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A Concurrent MAC Protocol based on Local Synchronization for Wireless Ad Hoc Networks with Directional Antennas

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Abstract. Using directional antennas is an effective method to improve the bandwidth utilization in wireless ad hoc networks. However, what remain unaddressed, are the new challenges with MAC protocol design induced by the directional transmissions, such as deafness problems, new hidden terminal problems etc. To solve these problems, in this paper, we propose a directional concurrent MAC protocol based on local synchronization for wireless ad hoc networks with directional antennas. In this protocol, we introduce a channel reservation gap based on local synchronization method for the adjacent nodes, i.e., a channel reservation gap is inserted between the transmission of the RTS/CTS and data packets to offer the neighboring nodes the chance to schedule possible overlapping directional transmissions. Further, the length of the channel reservation gap can dynamically adjust according to the channel situation. Simulation results show that, compared with the typical Nasipuri DMAC protocol, the protocol proposed in this paper can achieve significant throughput improvement.

Introduction

Wireless ad hoc networks is a new type of wireless network which is independent of fixed infrastructure[1]. It is composed of a group of mobile nodes with wireless transceivers. It can reconfigure the network quickly and flexibly. In addition, it has the advantages of high reliability and strong anti-destroying ability and be widely used in military and civil field. The traditional wireless ad hoc networks is realized by omnidirectional antennas[2-3].The omnidirectional antenna has the disadvantages such as limited transmission range and poor anti-interface ability. Compared with the omnidirectional antenna, the directional antenna can reduce the transmission power within the same coverage area, extend the battery life, and greatly improve the spatial multiplexing, which make the wireless ad hoc networks with directional antennas increasingly become an active research field. However, the use of directional antenna also brings deafness problems[4] and directional hidden terminal problems[5] and other new problems.

Related Work

In recent years, the researchers have proposed a lot of directional MAC protocols[6-8] to solve these problems. The authors proposed a protocol named RI-DMAC (Receiver Initiated Directional MAC) in [6]. In this protocol, when the sending node completes the data transmission, it sends a RTR (Ready to Receive) frame to the receiving node, so that the receiving node can receive the data frame of the potential sending node, thus

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greatly reducing the time of deafness. However, the protocol cannot completely solve the deafness problem. In [7], the authors proposed a MAC protocol with directional control frames. The sender sends control frames in turn at each beam direction to find the destination node. However, this method can lead to serious delay, which affects the performance of the entire network. In [8], The authors proposed a coordinated concurrent MAC protocol CDMAC(Coordinated Directional MAC)based on local synchronization. By introducing a channel reservation gap between the control frame and the data frame, nodes in the local area can transmit data concurrently. The introduction of the channel reservation gap also brings extra time overhead.

Overview of the CA-DCTMAC Protocol

The CA-DCTMAC Protocol Specification

The CA-DCTMAC protocol divides the network timeline into three phases, as shown in Fig.1.

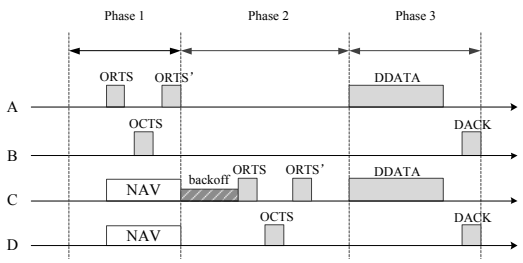

Fig.1. CA-DCTMAC protocol diagram

Master Node Pair Contends to Access the Channel. Because the node cannot predict the position of surrounding neighbors, we use omnidirectional RTS/CTS(ORTS/OCTS) to access the channel. In the network, the sending and receiving nodes, which complete the three-way (ORTS/OCTS/ORTS') handshake firstly, are called the master node pair.

Slave Node Pair Contends to Access the Channel. After the master node pair is generated in the network, a certain length of channel reservation gap is reserved before the directional data transmission, and the neighboring nodes are allowed to complete the ORTS/OCTS/ORTS' handshake in the channel reservation phase.

Master-slave Nodes Transmit Data Concurrently Without Collisions. The master and slave nodes that successfully access the channel in the channel reservation phase can transmit data in parallel at T_DATA and transmit ack at T_ACK.

