A Pseudo Random Sequence Based Multichannel MAC Protocol for Directional Ad Hoc Networks

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Abstract. In directional ad hoc networks, the character of directional transmission and directional reception of the links makes it difficult to let one directional link aware of the other concurrent transmission links, so that the collision probability of the concurrent transmission links need to be reduced. In this paper, a pseudo random sequence (PRS) based multichannel multiple access control (MAC) protocol is proposed to reduce the collision probability of the concurrent transmission links. The proposed PRS MAC protocol is based on the time division multiple access (TDMA) frame structures. After the neighbour discovering sub-frame, the proposed PRS MAC protocol works in the reservation sub-frame, and in each time slot it works in a three-way handshake method to reserve the data slots in the data transmission sub-frame. On one hand, with the introduction of multiple channels, the concurrent transmission links can be distributed to different channels such that the collision probability of each channel can be reduced. On the other hand, with the introduction of the pseudo random sequence, each of the concurrent transmission links may take different PRS such that the collisions of the concurrent transmission links are randomized. Simulation results show that the proposed PRS MAC protocol outperforms the existing DTRA protocol in terms of lower collision probability and higher aggregated throughput.

Keywords: Directional ad hoc networks · Pseudo random sequence
Multi-channel · Medium access control

1 Introduction

Directional ad hoc network is characterised as a distributed, easy-deployed, and self-organized network, composed of a set of wireless nodes equipped with directional antennas. It finds widely applications in search-and-rescue, battle scenario, and other emergency scenarios. Therefore, it has attracted many research interests from the academic and industrial areas [1,2].

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In directional ad hoc networks, each node is communicating with its neighbours through directional antennas, where the wireless signals are concentrated only in one direction instead of over all directions. Thus, directional transmitting and directional receiving (DTDR) has many advantages in terms of long transmission distances, small interference ranges and low collision probability between concurrent transmission links. However, at the same time DTDR also brings many challenges to the multiple assess control (MAC) protocols. For example, it is difficult for a directional communication link to discover the other concurrent transmission links such that the collisions between the concurrent transmission links are difficult to be avoided. Reference [3] studies the collision tolerant transmission with directional antennas, which finds that the transmission success probability is quite high when the antenna beamwidth is quite narrow. However, when the beamwidth is wide the collisions between the concurrent transmission can not be ignored. When the density of the network is high the collisions of the concurrent links become serious, which cause low throughput and even network meltdown. Thus, it is significant to design a high efficient MAC protocol which can reduce the collision probabilities of the concurrent links and increase the network throughput.

The conventional MAC protocols for directional ad hoc networks can be classified into two categories, i.e., the random access based and the synchronized, which is time division multiple access (TDMA) based [1]. It has been shown that the synchronized MAC protocols outperform the random access based ones in terms of the network throughput [4,5]. Reference [6] proposes a novel MAC protocol based on the DTRA algorithms in Ref. [4] to allocate the data transmission slots to the concurrent transmission links.

In this paper we also mainly focus on the synchronized ones. Reference [4,5] are the pioneers of the synchronized protocols for directional antennas, in which the time is divided into time frames and each frame is further divided into three sub-frames, i.e., the neighbour discovery sub-frame, the reservation sub-frame and the data transmission sub-frame. In the neighbour discovery sub-frame, each node discovers its neighbours with the neighbour discovery algorithms [7–12] and the discovered neighbours, or the node pairs, reserve a specified slot in the reservation sub-frame. The nodes pairs exchange information in the specified slot of the reservation sub-frame, and coordinate the data slots resources of the data transmission sub-frame. Although the synchronized protocols are better, the data slots coordination are distributed, i.e., the resource allocation between the concurrent links. Therefore, the collision problem of the concurrent links is also serious in the synchronized protocols.

