IACT-MAC: A New Interference Avoidance and Parallel Transmission MAC Protocol

Ning Li, Ping Guo* and Juan Zhao
Logistical Engineering University, Chongqing, P.R. China

Abstract

Traditional CSMA-based (carrier sense multiple access based) MAC protocol IEEE 802.11 DCF forbids parallel transmission within two hops due to exposed terminal problems in wireless sensor networks. Thus, DCF has achieved interference avoidance at the sacrifice of low throughput. To tackle the problem, this paper presents a new MAC protocol called IACT-MAC. Power control strategy is also introduced to reduce interference. Simulation results show that the implementation of IACT-MAC can achieve high throughput and low latency based on interference avoidance and parallel transmission.

Key Words: Interference Avoidance, MAC, Parallel Transmission, Power Control, Wireless Sensor Networks

1. Introduction

At present, wireless sensor networks (WSNs) have attracted widespread attention due to its unique advantages of low cost, reduced power consumption, and self-organization. A large number of sensor nodes have been deployed in several applications such as battlefield surveillance, environmental monitoring, smart home and so on. Earlier researches on WSNs have largely focused on energy efficiency because of limited energy capacity. However, to provide multitask support and efficient delivery of explosive traffic, attention has been pulled back to throughput and delay [1].

Unlike wired network, collisions or interference may occur when multiple nodes access the channel simultaneously. If the receiver cannot analyze signal correctly due to interference from the neighbors’ transmission, the packet will be retransmitted or discarded. As a result, the network throughput becomes very low especially when some nodes suffer explosive traffic. Moreover, the low throughput also leads to poor energy efficiency as retransmission and long active time of nodes.

To tackle the problem of low throughput caused by interference, many efforts have been made. Unlike omnidirectional antenna, data are transmitted on a narrow beam by directional antenna. Thus the interference may be reduced in WSNs with directional antenna, while the transmission power is low. However, the hidden terminal problems still need to be solved. Many medium access control (MAC) protocols, such as DirC-MAC [2], DU-MAC [3], have been proposed to support directional antenna. Multi-channel is another approach to avoid interference and increase throughput in WSNs. As with directional antennae, special MAC protocols [4,5] should be designed to make use of multi-channel.

Although both directional antenna and multi-channel can avoid interference in WSNs, additional hardware should be required. Some power control protocols [6–8] have been proposed to increase throughput and reduce energy consumption. However, traditional MAC protocols cannot solve both hidden and exposed terminal problems caused by power control strategy. Carrier sense multiple access (CSMA) MAC protocols may solve the problems of hidden terminal by carrier sensing and distributed channel reservation, without resolution of the exposed terminal problems. Because of exposed terminal,
CSMA forbids any parallel transmission, leading to low throughput and high delay. Therefore, the key goal of designing efficient MAC protocols is to achieve parallel transmission, high throughput and low latency. Some CSMA-based MAC protocols [9–11] were designed to achieve parallel transmission by modified RTS/CTS (request to send/clear to send) and distributed power control. However, those protocols have some shortcomings to improve. Control frames, such as RTS/CTS, have not been made use of to detect channel and neighbor status. In addition, power control strategy failed to fully consider possible interference that may occur during data transmission in receiver terminal.

To address the above problems, IACT-MAC, a new interference avoidance and parallel transmission MAC protocol, is proposed. Modified RTS/CTS frame is needed to inform neighbors of nodes’ status. The new sender calculates transmission power and checks concurrent conditions based on neighbor status information. DTS/AD (Deny to send/Acknowledge Deny) frame will be exchanged to update neighbor status, if collision occurs or parallel transmission check fails. The implementation of IACT-MAC can achieve high throughput and low latency based on interference avoidance and parallel transmission.

2. Parallel Transmission

Traditional CSMA-based MAC protocols forbid any parallel transmission because of exposed terminal problems. Just taking nodes within transmission range into consideration, there is only one transmission link in CSMA-based WSNs. Furthermore, low throughput caused by non-parallel transmission fails to provide multitask support and efficient delivery of explosive traffic. However, receiver is less susceptible to interference from neighbor signal sources because of capture effects. Therefore, parallel transmission should be allowed on the premise that receiver can analyze signal correctly with interference from neighbor signal sources.

2.1 Interference Model

In the physical interference model, let $\psi$ be the subset of senders which transmit over a certain channel simultaneously. Then the transmission from a node $X_i$ is successfully received by a node $X_j$, if

$$\text{SINR} = \frac{P_i}{d_{ij}^\alpha} \geq \beta$$

where $P_i$ is transmission power chosen by node $X_i$, $d_{ij}$ is Euclidean distance between node $X_i$ and $X_j$, environmental noise power level is $N_0$, and the decay rate of signal power is $1/r^\alpha$ with distance $r$. Interference of $X_j$ from source $X_k$ is denoted as

$$I_k = \frac{P_k}{d_{kj}^\alpha}$$

Equation (1) describes a situation where a minimum signal-to-interference-plus-noise-ratio (SINR) of $\beta$ is necessary for successful transmission.