Adaptive Adjustment of Channel Reservation Gap

In the CA-DCTMAC protocol, a channel reservation gap (CRG) is introduced between the control frame and the data frame in order to realize the concurrent transmission. The length of CRG has a decisive influence on the overall performance of the protocol. Under certain network conditions, if the length of CRG is too short, the transmission quantity is too small, which limits the total throughput of the network. On the contrary, if the length of CRG is too long, it will have unnecessary time overhead. Therefore, we must dynamically adjust the length of CRG to obtain the optimal overall network throughput. CA-DCTMAC uses the exponential smoothing model to dynamically adjust the length of CRG. D_{CRG} ,the length of the CRG, is defined as:

$$D_{\mathrm{CRG}} = N_{\mathrm{CRG}} \cdot (\mathrm{T_{RTS}} + \mathrm{T_{CTS}} + 3\mathrm{SIFS}) + \mathrm{T_{SBOmax}} \tag{1}$$

where T_{RTS}, T_{CTS}, SIFS and T_{SBOmax} are constants, T_{RTS} and T_{CTS} represent the transmission time of the RTS frame and the CTS frame respectively, and T_{SBOmax} represents the maximum backoff time. The variable N_{CRG} represents the number of slave transmissions predicted by the master receiving node, with initial and minimum value of 1 and a maximum value of 4. During each phase 1 of the master transmission, the master receiving node adjusts the N_{CRG} using an improved exponential smoothing model:

$$N_{\mathrm{PS}_i} = \alpha_i \cdot N_{\mathrm{RS}_{i-1}} + (1-\alpha_i) \cdot N_{\mathrm{PS}_{i-1}} + \beta_i \tag{2}$$

$$N_{\mathrm{CRG}} = \left| N_{PS_i} \right| \tag{3}$$

where $N_{\mathrm{RS}_{i-1}}$ and $N_{\mathrm{PS}_{i-1}}$ respectively represents the actual and predict number of slave transmissions in the (i-1)th master transmission. The notation |x| denotes a maximum integer not greater than x, the β_i and α_i are the coefficients. $N_{\mathrm{RS}_{i-1}}$, $N_{\mathrm{PS}_{i-1}}$, β_i and α_i are determined as followed:

The master receiving node maintains a linear list CGL that records CRG-related information. The CGL contains the following information:

- The address of the master sending node;
- The predicted number N_{PS} of slave transmissions in the last master transmission;
- A circular queue of length 5, and the five units are used to record the value of the actual transmission number N_{RS} and the smoothing adjustment coefficient β of the last five master transmissions.

The value of the smoothing adjustment coefficient β is [0,1]. If the predicted value number of slave transmissions is greater than the actual value, the β will be reduced. On the contrary, the β is increased. According to the CGL, the master receiving node can know the value of $N_{\mathrm{RS}_{i-1}}$, $N_{\mathrm{PS}_{i-1}}$ and β_{i-1} of the last master transmission. The master receiving node determines the smoothing adjustment coefficient β_i of the current master transmission according to the following formula:

$$N_{\mathrm{PS}_{i-1}} > N_{\mathrm{RS}_{i-1}}, \text{则} \begin{cases} \beta_i = 0, & (\beta_{i-1} - 0.4) \le 0 \\ \beta_i = \beta_{i-1} - 0.4, & (\beta_{i-1} - 0.4) > 0 \end{cases} \tag{4}$$

$$N_{\mathrm{PS}_{i-1}} \le N_{\mathrm{RS}_{i-1}}, \text{则} \begin{cases} \beta_i = \beta_{i-1} + 0.2, & (\beta_{i-1} + 0.2) \le 1 \\ \beta_i = 1, & (\beta_{i-1} + 0.2) > 1 \end{cases} \tag{5}$$

In order to predict the N_{CRG} more accurately, in the CA-CTMAC protocol, we use the absolute error least squares method to determine the smoothing adjustment coefficient α_i. The objective function is constructed from the sum of the square of the predicted number of the slave transmission and the actual slave transmission number of the last five master transmissions：

$$G = \sum_{i=1}^{5} \left(N_{\mathrm{PS}_i} - N_{\mathrm{RS}_i} \right)^2 \tag{6}$$

The objective function G is then derived and made equal to zero to obtain the optimal value of α_i:

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$$\alpha_i = \frac{\sum_{i=1}^{5}\left(\left(N_{\mathrm{RS}_i} - i\beta_i - 1\right)\cdot A + F - E\right)}{\sum_{i=1}^{5}\left(A^2 - 2\left(i\beta_i + 1 - N_{\mathrm{RS}_i}\right)\cdot B - \left(i^2\beta_i + 2i + 1 - N_{\mathrm{RS}_i}\right)\cdot A - C + D\right)} \tag{7}$$

where: $A = \sum_{j=1}^{i-1} N_{\mathrm{RS}_{i-1-j}}$, $B = \sum_{j=1}^{i-1} j \cdot N_{\mathrm{RS}_{i-1-j}}$, $C = \frac{1}{6} N_{\mathrm{RS}_i}\left(2i^3\beta_i - 3i^2\beta_i + i\beta_i + 6i^2\right)$

$D = \frac{1}{12}\left(7i^4\beta_i^2 - 12i^3\beta_i^2 + 5i^2\beta_i^2 + 28i^3\beta_i - 18i^2\beta_i + 2i\beta_i + 24i^2\right)$, $E = \frac{1}{2} N_{\mathrm{RS}_i}\left(i^2\beta_i - i\beta_i + 2i\right)$

$F = \frac{1}{2}\left(i^3\beta_i^2 - i^2\beta_i^2 + 3i^2\beta_i - i\beta_i + 2i\right)$.

Simulation and Result Analysis

In this section, we verify the validity of CA-DCTMAC in the GloMoSim network simulation environment, then we analyze the mechanism of adjusting the length of channel reservation gap. Finally, we compare the CA-DCTMAC protocol with the Nasipuri DMAC[9] protocol. The main simulation parameters are shown in the Table 1.

Table 1 Simulation parameters

Parameter name	Parameter value	Parameter name	Parameter value
transmission rate	2Mbps	propagation model	Two Ray
antenna pattern	Switched beam	ORTS' frame	40Bytes
transmission distance	500m	ACK fame	12Bytes
ORTS frame	48Bytes	SIFS	10μs
ORTS frame	48Bytes	DIFS	50μs

Verification of the Protocol Validity

The packet sending rate of the three service flows is 0.01packe/s, and the physical layer adopts 180º, 120º and 20º beam switching antennas respectively. The number of packets sent from the node 0, node 2 and node 4 is shown in Fig.2.

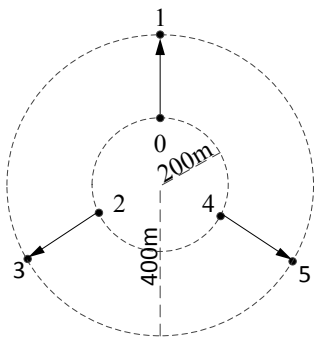

Fig. 2. Topology for protocol validity verification

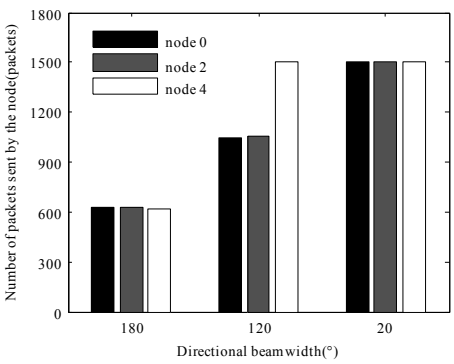

Fig.3. The number of packets sent by nodes

Under the network topology shown in Fig.2, when the physical layer adopts a directional antenna with different beam-widths, the collision relation of the link 0→ 1, link 2→3 and link 4→5 is not exactly the same. When we use a directional antenna with the beam-width of 180º, the link 0 → 1, link 2 → 3 and link 4 → 5 cannot transmit concurrently. When we use a directional antenna with the beam-width of 120º, the link 4 → 5 does not collide with the link 0 → 1 and the link 2 → 3, but the link 0 → 1 and link 2 → 3 conflict with each other, so at most two non-conflicting links can simultaneously transmit data, and the chance that the node 4 can transmit data is greater than the node 0 and the node 2. When we use a directional antenna with the beam-width

of 20º, there is no collision occurs when the link 0 → 1, link 2 → 3, and link 4 → 5 are transmitted concurrently. The simulation results in Fig.3 are consistent with the theoretical analysis described above, and demonstrate the effectiveness of the CA-DCTMAC protocol.