Reference [13] has studied the capacity of the directional ad hoc netowrk with multiple channels. The analysis results have shown that there exists a large improvement space when the multi-channel technology is introduced into the directional ad hoc networks. Reference [14] shows that there exists a upper bound on the number of channels to ensure collision free communication in multi-channel directional ad hoc network, when the total number of nodes is given. Particularly, the channel assignment problem is studied and is formulated as a graph colouring problem. Such that the number of the colors can represent the number of the channels. Thus it can be concluded that multiple channel technologies can be employed to reduce the collision probability of the concurrent transmission links. However, to the best knowledge of the authors, there are no synchronized multiple channel protocols proposed to assignment the channels to the concurrent links, which motivates our work.

In this paper, we propose a pseudo random sequence (PRS) based multi-channel MAC protocol for directional ad hoc networks, with the aim of reducing the collision probability of multiple concurrent transmission links. On one hand, with the introduction of multiple channels, the concurrent transmission links can be distributed to different channels such that the collision probability of each channel can be reduced. On the other hand, with the introduction of the pseudo random sequence, each of the concurrent transmission links may take different PRSs such that the collisions of the concurrent transmission links are randomized. Furthermore, with the introduction of PRSs, the anti-interference capability and the security of the concurrent links also can be enhanced.

The main contributions of this paper are three-folds and listed as follows:

- Firstly, to reduce the collision probabilities of the concurrent links a multiple channel TDMA frame structure is proposed.
- Secondly, a pseudo random sequence based method is proposed to organize the time-frequency blocks which not only can help to randomize the collisions but also help to improve the efficiency of the proposed MAC protocol when the PRSs are non-orthogonal.
- Thirdly, two algorithms are proposed which are used to generate the PRS mask for a selected PRS, and used to confirm the PRS mask respectively.

Simulation results show the advantage of the proposed PRS MAC protocol in terms of low collision of concurrent transmission links and high aggregated throughput.

The following sections are organized as follows. Section 2 presents the system model of the proposed PRS MAC protocol, and illustrates the proposed TDMA frame structures. The operation procedures of the PRS MAC protocol are illustrated in Sect. 3. Section 4 evaluates the performance of the PRS MAC protocol. And Sect. 5 concludes this paper.

2 System Model

2.1 Directional Antenna and TDMA Frame Structures

Suppose that there are several wireless nodes equipped with switched directional antennas randomly distributed in the directional ad hoc networks. Let B denote the number of the directional antennas. Each node also equips with a GPS chip, which can provide second pulse such that all of the nodes can operate in a synchronization mode. The system operates in time division multiple access (TDMA) mode, where each TDMA frame consists of three sub-frames, i.e., the neighbour discovery sub-frame, the reservation sub-frame and the data transmission sub-frame.

Assume that there are $(n+1), n \geq 0$, channels in the network, one of which is the control channel and the remaining n channels are the data channels. The control channel is responsible for neighbour discovering, reservation and data transmissions, while the data channels are responsible only for reservation and data transmissions. Among these $(n+1)$ multiple channels, in each timeslot of the reservation and data transmission sub-frames, any node can work on at most N_c, $1 \leq N_c \leq (n+1)$, channels. The TDMA frame structure of the proposed PRS MAC protocol is given in Fig. 1.

In the neighbour discovery sub-frame all nodes switch to the control channel to discover each other, and the neighbours make an agreement that when (in which time slot) and where (in which channel) to do the reservation and who will be the sender and receiver. Next in the reservation sub-frame the node pairs switch to the coordinated data channels to reserve the following data transmission slots, and the reservation result is stored in the *reserved link state table*. Finally in the data transmission sub-frame the nodes transmit or receive packets with their neighbours according to the reserved link state table. The proposed PRS MAC protocol mainly works in the reservation sub-frame, and details how the reservation result is produced with the PRS based method.

