Novel packet coding scheme immune to packet collisions for CDMA-based wireless *ad hoc* networks

D. Liu, Y. Cai and G. Tu

Abstract: A novel packet coding scheme for DS-CDMA *ad hoc* networks is developed. The scheme facilitates collision resolution by embedding the information of both transmitter and receiver in the coding scheme so that the receiver can identify packets addressing to it without actually decoding the information symbol bits. In addition, the present scheme also avoids the transmitter's retransmissions by resolving all packet collisions and avoids receivers wasting time in receiving a packet to completion if the packet is not addressed to it which causes additional battery energy consumption. A bank of matched filters is used to identify intended receivers, even though, any multiuser detection algorithm can easily be applied. The present scheme is evaluated and compared to an existing scheme through computer simulations.

1 Introduction

Ad hoc networks are expected to become a useful medium for various civilian forums such as electronic classrooms, convention centres, construction sites, disaster management groups and many more. Terminals in wireless *ad hoc* networks usually operate with limited battery energy. Thus, a general constraint we face is the short lifetime of mobile terminal batteries. Battery technology has not progressed as rapidly as computing technology. Hence, it is very important to design wireless *ad hoc* networks with power savings in mind.

In general, a radio module consumes more power in transmission mode than in reception mode. The least power is consumed by the radio module in idle mode. Packet collision is an important problem to be addressed. Conventionally, when a collision occurs, the colliding packets are discarded and later retransmitted. Such an approach results in unnecessary power consumption and waste of network resources. The present paper develops a scheme that is immune to packet collisions and avoids unnecessary information decoding for mobile terminals in *ad hoc* wireless networks by means of a novel code division multiple access (CDMA) packet coding scheme.

We consider slotted random access *ad hoc* networks where all users share a common radio channel for immediate packet transmission. A packet collision occurs when more than one user transmits in the same time slot. For conventional narrowband networks, this concurrent channel access by more than one user results in the destruction of all colliding packets. To recover the information in the colliding packets, they have to be retransmitted in later time slots, which has adverse effects on the network throughput and delays in addition to mobile terminal battery power consumption.

A defining characteristic of CDMA is the possibility of receiving multiple packets at the same time. Spreading code schemes can take several different forms in CDMA wireless *ad hoc* networks, including network-wide code where a common code is used by all users, receiver-based code and transmitter-based code. In CDMA wireless *ad hoc* networks, when multiple transmitters transmit to the same receivers at the same time, packet collisions occur. Such collisions cannot easily be resolved when a network-wide code or receiver-based code is used [1]; while collisions can be resolved with the help of multiuser detection techniques [2–5] when transmitter-based code is used. Even in the case of transmitter-based code, with the use of multiuser detection techniques to resolve collisions, the receiver cannot tell whether it is the intended receiver or not. A heavy decoding burden is placed on the receiver because at the beginning of each packet, it needs to retrieve the destination address information in the header of all concurrently transmitted packets to determine whether or not it is one of the intended receivers [6]. This will result in unnecessary receiver power consumption.

The goal of this paper is to develop a novel packet coding scheme that uses a modified transmitter-based spreading code scheme. We will restrict ourselves to packet-switched CDMA networks employing slotted Aloha random access protocols [7]. It turns out that by applying the present packet coding scheme, sufficient information is provided for packet separation, which simplifies the decoding of the destination address information and saves the power for those unintended receiver nodes. It is unlike the pure transmitter-based spreading code scheme, which cannot efficiently resolve the problem of how a receiver anticipate a transmission addressing to it so that it can choose the appropriate despreading code. Also, it is unlike the receiver-transmitter based spreading code scheme proposed in [8], in which each node is assigned two unique spreading codes thus results in the number of codes doubled, and the transmitter-receiver based spreading code scheme proposed in [6], in which the spreading code is the product of two different codes. The spreading codes used in this paper could be any codes used in a CDMA system. The unique

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feature of the present scheme is the way that the header information is constructed in a packet and the way that the destination information and source information are decoded. Simulation results will be presented to compare with an existing scheme in terms of the error probability for an unintended receiver to be mistakenly identified as the receiver and the error probability for an intended receiver to be mistakenly categorised as an unintended receiver.

2 A novel packet coding scheme

In this Section, we will develop a spreading code scheme for *ad hoc* networks that is immune to packet collisions.

