A SINR-based Transmission Power Control for MAC Protocol in Wireless Ad hoc Networks

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***Abstract*—This paper proposes a power control MAC protocol that allows the nodes to vary transmission power. By using the minimum required transmission power, our proposed protocol can improve the spatial reuse and energy saving. The main idea is to adopt IEEE 802.11 Power Saving Mechanism (PSM) and the appropriate power control scheme for the wireless ad hoc networks. All control messages are transmitted at the maximum transmission power in the ATIM window, while data packets are sent at the minimum required transmission power in the data window. Based on the receiving power and the transmission power information of the control messages from the neighboring nodes, a node checks whether it can transmit simultaneously while it guarantees the interference level at its neighboring nodes. Simulation results show that the proposed protocol outperforms the IEEE 802.11 in terms of aggregate throughput, average delay and energy efficiency.**

***Index Terms*—Power Control, MAC protocol, Ad hoc networks.**

I. Introduction

Wireless nodes are usually battery-powered and thus are limited in power capacity. The IEEE 802.11 PSM is used to conserve energy for the ad hoc networks by allowing nodes to enter doze mode when there is no need for data exchange. Transmission power control schemes are also used to save energy. The appropriate power control can also improve the spatial reuse of wireless channel.

In the simple power control schemes [3],[8], RTS/CTS packets are sent at the maximum power while DATA/ACK packets are sent at the minimum required power. Although these simple power control schemes can save energy consumption, they suffer from a severe collision problem, namely POwer control INduced hidden Terminal (POINT) problem [5]. The receiver's interference range depends on the sender's transmission power. When the transmission power is small, the interference range becomes larger. A node is outside the interference range when the transmission power is maximum, but it is in the expanded interference range of the receiver when the transmission power becomes smaller. An Adaptive Range-based Power Control (ARPC) MAC protocol [7] is proposed to avoid POINT problem.

In [4], [2], the nodes are allowed to periodically increase the transmission power during data transmission in order to inform the nodes in the carrier sensing range of its transmission. These schemes cannot avoid the POINT problem and cannot improve the spatial reuse because the node periodically uses P_{max} during its transmission.

In this paper, we propose a SINR-based Transmission Power Control for MAC Protocol (STPC-MAC) which can avoid POINT problem, save the energy consumption and improve the spatial reuse. After exchanging transmission power during the ATIM window successfully, nodes can transmit data packets in the data window without any collision.

The rest of the paper is organized as follows. The background of IEEE 802.11 PSM is given in Section II. In Section III, our proposed protocol is described in detail. Section IV presents simulation results. Section V concludes this paper.

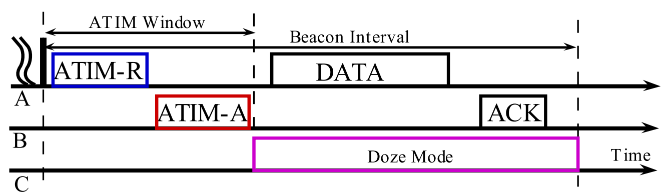

Fig. 1. The operation of IEEE 802.11 PSM.

II. The IEEE 802.11 PSM

In IEEE 802.11 DCF, Ad hoc Traffic Indication Message (ATIM) is used for power management. Fig. 1 illustrates the operations of the IEEE 802.11 PSM. Time is divided into beacon intervals, and there is a short interval called the ATIM window at the start of the beacon interval. All nodes have to be awake during the ATIM window. In the ATIM window, sender and receiver exchange ATIM-Request/ATIM-Acknowledgement. After the ATIM window, sender and receiver exchange DATA/ACK packets while other nodes which do not have packets to send or receive go to doze mode to save energy. In doze mode, a node consumes much less energy compared to idle mode, but it cannot send or receive packets.

III. The Proposed STPC-MAC protocol

First, we summarize our assumptions as follows.

- Each node is equipped with a single half-duplex transceiver.
- All nodes are synchronized, so that they begin their beacon intervals at the same time.