While power control strategy is adopted, transmission power may keep a low level if the receiver is less susceptible to interference, as implied in (1). On the contrary, less interference in receiving terminal will occur when other signal sources also have a low power level. Furthermore, interference will be reduced rapidly with the distance between the receiver and other signal source. To make it simple, only the interference caused by other signal source around receiver within maximum transmission range $d_{\text{max}}$ is considered. Minimum transmission power with the interference in receiving terminal can be denoted as

$$P_i = \beta d_{ij}^\alpha (N_0 + \sum_{k \in \psi} \frac{P_k}{d_{kj}^\alpha})$$

$\psi$ is the subset of senders, named neighbor signal sources, around node $X_j$ within $d_{\text{max}}$ range.

2.2 Parallel Transmission with Interference

MAC protocol supported, neighbor nodes can transmit simultaneously, provided that there is no destructive interference. Parallel transmission in WSNs may achieve efficient delivery with high throughput and low latency. Therefore, parallel transmission should be allowed on the premise that the receiver can analyze signal correctly with interference from neighbor sources.
If transmission between sender $X_1$ and receiver $X_2$ is ongoing, as illustrated in Figure 1, there are three types of parallel transmission shown as follow:

1. When node $X_3$, the neighbor of $X_2$, intends to build a new link with $X_4$ as a sender, parallel transmission is allowed only if $X_2$ can analyze signal correctly with interference from $X_3$.
2. When node $X_6$, the neighbor of $X_1$, intends to build a new link with $X_5$ as a receiver, parallel transmission is allowed only if $X_6$ can analyze signal correctly with interference from $X_1$.
3. When node $X_7$ and $X_2$ were not neighbors, and $X_8$ is less susceptible to interference, transmission link between node $X_3$ and $X_6$ is allowed.

### 3. Design and Implementation of IACT-MAC

Hidden terminal problems have been solved in traditional CSMA-based MAC protocols. However, exposed terminal problems still exist. To tackle it, Interference Avoidance and Parallel transmission MAC (IACT-MAC) protocol is proposed. In IACT-MAC, every node maintains a table that records neighbor status. Transmission power is calculated according to relay distance, and neighbor status table acquired by modified request to send (RTS) frame and clear to send (CTS) frame. Furthermore, another two control frames are introduced, including Deny to send (DTS) frame and Affirm Deny (AD) frame, to update neighbor status information, if parallel transmission is forbidden. All control frames are transmitted at maximum power due to hidden terminal problems.

To guarantee that every node can detect neighbors’ control frames and avoid their interference to data frames, time synchronous protocol should be adopted. Moreover, additional slots should be scheduled to transmit control frames. Except this approach, dual-channel can achieve the same goal. However, this paper focuses on modified CSMA and power control strategy. Thus, time schedule of frames or dual-channel is not introduced in the paper.

#### 3.1 Neighbor Status Table

Every node maintains a table, named NS table, which includes every neighbor’s ID, Allocation Vector NAV, transmission power $P_T$, interference level $I_{sum}$, neighbor distance $d_n$, and other parameters. Only a maximum NAV is recorded in traditional CSMA-based MAC protocols. However, an individual NAV for each neighbor is recorded in IACT-MAC. NAV and $P_T$ represent various node statuses, shown as follow.

1. Only if NAV = 0 and $P_T$ = 0, the status of the neighbor is idle.
2. Only if NAV > 0 and $P_T$ > 0, the status of the neighbor is sending.
3. Only if NAV > 0 and $P_T$ = 0, the status of the neighbor is receiving.

#### 3.2 Acquiring Neighbor Status Information

In order to acquire neighbor status information, RTS frame and CTS frame should be modified. Field $P_T$ is added to RTS to inform the neighbor of sender’s status and forecast transmission power $P_f$, equal to $P_T$ of last successful transmission in value. Neighbors of the sender except the receiver record $P_f$ in field $P_f$ after transmitting RTS. Interference of the receiver from every signal source is calculated by (2). Then field $I_{sum}$ is added to CTS to inform neighbors of receiver’s interference level. After exchanging RTS and CTS, every node records the transmission power of neighbor signal sources and the interference level of neighbor receivers.

#### 3.3 Power Control Strategy

To reduce interference and increase throughput, power control strategy should be adopted. If the packet is transmitted at the power calculated by (3), neighbors of the receiver cannot request a new transmission due to interference with receiver. Thus, parallel transmission is forbidden, if one neighbor of sender is undergoing recep-
tion. Equation (3) is modified and the regulation-coefficient \( \gamma (\gamma > 1) \) is brought in to achieve parallel transmission and maximize throughput. Transmission power can be denoted as:

\[
P_i = \gamma \beta d_j^n (N_0 + \sum_{k \neq j} \frac{P_k}{d_{kj}^n})
\]

(4)

3.4 Parallel Transmission Check

The purpose of parallel transmission check is to estimate whether the new transmission is allowed concurrently with ongoing transmissions. There are two principles shown as follow:

(1) If calculated transmission power is larger than the power threshold, the new transmission is forbidden.