In the reservation sub-frame, each slot consists of 3 mini-slots, and the neighbours reserve the data slots in the data transmission sub-frame in a 3-way handshake process, i.e., the HELLO-RESPONSE-CONF packet exchanging process. In each mini-slot, one packet is sent. Let N_d denote the numbers of slots in the data transmission sub-frame. Then the *reserved link state table* can be denoted as $\mathbf{A} = [a_{i,b,c}]_{N_d \times B \times (n+1)}$, where $a_{i,b,c} = (u, v)$ denotes that node u will send data to node v at slot i, beam b, in channel c. Let $\mathbb{I}(a_{i,b,c}) = 0$ if $a_{i,b,c} = (-1, -1)$ and $\mathbb{I}(a_{i,b,c}) = 1$ otherwise.

In directional ad hoc networks, with the switched directional antenna constraint, at any timeslot i only one beam can be activated and thus we have $B_i = \sum_b \sum_c \mathbb{I}(a_{i,b,c}) \leq 1$. And if one beam b is activated the N_c multiple

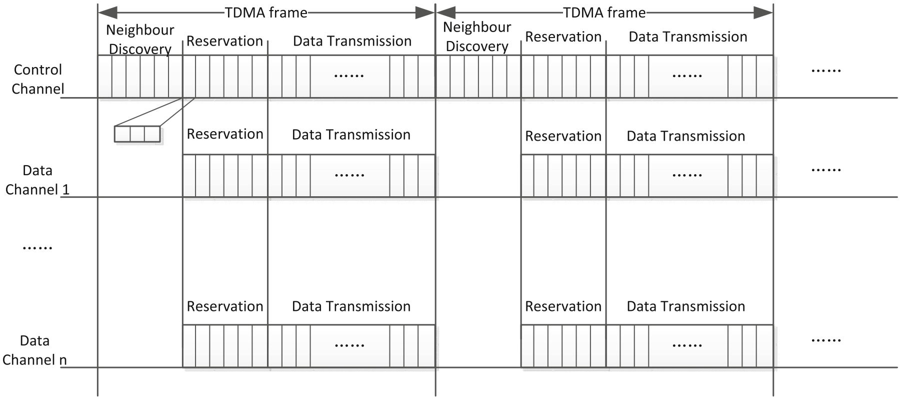

Fig. 1. TDMA frame structures of the proposed PRS MAC protocol

channels can only be used within this beam, which means $C_{i,b} = \sum_c \mathbb{I}(a_{i,b,c}) \leq N_c$. We note that this is the main distinguish of directional ad hoc networks from the traditional wireless ad hoc networks.

2.2 Pseudo Random Sequence

Let $\mathbf{P} = [p_{m,i}]_{M \times N_d}$ be a pseudo random sequence (PRS) pattern held by all of the nodes in the network, where M is the total number of PRSs listed in the pattern. Let P_m denote the mth PRS with size of N_d. In other words, the PRS is a sequence of channel numbers corresponding to each time slot. Thus, $p_{m,i}$ denotes the channel index at slot i in channel $p_{m,i}$, where $1 \leq p_{m,i} \leq (n+1)$. Figure 2 shows an example of PRS pattern, and the shaded area is the first PRS in pattern $\mathbf{P}$, which means that at time slot 1 to slot 4 the channels $\{1, 2, 3, 4\}$ are employed.

We note that there may exist several PRS pattern generation methods, and each different PRS pattern may have different attributes. For example, any two PRSs in a given PRS pattern may be orthogonal, i.e., no overlapped time-frequency blocks, or non-orthogonal, i.e., having one or multiple overlapped time-frequency blocks. Therefore, when different concurrent transmission links employ different PRSs the collisions can be controlled. In other words, when the PRSs are orthogonal and different links choose different PRSs then there are no collisions between the concurrent links. While when the PRSs are non-orthogonal and different links choose different PRSs then the collisions can be controlled smaller than the number of overlapped time-frequency blocks.

Note that given the number of the data slots N_d and the number of channels $(n+1)$, the more overlapped time-frequency blocks of any two PRSs, the more collisions may occur. However, there always exist a trade-off between the aggregated throughput and the collision. Thus, to improve the efficiency of the proposed PRS protocol, the relationships between the number of the concurrent transmission links and the level of the non-orthogonal of the PRSs should be studied. In this paper, we only focus on the procedures how to use PRS in the proposed MAC protocol, and omit the studies of the relationships, and the discussions of the PRS pattern generation method and the attributes of the PRSs due to the space limitation, which will be studied as a future work.