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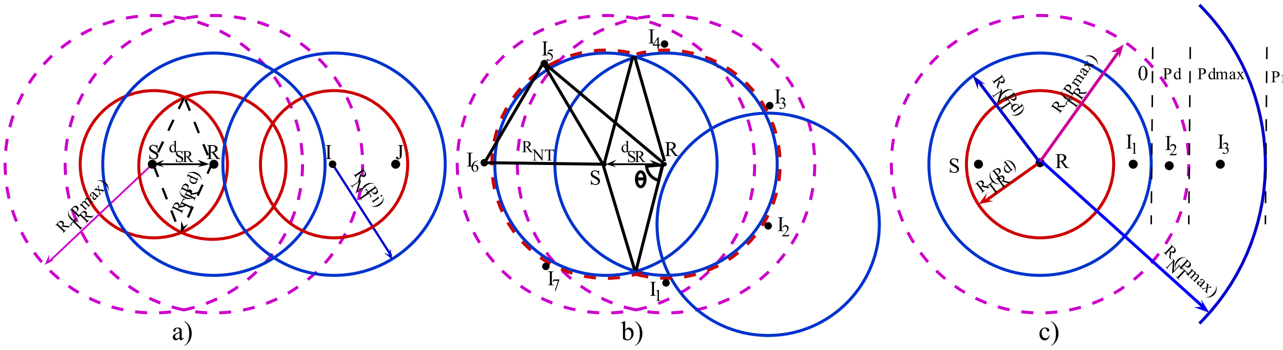

Fig. 2. The interference model.

- The transmission power consumption is proportional to the radio transmission power. The node consumes the power of 1.65 W when it transmits at the maximum radio power of 250 mW.

The transmission range, the carrier sensing range and the noise threshold range are defined as follows.

- Transmission Range (R_{TR}): the range within which a packet can be successfully received and correctly decoded. This range can be estimated based on the receiving power threshold $P_{RXthold}$ and the receiving SINR threshold $SINR_{thold}$.
- Carrier Sensing Range (R_{CS}): the range within which a node defines as the busy channel. This range depends on the carrier sensing threshold $P_{CSthold}$.
- For our proposed protocol, we define the Noise Threshold Range (R_{NT}) as the range within which node receives the interference level greater than the noise power threshold P_{Nthold}.

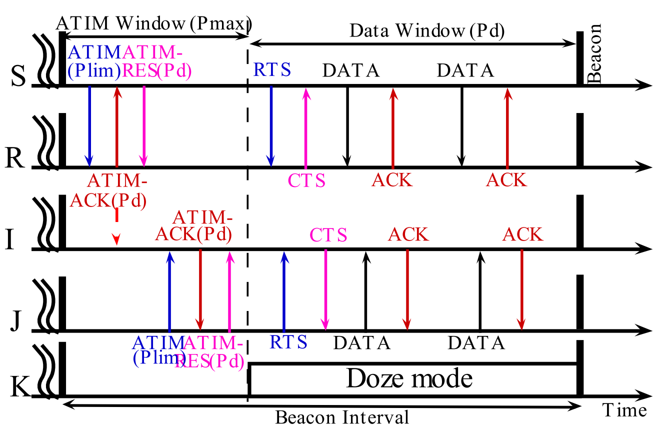

Fig. 3. The operation of STPC-MAC protocol.

The main idea is using the ATIM window to exchange ATIM messages with the transmission power information. Then, the nodes use the minimum required power to transmit data packets without interfering with their neighbors.

Without loss of generality, nodes S and R indicate the sender and receiver, respectively. Since node S has data for node R, nodes S and R use 3-way handshake to estimate the transmission power. The ATIM/ATIM-ACK/ATIM-RES messages are exchanged in the ATIM window to indicate which transmission power level P_d is used to transmit data packets in the data window. Then both nodes S and R will stay awake and exchange data packets for the entire beacon interval. If a node has no data packet in its buffer or does not receive any ATIM message, it goes into doze mode after the ATIM window to save energy.