Analysis of the Influence of Channel Reservation Duration on the Protocol Performance

In this section, we modify the channel reservation duration of the CA-DCTMAC protocol, and analyze the influence of the channel reservation duration on network saturation throughput. It can be seen from Fig. 4 that when the channel reservation duration is too small, there is only one pair of nodes participating in the concurrent transmission, so the saturated throughput is about 1.2Mbps. When the channel reservation duration is 3000μs, the network saturation throughput gets higher. And then we continue to increase the channel reservation duration, due to the limited number of nodes in the network, too long channel reservation duration does not increase the number of concurrent transmissions, but causes unnecessary time overhead, resulting in saturated throughput's decline.

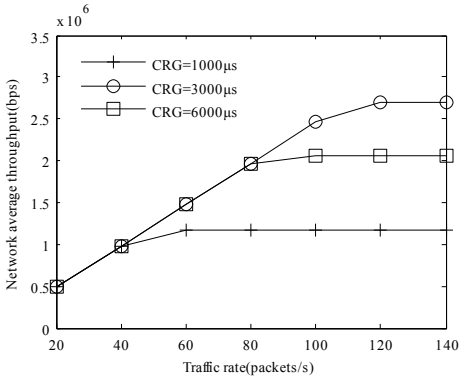

Fig.4. Average throughput of different channel reservation durations

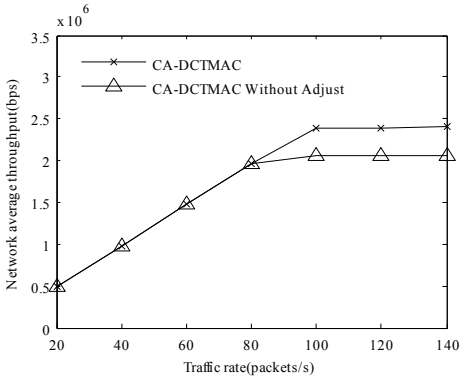

Fig.5. Comparison of the average throughput

In Fig.5, we compare the CA-DCTMAC protocol with the CA-DCTMAC protocol without the adaptive adjustment channel reservation duration mechanism. In contrast, CA-DCTMAC Without Adjust does not take into account the adaptive adjustment of reservation duration, and in order to allow as many nodes to transmit concurrently, the pre-set reservation duration is generally larger, when the number of nodes that can concurrently transmit data in the network is small, the extra reserved duration will incur additional time overhead, thus affecting the final saturated throughput. Therefore, the saturated throughput of the CA-DCTMAC protocol is better than that of the CA-DCTMAC Without Adjust protocol.

Comparison In The Case of Random Topology

In this section, we compare the CA-DCTMAC protocol with the Nasipuri DMAC in the random network topology. In a square area with the length of 500m, 20 nodes are randomly distributed, and three CBR traffic streams with different origins and terminations are randomly generated. We choose different seed values to simulate the average throughput in the static random topology environment. As shown in Fig.6，with different seed values, the average throughput of the CA-DCTMAC protocol is superior to that of the Nasipuri DMAC protocol in general.

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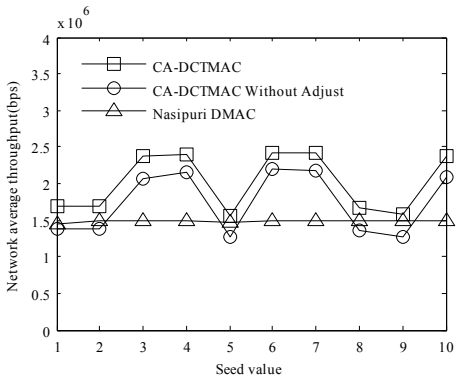

Fig.6. Comparison of three protocols' average throughput

Conclusions

In this paper, we propose a MAC protocol based on local synchronization for wireless ad hoc networks. The protocol allows the master and slave nodes in the local area of the network to transmit the data packets synchronously. We use the exponential smoothing model to dynamically adjust the length of the channel reservation gap to reduce the overhead of the control gap as much as possible. The protocol solves the deafness problem of the directional MAC protocol and alleviates the hidden terminal problem to a certain extent, and makes full use of the spatial multiplexing advantage of the directional antenna, which greatly improves the overall performance of the network.

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