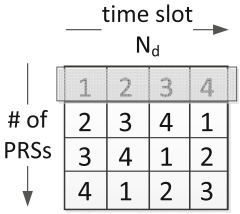

Fig. 2. An example of PRS pattern

3 PRS Based Multi-channel MAC Protocol

In this section, we detail how the proposed PRS MAC protocol works. The proposed PRS MAC protocol mainly works in the reservation and data transmission sub-frames, and the neighbour discovering is assumed completed in the neighbour discovery sub-frame. Then for each slot in the reservation sub-frame, a three way handshakes is completed to reserve the data slots in the data transmission sub-frame.

At each time slot of the reservation sub-frame, let node S be the sender and let node D be the corresponding receiver. Figure 3 shows an overview of the proposed PRS based method working process. Next we detail how each step works.

Step 1: Node *S* sends HELLO. At the beginning of each time slot, node S will select m available PRSs which have not been used by node S's neighbours as far as node S knows. Then these m PRSs will be packed into the HELLO packet. After HELLO is sent out, node S will wait for the response packet REP from node D.

The formats of the HELLO, REP and CONF packets are given in Fig. 4, where TYPE is the packet type, and SA and DA are the source address and destination address of the packets. PRSnum is the number of PRSs packed in the HELLO packet, i.e., m. PRS1, $\cdots$, PRSm are the m PRSs. A2Breq is the data transmission requests from node S to node D. PRSsel in REP is the selected PRS by node D from the m PRSs listed in HELLO. PRS mask is generated by node D with the data transmission request B2Areq by using the selected PRS PRSsel.

Step 2: Node *D* receives HELLO and responds REP. After node D receives the HELLO packet from node S, it will check each PRS listed in the HELLO packet whether available or not from its view. In other words, there may exist some PRS which is available from node S's view but is not available from node D's view. If no available PRS is found it will ignore this HELLO packet.

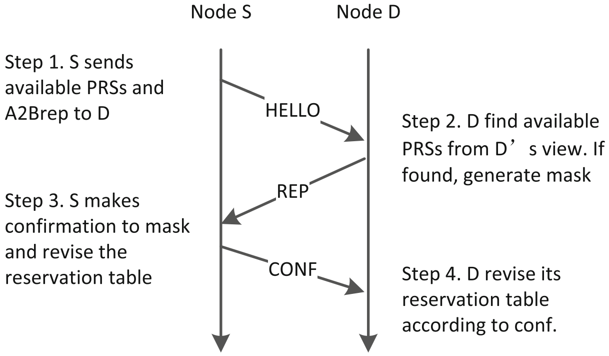

Fig. 3. An overview of PRS working process

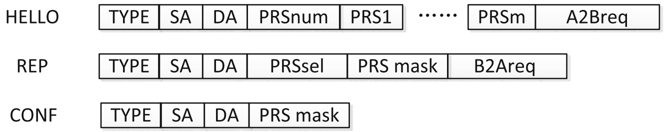

Fig. 4. The formats of the HELLO, REP and CONF packets

Otherwise if at least one available PRS is found the PRSsel can be selected. For example, with the consideration of the number of available time-frequency blocks, the one with the maximum of available time-frequency blocks can be selected out as the PRSsel, which will be packed into the REP. Then node D will generate the PRS mask with the inputs of PRSsel, A2Breq, B2Areq and node D's reserved link state table $\mathbb{A}^D$.