A. The power control

Let P_t^S be the transmission power of node S, P_r^S be the receiving power from node S at node R. By using the two-ray ground reflection model [9], the receiving power P_r^S is calculated from the following formula

$$P_r^S(R) = P_t^S G_t G_r \frac{h_t^2 h_r^2}{d^\alpha L} = c\frac{P_t^S}{d^\alpha}, \qquad (1)$$

where

G_t, G_r	antenna gains of transmitter and receiver;
h_t, h_r	the heights of the transmit and receive antennas;
d	distance between transmitter and receiver;
α	path loss coefficient with range of 2-4;
L	other losses, assume L=1 here then c is constant.

And the Signal to Interference plus Noise Ratio (SINR) of the node R is given as

$$SINR(R) = \frac{Signal}{Interference} = \frac{P_r^S(R)}{\sigma_0^2 + \sum\limits_{i=1, i\neq S} P_r^i(R)}, \qquad (2)$$

where $P_r^i(R)$ is the interference caused by the simultaneous transmission of node R, and the thermal noise σ_0 is neglected.

The packet is successfully received and correctly decoded when the two following conditions are satisfied

1) $P_r^S(R) \geq P_{RXthold}$: the receiving signal strength should be greater than or equal to the signal strength threshold.
2) $SINR(R) \geq SINR_{thold}$: the receiving SINR should be greater than or equal to the SINR threshold.

Let's consider the Fig. 2a. We consider the interfering nodes at the first tier to find out the maximum interference that a certain node receives in the worst case. Since other interfering nodes are far away and contribute a smaller interference than the first tier interfering nodes, we ignore them in SINR calculation. The circumference C of the noise threshold range of nodes S and R can be calculated easily

$$C = 4(\pi \quad \theta)R_{NT}, \tag{3}$$

where $\theta = \cos^{-1}(\frac{d_{SR}}{2R_{NT}}) \in (\frac{\pi}{3}, \frac{\pi}{2})$ and R_{NT} is the noise threshold range.

The minimum arc length between 2 interfering nodes is $\pi R_{NT}/3$. Then the maximum number of interfering nodes No_Int is given by

$$No\_Int = \frac{C}{\pi R_{NT}/3} = \frac{12(\pi \quad \theta)}{\pi}. \tag{4}$$

We can see that there is only $No\_Int = 7$ which satisfies the Eq. 4. Fig. 2b shows the worst case of 7 interfering nodes and the distance between nodes S and R is $d_{SR} = \frac{-1+\sqrt{4\sqrt{3}-3}}{2} R_{NT} = 0.491 R_{NT}$. Nodes I_1, I_2, I_3 and I_4 contribute P_{Nthold} to node R. By calculating the distance from node R to the remaining interfering nodes, we can determine the total interference in this case by

$$Total\_Int = 4.869 P_{Nthold}. \tag{5}$$

But when the distance between nodes S node R is less than $0.491 R_{NT}$, the maximum number of interfering nodes is 6. In the worst case, when node S is very close to node R, the maximum total interference is given

$$Total\_Int = 6 P_{Nthold}. \tag{6}$$

And the SINR in the worst case is

$$SINR_{worstcase} = \frac{P_r^S(R)}{6.P_{Nthold}}. \tag{7}$$

Now, we can find the value of P_{Nthold} by using the Eq. 7 and two above conditions

$$SINR(R) \geq \frac{P_r^S(R)}{6.P_{Nthold}} \geq \frac{P_{RXthold}}{6.P_{Nthold}} \geq SINR_{thold}. \tag{8}$$

Eq. 8 implies that

$$P_{Nthold} \leq \frac{P_{RXthold}}{6.SINR_{thold}}. \tag{9}$$

Node R receives the ATIM message from node S with the receiving power $P_r^{P_{\max}}$. Then, node R has to estimate the minimum required transmission power P_d that node S has to use to transmit data packets by

$$P_d = \frac{P_{\max} P_{RXthold}}{P_r^{P_{\max}}}. \tag{10}$$

Nodes S and R exchange control messages with the maximum power P_{max}. The transmission range $R_{TR}(P_{max})$ has to satisfy the following equation.