In our packet coding scheme for wireless *ad hoc* networks, each node in the network is assigned a unique binary spreading code $\mathbf{c}_m$ ($m = 1, \ldots, M$) of processing gain equal to N, where M is the total number of nodes in the network. Suppose that node l needs to transmit a packet of binary symbols to node i. The spreading code used by node l is $\mathbf{c}_l$, which is the code assigned to the transmitting node l. $\mathbf{c}_i$ is the spreading code assigned to the receiver node i. The packet structure is shown in Fig. 1. The packet is divided into header and data sequence. The header is the spreading code sequence assigned to the receiver i, $\mathbf{c}_i$, followed by the data sequence. The length of the header is N, since the processing gain is N. The whole packet will be spread using the spreading code $\mathbf{c}_l$, which is assigned to the transmitter l. We next explain our spreading code scheme in one packet of symbols.

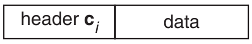

Fig. 1 *Packet structure*

Consider packet transmission from node l to node i. From Fig. 1, we can see that the header information in a packet is the spreading code $\mathbf{c}_i$ of receiver node i, and the packet will be spread using the spreading code $\mathbf{c}_l$. To explain the above packet coding scheme more clearly, we use the following specific example.

Assume that the processing gain is $N = 4$. The data bits to be transmitted from node l to node i is (1, 1, 1, −1, −1, 1, −1, −1), and the spreading codes for node l and node i are (−1, 1, −1, 1) and (−1, −1, 1, 1), respectively. The whole packet according to Fig. 1 is

$$(\underbrace{-1, -1, 1, 1}_{\mathbf{c}_i}, \underbrace{1, 1, 1, -1, -1, 1, -1, -1}_{\text{data}}).$$

In the above, the first four bits carries the information of the spreading code of the intended receiving node, $\mathbf{c}_i$. The packet formed this way will be spread using the spreading code of node l as follows:

$$\left(\begin{array}{ccccccc} 1 & 1 & -1 & -1 & \vdots & -1 & -1 \\ -1 & -1 & 1 & 1 & \vdots & 1 & 1 \\ 1 & 1 & -1 & -1 & \vdots & -1 & -1 \\ -1 & -1 & 1 & 1 & \vdots & 1 & 1 \end{array}\right.$$

$$\left.\begin{array}{cccccc} -1 & 1 & 1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & -1 \\ -1 & 1 & 1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 & -1 & -1 \end{array}\right)$$

The first advantage of the coding scheme mentioned above is that after receiving the header of the packet, any receiver can recognise whether it is an intended receiver by multiplying its own spreading code with the header (i.e., matched filter technique) under the assumption of perfect synchronisation and the orthogonality of the spreading code assigned to each node. Alternatively, if multipath fading destroys the orthogonality or when nonorthogonal codes are employed by the network, a multiuser detector can be used instead of the matched filter technique. The second advantage is that after the node determines that it is an intended receiver, it is easy to tell where the information comes from, because the packet (including the header) is spread by the transmitter's spreading code. Any multiuser detection techniques can be used to recover the packets of interest among unknown interferers.

Consider a synchronous DS-CDMA wireless *ad hoc* network with M nodes. Each node is free to enter or leave the channel in a random fashion with data transmitted in packets. The system is slotted and the nodes are only allowed to initialise transmission at the beginning of each time slot. Nodes transmit to each other directly through a common channel. Each node can be a transmitter or a receiver. The transceiver at each node is half-duplex [7], which means that a transmitting node in an *ad hoc* network cannot receive packets from other nodes. Every node is assigned a unique spreading code. In order to receive packets from any potential nodes, we assume that each node has the knowledge of all neighbouring nodes' spreading codes [7] and the receiver at each node is a bank of matched filters for simplicity. Any multiuser detectors can be used instead of matched filters.

The received signal at node i within a time slot can be written as

$$y_n(t) = \sum_{k \in \mathcal{I}_n} A^{(k)} c^{(k)} d_n^{(k)}(t) + v_n(t)$$

where n is the packet index, t is the symbol index within a packet, k is the transmission index, $A^{(k)}$ is the amplitude of the kth transmission at the receiving node, $c^{(k)}$ is the signature waveform of kth transmission with $||c^{(k)}|| = 1$, $d_n^{(k)}(t)$ is the tth symbol within the nth packet for kth transmission, $v_n(t)$ is the additive white Gaussian noise with zero mean and variance σ^2, and $\mathcal{I}_n$ is the index set of active transmissions in the nth time slot. Thus, $\mathcal{I}_n \subset \{1, 2, \ldots, M\}$. Note that the above expression is for signal received at node i even though we do not use any index i. The receiver's task is to determine if node i is the destination node and detect the symbols $d_n^{(k)}$ if needed.