Let $P_m = [p_{m,i}]_{1\times N_d}$ denote the selected PRS, and we recall that $p_{m,i}$ denote the time-frequency block at slot i in channel $p_{m,i}$. Let $K_m = [k_{m,i}]_{1\times N_d}$ denote the PRS mask of P_m, and $k_{m,i}$ denote the mask of $p_{m,i}$, where $k_{m,i}$ is a two bits variable. Assume that $k_{m,i} = B'00$ means $p_{m,i}$ is not available for the communication link $S \leftarrow D$ or $S \rightarrow D$, and $k_{m,i} = B'11$ means $p_{m,i}$ is available for the communication link $S \leftarrow D$, and $k_{m,i} = B'10$ means $p_{m,i}$ is available for the communication link $S \rightarrow D$. The basic idea of generating the PRS mask is to check whether each time-frequency block available or not. Then the available time-frequency blocks will be allocated to link $S \leftarrow D$ or $S \rightarrow D$, according to the comparisons of the values of A2Breq and B2Areq. The pseudo code of the PRS mask generating algorithm is given in Algorithm 1. After the PRS is selected and the PRS mask is generated, they will be packed into the REP packet and then sent back to node S.

Step 3. Node *S* receives REP and responds CONF. If node S receives REP, the PRSsel and PRS mask will be extracted, which will be used by node S to confirm the reservation of data slots. Let P_m denote the PRSsel, and K_m denote the PRS mask, and K'_m denote the final confirmation information. After the confirmation, the link state table of node S, $\mathbf{A}^S$, will be revised and the confirmation information K'_m will be packed into the CONF packet by node S. Finally, the CONF packet will be sent to node D.

The basic idea of confirmation to REP is as follows. For each time-frequency block in the selected PRS of node D, i.e., PRSsel, it will be checked whether it is available or not in $\mathbf{A}^S$. If it is available then the corresponding element in $\mathbf{A}^S$ will be set as a reservation for transmission from node S to D or from node D to S. The pseudo code of the confirmation to REP algorithm is given in Algorithm 2.

Step 4: Node *D* receives CONF. After node D receives CONF, it will extract the confirmation information, i.e., PRS mask. Let K'_m denote the confirmation information, i.e., PRS mask. Then node D will check each two bits in K'_m and revise the corresponding element in node D's link state table, i.e., $\mathbf{A}^D$. For the ith two bits in K'_m, if $k_{m,i} = B'11$ then revise $a_{i,p_{m,i}} = (S, D)$, otherwise if $k_{m,i} = B'11$ then revise $a_{i,p_{m,i}} = (D, S)$.

Algorithm 1. PRS Mask Generating Algorithm

```
Require: $P_m$, A2Breq, B2Areq and $\mathbf{A}^D$.
Ensure: $K_m$.
for $i = 1 \rightarrow N_d$ do
    if $B_i \neq 0$ and $\{(S$ is not in $D$'s $b_i$ area) or ($S$ is in $D$'s $b_i$ area but the number of used multiple channel is larger than $N_c)\}$ then
        $k_{m,i} = B'00$, continue;
    $j = p_{m,i}$;
    if $a_{i,j} = (-1,-1)$ then
        if $A2Breq > 0$ and $A2Breq > B2Areq$ then
            $k_{m,i} = B'11$, $A2Breq = A2Breq - 1$;
        else if $B2Areq > 0$ and $A2Breq \leq B2Areq$ then
            $k_{m,i} = B'10$, $B2Areq = B2Areq - 1$;
    else
        $k_{m,i} = B'00$;
```

Algorithm 2. Confirmation to REP Algorithm

```
Require: $P_m$, $K_m$ and $\mathbf{A}^S$.
Ensure: $\mathbb{A}^S$ and $K'_m$.
for $i = 1 \rightarrow N_d$ do
    if $k_{m,i} \neq B'00$ and $a_{i,p_{m,i}} = (-1,-1)$ then
        if $k_{m,i} = B'11$ then
            $a_{i,p_{m,i}} = (S, D)$, $k'_{m,i} = B'11$;
        else if $k_{m,i} = B'10$ then
            $a_{i,p_{m,i}} = (D, S)$, $k'_{m,i} = B'10$;
        else
            $k'_{m,i} = B'00$;
    else
        $k'_{m,i} = B'00$;
```

4 Performance Evaluation

Extensive simulations are done in *NS2* to evaluate the performance of the proposed PRS MAC protocol. The simulations parameters are set as follows.

