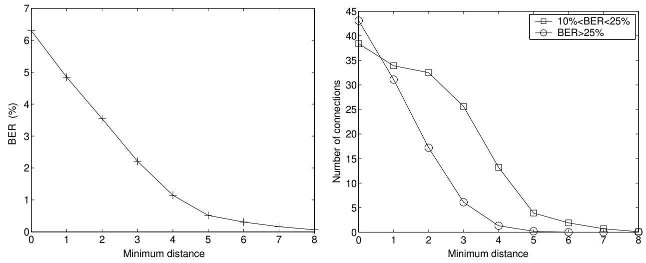

Figure 2. Influence of minimum distance

We see that the minimum distance plays a vital role for the BER: If nodes come too close to each other, the BER increases significantly. On the other hand, if nodes are further apart, which translates to a more uniform distribution of the nodes on the plane, then the BER decreases steadily, dropping to zero after only 8 units. This is due to the fact that with increasing minimum distance, all neighbor nodes have approximately equal distance from a node. In consequence, the near-far problem, which arises when a node with a small receiver correlator value is in the vicinity of a node with high transmission power, is less likely to occur.

Hence, we should take care not to place nodes too close to each other. Unfortunately, we may not be able to influence the node placement in the W2F network. As an alternative, we consider a solution where nodes too close to each other coordinate their transmissions, such that they appear to other nodes in the network as only one node. This ensures that only one of the nodes in this group uses a long-range connection which may interfere with the short-range connections. The long-range connection is scheduled so as not to cause a collision with the internal short-range communications.

In Figure 3, we varied the number of nodes n and again observe their influence on the average BER in the left figure. The percentages of connections with medium and high BER are plotted in the right figure.

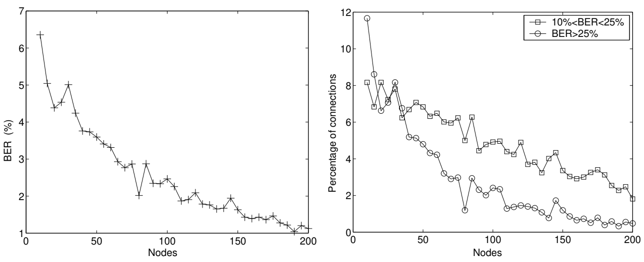

Figure 3. Variation of node number

Again, we see a decrease in the bit error rates with increasing number of nodes. At a first glance, this contradicts our observations from the previous simulation, which states that the farther away nodes are, the better the BER gets. With more nodes distributed in the same 100×100 plane, however, their respective distances become shorter. But at the same time, their distribution again becomes more uniform, and since all distances are short, there are no long-range connections which may cause exceptionally high interference.

The left plot of Figure 4 gives the influence of the number of connections per node m on the average BER. In the right plot, we showed its effect both in unidirectional and bidirectional networks.

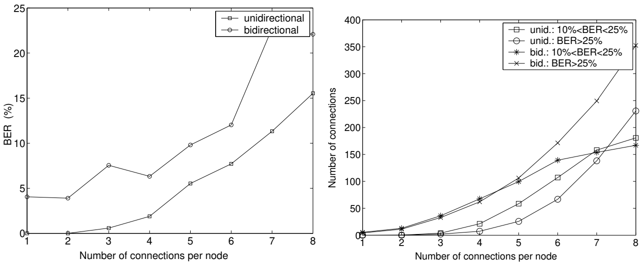

Figure 4. Influence of number of connections per node

Naturally, the BER increases with a higher number of connections, since there are now more interfering connections.

An interesting aspect of the right plot is the leveling of connections in the $10-25\%$ range both in the uni- and bidirectional case. For the bidirectional network, this range actually gets better than that of the unidirectional network. We suspect that this is related to our observation from Figure 1 that connections with high BER tend to be close together. If we increase the number of connections, we significantly increase the overall BER in these regions and pull connections from the $10-25\%$ range into the $\geq 25\%$ range. Apparently, the problem is less pressing in regions of lower BER, which are less affected by the increased interference from additional connections. Nevertheless, the overall performance of the unidirectional network is still superior.

The result, although expected, puts us into a problematic situation: On one hand, we want fault tolerance, which we must achieve through connection redundancy and in consequence through a high number of connections per node. On the other hand, this redundancy causes the BER to increase, thereby increasing the probability of link faults in our network. Thus, our aim in the W$_2$F network is to increase m as much as possible while still keeping the BER in a range that is acceptable to our algorithms.

Figure 5 simulates the influence of the chip length l, again in an unidirectional network.

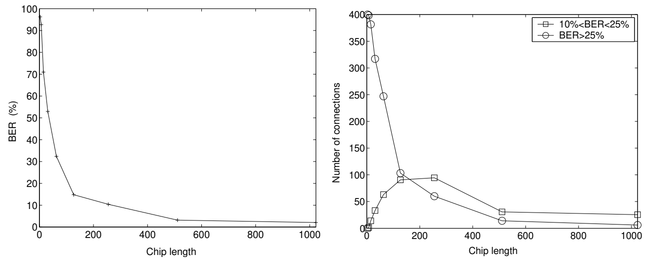

Figure 5. Influence of chip length

We see that the higher the chip length, the lower the BER. This is to be expected, since the cross correlation X depends on the chip length. Note that this is true for other code families as well.

Figure 6 explores the influence of different homogeneous signal propagations on the bit error rate.

We observe a steady increase of the average BER with increasing attenuation of the signal, which correlates with the plot of $\geq 25\%$ BERs. As in the previous simulation, the $10-25\%$ range again decreases, most likely due to the same reasons as stated above.