By passing the received signal $y_n(t)$ through chip-matched filter followed by chip rate sampling in a packet interval yields an $N \times P$ signal matrix $\mathbf{X}$ given by

$$\mathbf{X} = [\mathbf{X}_H \vdots \mathbf{X}_D] \tag{1}$$

where P is the packet length, $\mathbf{X}_H$ is the $N \times N$ matrix that carries the receiver's spreading code information, and $\mathbf{X}_D$ is an $N \times (P - N)$ matrix that contains the data. These matrices can be expressed as

$$\mathbf{X}_H = \sum_{k \in \mathcal{I}_n} A^{(k)} \mathbf{c}_k \mathbf{c}_{m(k)}^T + \mathbf{V}_H \tag{2}$$

and

$$\mathbf{X}_D = \sum_{k \in \mathcal{I}_n} A^{(k)} \mathbf{c}_k \mathbf{b}_k^T + \mathbf{V}_D \tag{3}$$

where $m(k)$ is the intended receiver of kth transmission, and $\mathbf{c}_k$ and $\mathbf{c}_{m(k)}$ are the spreading codes assigned to node k and node $m(k)$, respectively. The vector

$$\mathbf{b}_k = [b_k(1), \ldots, b_k(P-N)]$$

is the vector of data information symbols to be transmitted from node k to node $m(k)$ in one packet. $\mathbf{V}_H$ and $\mathbf{V}_D$ are vectors of additive white Gaussian noise with zero mean.

The implementation of a multiuser detector at the last stage is straightforward, given that the receiver node has the knowledge of all the possible spreading codes of its neighbourhood nodes. For simplicity, we illustrate the use of a simple matched filter for user detection. For a node i in receiving mode, multiplying $\mathbf{X}_H$ with $\mathbf{c}_i$, we get

$$\mathbf{x}_{Hi} \triangleq \mathbf{X}_H \mathbf{c}_i = \sum_{k \in \mathcal{I}_i} A^{(k)} \mathbf{c}_k + \mathbf{v}_H \tag{4}$$

where $\mathcal{I}_i$ is the index set of the nodes which are transmitting to node i. If all elements of $\mathbf{x}_{Hi}$ are zero (or close to zero), it indicates that node i is not an intended receiver. Otherwise, the node is an intended receiver. Since the spreading codes are orthogonal to each other, if we multiply $\mathbf{x}_{Hi}$ with the spreading code matrix $\mathbf{C}^T = [\mathbf{c}_1 \vdots \mathbf{c}_2 \vdots \ldots \vdots \mathbf{c}_M]^T$, we get

$$\mathbf{z}_i \triangleq \mathbf{C}^T \mathbf{x}_{Hi} = \mathbf{C}^T \sum_{k \in \mathcal{I}_i} A^{(k)} \mathbf{c}_k + \mathbf{C}^T \mathbf{v}_H \tag{5}$$

In a noise free environment, $\mathbf{z}_i = [\ldots, A^{l_1}, 0, \ldots, A^{l_2}, \ldots, 0, \ldots]^T$, and a non-zero element will only appear at lth position if node l transmits to node i. Thus, it is easy to determine whether the node l is an intended receiver and where the information comes from. For those nodes which determine that they are not intended receivers, they can go back to idle state to save power. Complete symbol information is contained in matrix $\mathbf{X}_D$, and standard multiuser detection techniques can be used to recover those information symbols.

In the following, we provide a procedure for data symbol detection of the desired user (say, node i).

1) Pass the observation matrix $\mathbf{X}_H$ through a matched filter to get

$$\mathbf{x}_{Hi} = \mathbf{X}_H \mathbf{c}_i \tag{6}$$

2) Pass the vector $\mathbf{x}_{Hi}$ through a thresholding device. If all elements in $\mathbf{x}_{Hi}$ are zero or close to zero, then node i is not an intended receiver. Stop. Otherwise, node i is an intended receiver. Go to step 3.