$$\frac{c.P_{max}}{R_{TR}^{\alpha}(P_{max})} \geq P_{RXthold}. \tag{11}$$

Now, we consider the interfering node I which is within the transmission range $R_{TR}(P_{max})$ of the control messages. The maximum transmission power that node I can use is P_{dmax}. The P_{dmax} can be obtained when the distance between node I and node R is $R_{TR}(P_{max})$. Node I keeps the interference level at node R less than the threshold P_{Nthold}.

$$\frac{c.P_{dmax}}{R_{TR}^{\alpha}(P_{max})} \leq P_{Nthold}. \tag{12}$$

The maximum transmission power used to transmit data packets can be extracted from Eq. 9, 11 and 12.

$$P_{dmax} \leq \frac{P_{Nthold}.P_{max}}{P_{RXthold}} \leq \frac{P_{max}}{6.SINR_{thold}}. \tag{13}$$

It means that node I_2 in Fig. 2c can transmit packets at the maximum power P_{dmax} which does not contribute interference greater than P_{Nthold} to node R.

B. The operation of STPC-MAC protocol

Each node maintains a variable power limit P_{lim}. This value limits the maximum transmission power of each node in the current beacon. P_{lim} is set to P_{max} at the beginning of each beacon, and it is updated by Algorithm 1 whenever the node overhears the ATIM messages. Fig. 2c shows 4 regions which are used to update the P_{lim}.

The operation of STPC-MAC protocol is illustrated in Fig. 3. Assume that node S has data packets for node R, we now describe the procedure used in STPC-MAC protocol as the following:

1) Node S sends ATIM including its P_{lim} to node R at the maximum power P_{max}.
2) Based on the receiving power of ATIM, node R estimates the required transmission power P_d for DATA transmission. If P_d is less than P_{lim} of both nodes S and R, node R sends ATIM-ACK(P_d) to node S. Otherwise, node R sends ATIM-ACK($P_d = 0$) to indicate that they cannot exchange data in this beacon.
3) If node S receives ATIM-ACK(P_d), it confirms by sending ATIM-RES(P_d); otherwise, it does not send ATIM-RES to node R.
4) Based on the overheard ATIM messages or the sensing power, the neighboring nodes update their P_{lim} by Algorithm 1.
5) After the ATIM window, both sender and receiver exchange RTS/CTS followed by multiple DATA/ACK packets while the other nodes go to doze mode to save energy.

IV. Performance Evaluation

In this section, we compare the IEEE 802.11, PCM [4], ARPC [7] and our proposed STPC-MAC protocol in terms of the aggregate throughput, average delay and energy efficiency.

A. Simulation Model

The network consists of 36 nodes placed randomly in a 500m x 500m area. Each node selects the neighboring node in its transmission range to form a pair of nodes. We simulated 10 different topologies (scenarios). Each node generates and transmits constant-bit-rate (CBR) traffic to its destination. Both sender and receiver have 1.5 m height antennas with the gain

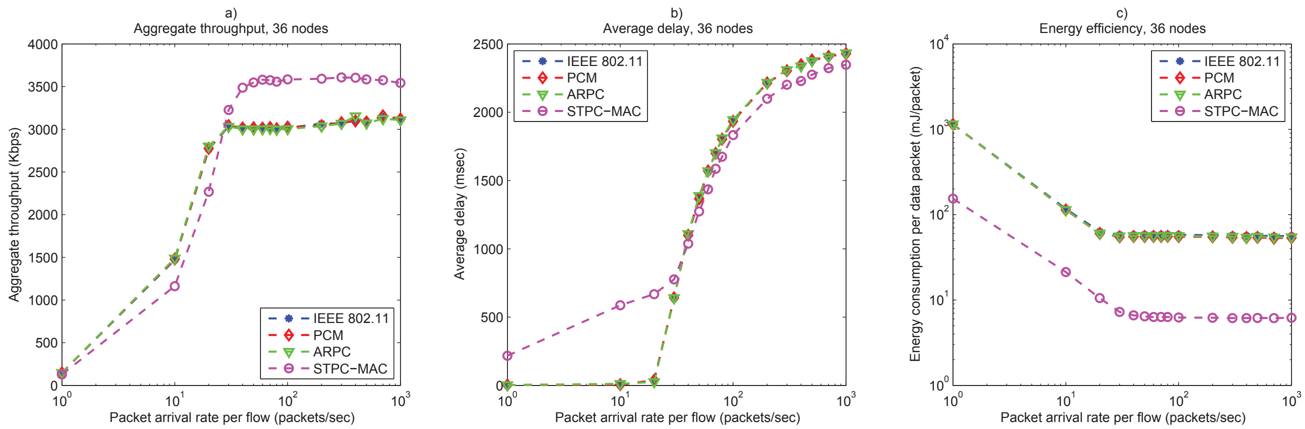

Fig. 4. Performance comparisons of different protocols.