(2) If one neighbor of the new sender is undergoing reception and the neighbor cannot analyze signal correctly due to interference from the sender, the transmission is forbidden.

3.5 Updating Neighbor Status Information

If parallel transmission is allowed, the packet at the top of the sender’s queue will be delivered to the receiver. Then, the receiver transmits an Acknowledge (ACK) frame to inform the sender of successful transmission.

Collision may occur during contention time. Thus, some nodes may not receive RTS in time. If collision is detected during exchanging RTS and CTS or parallel transmission check fails, DTS will be transmitted by the sender. After hearing DTS, all neighbors besides the receiver reset their corresponding NAV and \( I_{sum} \) to zero. After DTS and AD exchange, back-off time will be set and back-off mechanism begins to work.

4. Simulation and Results

In this section, we evaluate the performance of IACT-MAC and traditional CSMA-based MAC protocol IEEE 802.11 DCF. The main purpose of the performance evaluation is to demonstrate the advantage of parallel transmission at the MAC layer. We consider a multi-hop network with nodes randomly distributed in a circular area. Simulations were carried out in MATLAB to calculate the network throughput at sink node and the average packet transmission delay. The setup of the simulation parameters is described in Table 1.

To observe different network densities, the numbers of nodes are changed between 50 and 350. A larger number means a denser network. For every node except sink, packets were produced in a Poisson random way at a rate of 1 second per packet. Figures 2 and 3 show the throughput and delay for different number of nodes in IACT-MAC compared with DCF. In fact, traffic is under load and collision rarely happens in a sparse network due to a small packet sum. Thus, as the number of nodes becomes larger, throughput achieves a rapid increase and the delay maintains a low level for both protocols. However, collision and retransmission are increasingly heavier in a dense network because of overload, leading to a gradual decrease in throughput for DCF and an increase in delay for both protocols. Supported by parallel transmission, IACT-MAC is relatively better in terms of maximizing throughput and minimizing delay, especially in a dense network.

Table 1. Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time</td>
<td>200 s</td>
<td>Control frame length</td>
<td>4 slot</td>
</tr>
<tr>
<td>Radius of circular area</td>
<td>200 m</td>
<td>Data frame length</td>
<td>2000 slot</td>
</tr>
<tr>
<td>Transmission range</td>
<td>60 m</td>
<td>Minimum contention window</td>
<td>31</td>
</tr>
<tr>
<td>Maximum transmission power</td>
<td>75 dbm</td>
<td>Maximum contention window</td>
<td>1023</td>
</tr>
<tr>
<td>Channel data rate</td>
<td>2 Mbps</td>
<td>( N_0 )</td>
<td>( 1 \times 10^{-6} )</td>
</tr>
<tr>
<td>Slot time</td>
<td>20 us</td>
<td>( \alpha )</td>
<td>4</td>
</tr>
<tr>
<td>SIFS</td>
<td>0.5 slot</td>
<td>( \beta )</td>
<td>5 dB</td>
</tr>
<tr>
<td>DIFS</td>
<td>2.5 slot</td>
<td>( \gamma )</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Then, we changed the packet generation interval between 0.1 seconds and 1.9 seconds, while packets were produced in a Poisson random way for every node except sink. A low generation interval means a heavy traffic. Figures 4 and 5 shows the throughput and delay for different packet production rate in IACT-MAC compared with DCF. It can be seen from Figure 4 that the improved MAC protocol IACT-MAC’s throughput is obviously higher than that of DCF’s. Meanwhile, with the increase of packet generation interval, the throughput decreases quickly when the network is extremely sparse. However, the throughput increases in another extreme case, with 350 nodes in a network. The reason is that the traffic is under load and the collision rarely happens in a sparse network, resulting in a decreased throughput with the reduction of traffic; however, the collision and retransmission are increasingly heavier in a dense network because of the overload with the rise of traffic, leading to the increase of throughput as the packet generation interval grows.

From Figure 5, we can see that IACT-MAC maintains a lower delay than DCF in a dense network, while there is little difference in the performance of delay in an extreme sparse network. Furthermore, the delay is reduced with the increase of packet generation interval when the network is extremely dense. The phenomenon can be explained with the same reason as the change of throughput.

5. Conclusions

To avoid interference and achieve parallel transmission, IACT-MAC is proposed based on the traditional CSMA MAC protocol. RTS/CTS control frames are modified and DTS/AD frames are introduced to inform the neighbors of the nodes’ statuses. Power control strategy is adopted to allow more parallel transmission along with IACT-MAC. Simulation results show that IACT-MAC.
MAC have a higher throughput than DCF, while maintaining a low latency, especially in a dense network.

References


Manuscript Received: Dec. 2, 2014
Accepted: Apr. 23, 2015