3) Multiply spreading code matrix $\mathbf{C}$ with $\mathbf{x}_{Hi}$ to get

$$\mathbf{z}_i = \mathbf{C}^T \mathbf{x}_{Hi} \tag{7}$$

4) Pass the vector $\mathbf{z}_i$ through a thresholding device. By looking at the vector $\mathbf{z}_i$, its nonzero entries indicate that node i is an intended receiver and the locations of these nonzero entries indicate where the information comes from. For example, in a noise free environment, they are from node l_1 and node l_2 if

$$\mathbf{z}_i = [\ldots, A^{l_1}, 0, \ldots, A^{l_2}, \ldots, 0, \ldots]^T$$

5) Pass the observation matrix $\mathbf{X}_D$ through matched filters $\mathbf{c}_{l_1}$ and $\mathbf{c}_{l_2}$ to get, respectively,

$$\mathbf{b}_{l_1} = \mathbf{X}_D \mathbf{c}_{l_1} \text{ and } \mathbf{b}_{l_2} = \mathbf{X}_D \mathbf{c}_{l_2}$$

The above packet coding scheme achieves some of the benefits of transmitter-based spreading code scheme while using a receiver code for a small portion of the packet, that is, only to get the receiver's attention. The present packet coding scheme has the added advantage that resolves collisions when multiple packets are addressed to the same destination. Although these multiple packets use the same header information (receiver's spreading code), the header is spread by different spreading code assigned to different transmitters. Another advantage of the present coding scheme is that it makes it possible for intended receivers to quickly determine transmissions addressing to them and choose the appropriate despreading codes. For unintended receivers, the present coding scheme makes it possible for them to make a quick decision and not waste time in decoding a complete packet if it is not addressed to them. The drawback of the method presented above, obviously, is that the matched filter is still subject to multiple access interference. The advantage is that it does not impose any restriction on the rank of the correlation matrix of all spreading codes.

3 Simulation results

In this Section, we present a numerical example to demonstrate the performance of the coding scheme and detection algorithm proposed in previous Sections. We compare the performance of our scheme to that of the scheme proposed in [6] when different detection algorithms including matched filter detector and minimum output energy (MOE) multiuser detector are used. The simulation setup is as follows. We assumed $M = 9$ nodes in the network, a total of six transmissions in each simulation, six nodes in transmission mode, and three nodes in receiving mode (*cf.* Fig. 2). Each transmission's channel is assumed flat with a single path experiencing Rayleigh fading.

We randomly generate one packet to be transmitted in each simulation, and the packet contains 1000 binary data symbols. The length of the header in each packet is $N = 32$ (processing gain of 32), and the pseudo noise (PN) code sequence is applied. As for the coding scheme proposed in [6], the spreading codes are generated from the Schur product of a group of Walsh codes of length 32 and a set of PN codes of length 32. The simulation results in this Section are obtained by averaging over 1000 independent runs.

We consider the probability of false alarm and missing detection. False alarm means that when an unintended receiver is mistakenly identified as the receiver, and missing detection means that an intended receiver is mistakenly categorised as an unintended receiver. Figure 3 shows the