Algorithm 1 Algorithm to update P_{lim} in each beacon

$P_{lim} \leftarrow P_{max}$ /*At the start of each beacon*/
repeat
  if Receives ATIM-ACK(P_d)/ATIM-RES(P_d) correctly **then**
    if $P_r \geq \frac{P_{max}.P_{Nthold}}{P_d}$ **then**
      $P_{lim} \leftarrow 0$
    else
      $P_{lim} \leftarrow P_d$
    end if
  else
    if The sensing power $P_{sense} \geq P_{Nthold}$ **then**
      $P_{lim} \leftarrow P_{dmax}$
    else
      $P_{lim} \leftarrow P_{max}$
    end if
  end if
until ATIM window ends **or** $P_{lim} = 0$

of 1 dBi. The other simulation parameters in our simulations are listed in Table I. Each simulation was performed for 5 seconds and the simulation results are the average of 30 runs.

B. Simulation Result

The performance comparisons of different protocols as the packet arrival rate increases are shown in Fig. 4. The aggregate throughput of different protocols is shown in Fig. 4a. When the network load is low, the aggregate throughput of STPC-MAC is little lower than that of the others. This is due to the overhead of the ATIM window. In STPC-MAC, 5% of channel bandwidth is used for the ATIM window. Another reason is that when nodes exchange ATIM messages successfully, they can use the channel during the entire of data window regardless to the number of data packets in their buffers. When the packet arrival rate is low, they cannot fully utilize the channel during data window. Since some nodes within the carrier sensing range of P_{max} can transmit simultaneously, the STPC-MAC has more concurrent transmissions than the others. The power control algorithm in PCM and ARPC do not improve the spatial reuse of the wireless network. The aggregate throughput of STPC-MAC is higher as the network load grows to near saturation.

In Fig. 4b, the average delay increases as the network load increases. Since STPC-MAC has the overhead of the ATIM window and nodes cannot fully utilize the channel when the network load is low, the average delay of STPC-MAC is higher than that of other protocols. When the packet arrival rate is high, STPC-MAC has lower delay because it supports more concurrent transmissions than the others.

The energy efficiency is one of the benefits of the proposed STPC-MAC protocol. We compare the total energy consumption over the packets transmitted successfully in the network of the different protocols in Fig. 4c. Although the transmitting nodes adjust their transmission power in PCM and ARPC protocols, the idle nodes stay awake and consume the idle power of 1.15W. In STPC-MAC, the PSM is adopted by using the ATIM window and the data window. It allows nodes to enter doze mode with a doze power consumption of 0.045W when there is no need for data exchange. The doze power consumption is much smaller than the idle power consumption. That's why the total energy consumption of STPC-MAC is

TABLE I
SIMULATION'S PARAMETERS

Parameters	Value
Simulation time	5000 ms
Physical area	500 m x 500 m
Number of nodes	36 nodes
Beacon Interval / ATIM window	100 ms / 5 ms
SIFS / DIFS / Slot time	16 μs / 34 μs / 9 μs
Basic rate / Data rate	1 Mbps / 2 Mbps
Data packet size	512 bytes
Retry Limit	4
Path loss coefficient (α)	4
Maximum radio power	250 mW
Receiving power threshold ($P_{RXthold}$)	-82 dBm
Noise power threshold (P_{Nthold})	-95.78 dBm
SINR threshold ($SINR_{thold}$)	6 dB
Transmit/Receive power consumption	1.65 W / 1.4 W
Idle / Doze power consumption	1.15 W / 0.045 W