There are N nodes deployed in a $200\,\mathrm{m} \times 2000\,\mathrm{m}$ area, where N is increased from 10 to 50. The total number of channel is set from 1 to 4. The traffic load for each discovered neighbours is increased from 5 to 30, with a step of 5.

Figure 5 shows that with the increase of the number of nodes N, i.e., from 10 to 50 with a step of 5, the total number of the successful transmitted packets increases. And when the number of nodes is 10, PRS and multichannels do not provide much improvements since there are few collisions between the concurrent transmission links. In other words, the collisions when there are 10 nodes is not so seriously, such that the multi-channel do not provide much performance enhancement. However when there are more nodes, e.g., 50 nodes, with the number of the multi-channel increase, the total number of successful transmitted packets increases. That is because when there are more nodes the number of concurrent transmission links is large, thus there are more collisions when there is only one channel.

It also can be found that the gap of successful transmitted packets between 1 channel and 2 channels, is smaller than that between 2 channels and 3 channels. This implies that the collisions are reduced from high collision probability when there are 2 channels to a low level, and so when one more channel is added not so much improvement is obtained.

Figure 6 shows that when the traffic load between each discovered neighbours, i.e., a directional link, is increased, how the total number of successful transmitted packets varies with the number of channels. It can be seen that with the increase of the traffic load, the number of successful transmitted packets first increase and then also saturate when the traffic load is large. The gaps between different nodes number, i.e., $N = 10, 20, 50$, with different channel numbers are different, and the the gaps for $N = 50$ is largest. This is because the collisions are more serious when the nodes number is large, from which it can also be seen the gain of the proposed PRS MAC.

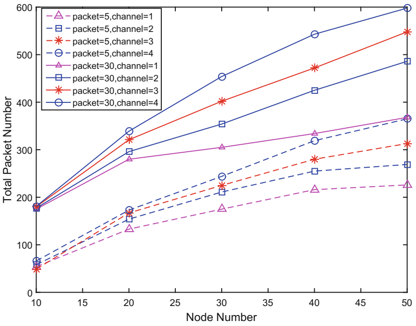

Fig. 5. The total number of the successful transmitted packets with variable nodes numbers when the traffic load is fixed.

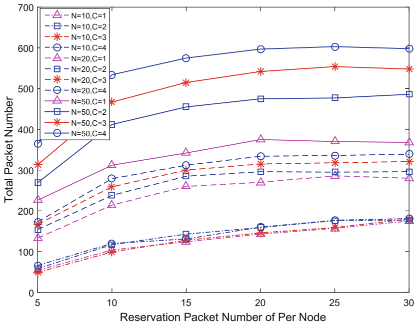

Fig. 6. The total number of the successful transmitted packets with variable traffic load when the number of nodes is fixed.

5 Conclusion

Directional transmission and directional reception brings many advantages comparing with the omni-directional transmission, in terms of longer transmission distance, smaller interference range and lower collision probability between concurrent transmission links. However, it also challenges the MAC protocol since the existence of the other concurrent transmission links may not be aware by one specified link which is reserving the data slots. If one data slot is reserved by more than one directional links, they may collide with each other.

To reduce the collision probability of the concurrent transmission links, a pseudo random sequence (PRS) based multi-channel MAC protocol is proposed, which is based on the TDMA frame structures. With the introduction of multiple channels, the concurrent transmission links may be scattered to different channels such that the collisions may be scattered. With the pseudo random sequence, the time-frequency block, i.e., a frequency resource within a slot, is organized in a random sequence, such that when different concurrent links select different PRSs the collisions may be randomized and the collision probability is reduced. The detailed three-way handshake process to fulfil the proposed PRS based method is given in a step by step way. Extensive simulations are carried to evaluate the performance of the proposed PRS MAC protocol.

As future works, the generation method of the PRSs and PRS patterns, the relationship between the level of non-orthogonal PRSs and the collision probability will be studied.

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