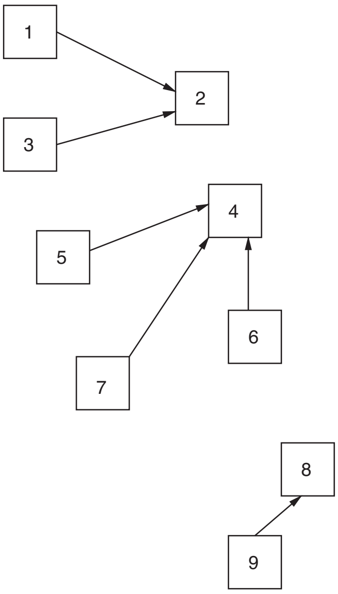

Fig. 2 *Ad hoc network simulation set up*

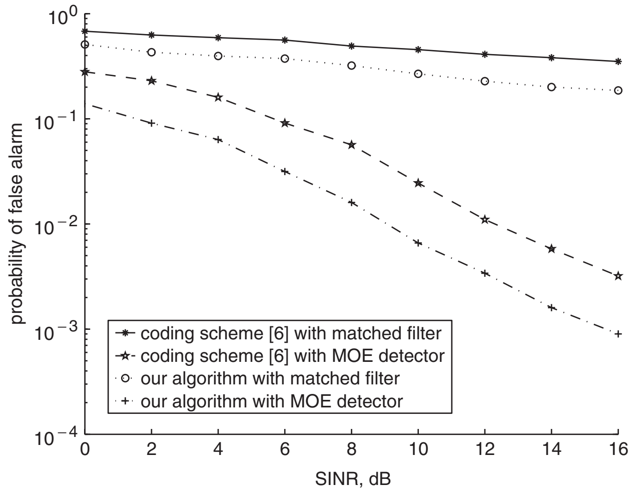

Fig. 3 *Probability of false alarm over flat Rayleigh fading channel*

probability of false alarm over a flat Rayleigh fading channel for one of the nodes (node 5 in this case). The signal-to-interference plus noise ratio (SINR) is fixed in this example at 5 dB. We only show the performance of the scheme with different detection algorithms under different SINR. From the Figure, obviously we can see that both schemes with MOE detector have much better performance than the ones with matched filter detector. In addition, the Figure shows that our coding scheme provides smaller false alarm rate than the coding scheme in [6]. Figure 4 shows the probability of missing detection over a flat Rayleigh fading channel for one of the nodes (node 4), which receives signals from nodes 5, 6, and 7 at the same time. With help from the MOE detector, the probability of missing detection is much smaller for both schemes than those with matched filter. Again, we can see from Fig. 4 that performance of our coding scheme is better than the one in [6]. Finally, Fig. 5 shows the probability of false alarm for node 3 and probability of missing detection for node 2 over a flat Rayleigh fading channel when there is no multiple access interference (MAI). We can see that the performance is very good even when using matched filter detector under the condition that there is no MAI. However, it is impossible for the coding scheme in [6] to use matched filter detector to identify whether a node is an intended receiver or not, because the Schur product of Walsh codes and PN codes does not lead to orthogonal codes any more when different transmissions to different receivers exist at the same time.

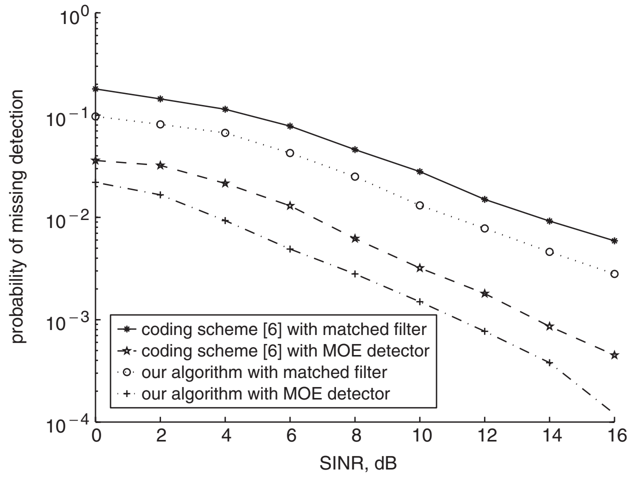

Fig. 4 *Probability of missing detection over flat Rayleigh fading channel*

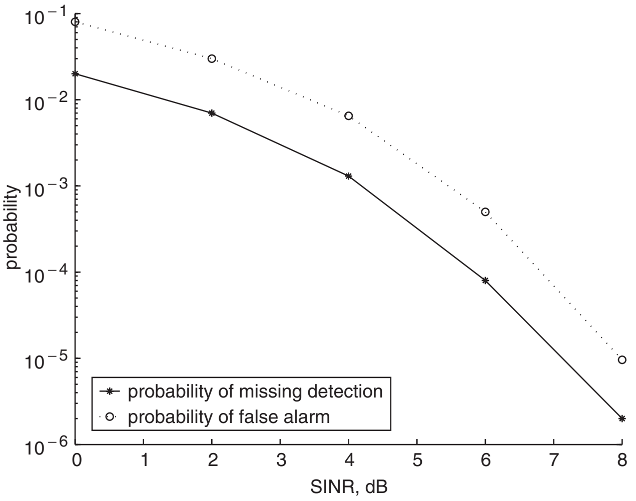

Fig. 5 *Probability of false alarm and missing detection over flat Rayleigh fading channel without MAI*

4 Conclusions

In this paper, we developed a novel packet coding scheme for DS-CDMA *ad hoc* networks that embeds the information of both the transmitter and receiver in the coding scheme so that the receiver can identify the packet addressing to it without actually decoding the information symbols. The present scheme begins a transmission on the receiver's code, which is the header information of a packet, followed by the data. The information is spread in a transmitter-based manner. The present scheme is immune to packet collisions and thus eliminates transmitter's retransmissions owing to packet collisions. It avoids receivers wasting time in receiving a packet to completion if the packet is not addressed to it which causes additional battery energy consumption. A bank of matched filters is used for simplicity in this paper, even though, any multiuser detection algorithm presented in [2–5] can easily be applied. Simulation results are presented for comparison with an existing scheme in terms of the false alarm probability and the missing detection probability.

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