As a comparison, Table 2 shows the effect of a highly inhomogeneous signal propagation as it may be found in indoor environments ([9], [10]). For this indoor simulation, the path loss for a connection was assumed to be equally distributed in the range of the inverse second to the inverse sixth power of the distance.

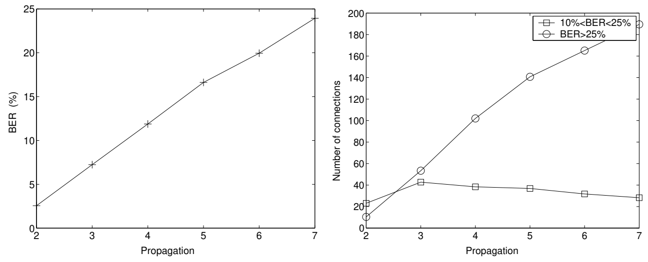

Figure 6. Influence of signal propagation

BER$\leq$ 10%	216.25
10% <BER< 25%	37.25
BER$\geq$ 25%	146.5
average BER	17.7752%

Table 2. Indoor signal propagation

If we compare this data with the plot of Figure 6, we can see that the indoor simulation roughly corresponds with a homogeneous attenuation of 5, which is not very good.

Table 3 compares the BER of two different power management strategies. The simplest strategy, which is also used in all our simulations, is for any node p to employ the same signal amplitude on all its links. We assume that the farthest neighbor of a node p receives p's signal with an amplitude of 1 and that all nearer neighbors therefore receive p's signal with a higher amplitude. A more elaborate power management strategy is to adjust the transmission power for each connection. In this case, the transmission from p to any neighbor q is received at q with an amplitude of 1 regardless of its distance. This method reduces the power consumption, but deteriorates the average BER, as we can see in Table 3.

$$R_{\text{interf.}}(i,j) = l*1 + \sum_{\{(x,y)\,|\,x\in N\setminus\{j\} \text{ and } y\in M_x\setminus\{j\}\}} X_{(x\to y)}^{(i\to j)} * \left(\frac{dist(x,y)}{dist(x,j)}\right)^2$$

The first strategy shows an improvement of about 20% in the average BER over the second one. This is most likely due to the exponential signal attenuation in conjunction with the fact that we use the nearest nodes as neighbors. If we use cubic or higher attenuation, the improvement becomes slightly more pronounced.

Since many connections with high BER are only affected by a few connections with high interference, one of our most pressing concerns was whether we can alleviate the problem by equipping nodes with additional correlators to cancel the influence of the heavily interfering connections. This could, for example, be done with Successive Interference Cancellers (SIC) [5], where the correlation values of the interfering nodes are subtracted from all relevant incoming connections.

	constant	individual
BER$\leq$ 10%	372.84	365.29
10% <BER< 25%	20.52	27.21
BER$\geq$ 25%	6.64	7.5
average BER	2.1594%	2.6919%

Table 3. Comparison of different power managements

Let $O_j = max_{A(x,j)}\{(x,y)|x \in N \setminus \{j\}$ and $y \in M_x \setminus \{j\}\}$ be the set of connections which interfere most and therefore should be eliminated. Then the receiver correlator value with multi-user interference reduction is now calculated as

$$R_{\text{IR}}(i,j) = l * A(i,j) + \sum_{\{(x,y)\,|\,x\in N\setminus\{j\} \text{ and } y\in M_x\setminus\{j\}\}\setminus O_j} X_{(x\to y)}^{(i\to j)} * A(x,j)\,.$$

The simulation of Figure 7 explores how the additional correlators in each node, which determine the maximum cardinality of O_j, influence the BER. In the figures, we plotted $|O_j|$ on the horizontal axis.

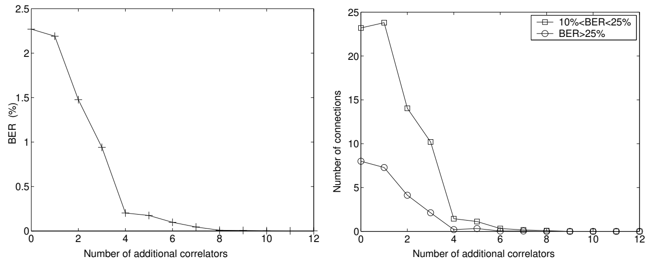

Figure 7. Influence of additional correlators for SIC

We see a dramatic drop of the BER with only a few correlators, showing that moderate hardware support can significantly increase the overall performance of the network. In our simulation run, four receiver units would already be sufficient to improve nearly all connections to a BER $\leq$ 10%.

In the right figure, we see a slight increase of the BER in the $10 - 25\%$ range if just one connection is removed, which corresponds to the decrease in the $\geq$ 25% range. Here, the interference reduction simply improved the existing connections and moved some from the high BER range into the medium range. Normally, both BERs drop, since some connections from the $10 - 25\%$ range fall into the $\leq$ 10% range. In our simulation, we observe this effect if we remove more than one connection.

5 Conclusions

In this paper, we investigated the feasibility of CDMA-based communication in a homogeneous wireless ad hoc network by simulating such a network and computing the bit error rate of its connections. We were interested in whether communication is possible at all, and if so, what constraints on the topology and requirements to the hardware we have.

Our most important result is that CDMA-based communication is indeed feasible. The best results are obtained in unidirectional networks. We found that in the interest of a low BER, we should either demand a minimum distance between nodes or should use some other solution to combat the near-far problem. Although a high number of nodes has a beneficial effect on the system, the number of connections per node should remain low. In our particular simulation run, four additional correlators used for multi-user interference reduction are sufficient to reduce the bit error rate to an acceptable level.

Future work will focus on improving our simulation with more low level details like e.g. data block communication, modulation, or external interference. We will also complement our simulation with a theoretical analysis. In particular, we want to combine the results of [1] with our multi-user interference concept.

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