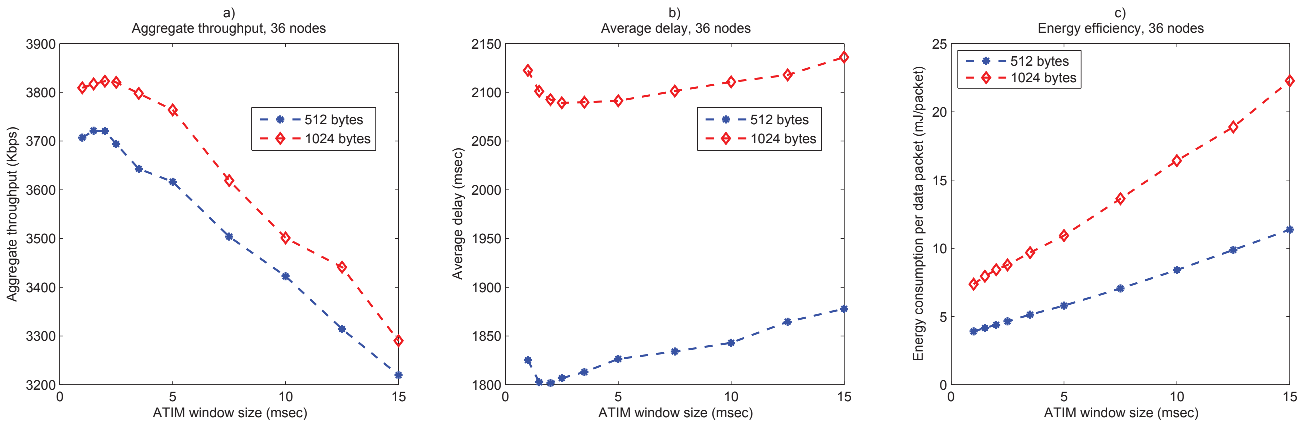

Fig. 5. The impact of the ATIM window on the performance metrics.

less than other protocols. Having the higher throughput and less energy consumption, the STPC-MAC protocol has better energy consumption per data packet than the others.

Fig. 5 shows the impact of the ATIM window size on the performance of STPC-MAC protocol. In this simulation, we fix the network size of 36 nodes, the packet arrival rate of 100 packets/second while varying the ATIM window size for 512 and 1024 bytes of packet size. When the ATIM window is small, there is not enough time for all nodes to exchange ATIM messages. So the spatial reuse of wireless channel cannot be fully utilized. On other hands, if the ATIM window size is too large, node cannot use up the ATIM window. Much of time the channel will be left as idle because data packets are not allowed to be transmitted in this interval. As we see in Fig. 5a, an ATIM window of around 1.5-2.5ms is shown to be the best for aggregate throughput and average delay in this network. During the data window of STPC-MAC, nodes can transmit multiple DATA and ACK packets. Since the ACK is sent for each successful transmitted DATA packet, the throughput of 1024-byte packet size is higher than that of 512-byte packet size. But the average delay of 1024-byte packet size is also higher than 512-byte packet. In the case of longer data packet size, the other packets in the buffer have to wait longer before being transmitted. The energy consumption depends mainly on the ATIM window size as shown in Fig. 5c. During the ATIM window, although nodes do not have data to exchange, they have to stay awake and consume the idle power of 1.15W compared to doze power of 0.045W if they go to doze mode earlier. Obviously, the ATIM window size affects the performance of the network, therefore, it needs to be adjusted dynamically.

V. Conclusions

We have proposed a new power control scheme for ad hoc networks, named STPC-MAC, that improve the spatial reuse of wireless channels and the energy efficiency for the wireless nodes. Although the nodes are within the carrier sensing range of another, they may transmit simultaneously while they guarantee the interference below the threshold at the neighboring node. Therefore, the STPC-MAC protocol has more concurrent transmissions than other protocols. Simulation results show that the STPC-MAC protocol has better performance compared to the others.

Since the STPC-MAC uses the ATIM window to exchange the transmission power information, we can apply this power control algorithm for the multi-channel MAC protocol to improve the network performance. We are going to implement the multi-channel MAC protocol with power control as the future work.

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