A SINR-Based MAC Protocol for Wireless Ad Hoc Networks

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***Abstract*—In this paper, we propose a power control MAC protocol that improves the spatial reuse of wireless channels and the energy efficiency for the wireless nodes. The main idea is to adopt IEEE 802.11 [1] Power Saving Mechanism (PSM) with the appropriate power control scheme for the wireless ad hoc networks. All control messages containing the transmission power information are transmitted at the maximum transmission power in the Announcement Traffic Indication Message (ATIM) window while the data packets are sent at the minimum required transmission power during the data window. Based on the sensing power or the transmission power information of the control messages, a neighbor node checks whether it can transmit simultaneously. Simulation results show the advantages of the proposed protocol in terms of the aggregate throughput, average delay, energy efficiency and fairness index.**

***Index Terms*—SINR, power control, MAC protocol, spatial reuse, ad hoc networks.**

I. INTRODUCTION

IN an ad hoc network, wireless nodes are usually powered by battery and thus are limited in power capacity. The IEEE 802.11 PSM is used to conserve energy by allowing nodes to enter doze mode when there is no need for data exchange. Another way is to use power control schemes which allow wireless nodes to vary power level to transmit packets. In addition to providing energy conservation, the power control can improve the spatial reuse of wireless channel.

Simple power control schemes are proposed in [2], [3]. In these schemes, RTS/CTS are sent at the maximum power while DATA/ACK are sent at the minimum required power. Although these simple schemes can reduce energy consumption, they suffer from a severe collision problem, namely POwer control INduced hidden Terminal (POINT) problem [4]. In [5], an Adaptive Range-based Power Control (ARPC) MAC protocol is proposed to avoid POINT problem.

Other power control schemes allow a node to periodically increase the transmission power during the DATA transmission in order to inform the nodes in carrier sensing range of its transmission [6], [7]. These schemes can save the energy but they cannot improve the spatial reuse because the node periodically uses the maximum power P_{max} during its transmission. They also cannot avoid the POINT problem.

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In [8] and [9], they propose optimization algorithms for the joint rate and power control with and without outage constraint for the wireless network. An optimal SINR-based random access scheme is proposed in [10].

In this paper, a Signal to Interference plus Noise Ratio (SINR) based Transmission Power Control for MAC Protocol (STPC-MAC) is proposed. With guaranteed receiving SINR at the receiver, this scheme not only can save the energy but also can avoid the POINT problem and improve the spatial reuse.

II. THE PROPOSED STPC-MAC PROTOCOL

In our proposed protocol, each node has a single half-duplex transceiver. We assume that all nodes are time-synchronized. Besides the Transmission Range (R_{TR}), 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}. The first tier interfering nodes of node R are nodes which are closest to node R and on the edge of Noise threshold range of node R. Since other interfering nodes are far away and contribute a smaller interference than the first tier interfering nodes, we ignore them in our SINR calculation.

A. The power control

Without loss of generality, nodes S and R indicate the sender and receiver, respectively. 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 [12], the receiving power P_r^S is calculated from the following formula

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

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 SINR of the node R is given as

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

where $P_r^i(R)$ is the interference caused by the simultaneous transmission of node R, and the thermal noise σ_0^2 is neglected.

The packet is successfully received if it is correctly decoded. It is correctly decodable with higher probability than a threshold when

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

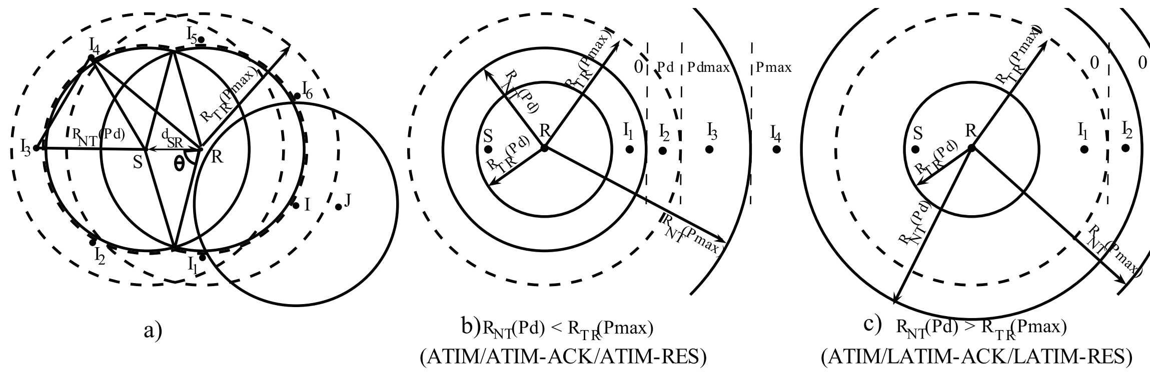

Fig. 1. The interference model.

2) $SINR(R) \geq SINR_{thold}$: the receiving SINR should be greater than or equal to the SINR threshold.

Let's consider the Fig. 1(a). We have to find out how many interfering nodes at the first tier affect the transmission between nodes S and R for the worst case. And the maximum interference level is determined. The circumference C of the noise threshold range of nodes S and R can be calculated as

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

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

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

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

Fig. 1(a) shows the only worst case of 7 interfering nodes that satisfies the Eq. 4 where the distance between nodes S and R is $d_{SR} = \frac{-1+\sqrt{4\sqrt{3}-3}}{2}R_{NT} = 0.491R_{NT}$. Nodes I, I_1, I_5 and I_6 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 as

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

But when the distance between node S and node R is less than $0.491R_{NT}$, the maximum number of interfering nodes is then 6. And if node S is very close to node R ($\theta = \frac{\pi}{2}$), the maximum total interference is now given as

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

Another approach can also give the maximum total interference by using the interference model in [11].

Next, we find the value of P_{Nthold} by using the total interference in Eq. 6 and two above conditions

$$SINR(R) \geq \frac{P_r^S(R)}{6 \cdot P_{Nthold}} \geq \frac{P_{RXthold}}{6 \cdot P_{Nthold}} \geq SINR_{thold}. \tag{7}$$

Therefore, we set

$$P_{Nthold} = \frac{P_{RXthold}}{6 \cdot SINR_{thold}} \tag{8}$$

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

$$P_d = \frac{P_{\max} \cdot P_{RXthold}}{P_r^{P_{\max}}}. \tag{9}$$

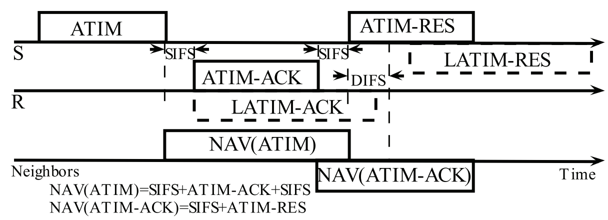

Fig. 2. Timing of ATIM messages exchange.

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

$$c\frac{P_{max}}{R_{TR}^{\alpha}(P_{max})} = P_{RXthold}. \tag{10}$$

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

$$c\frac{P_{dmax}}{R_{TR}^{\alpha}(P_{max})} = P_{Nthold}. \tag{11}$$

The maximum transmission power used to transmit data packets should satisfy Eqs. 8, 10 and 11

$$P_{dmax} = \frac{P_{Nthold} \cdot P_{max}}{P_{RXthold}} = \frac{P_{max}}{6 \cdot SINR_{thold}}. \tag{12}$$

It implies that when a node overhears the ATIM messages (ATIM/ATIM-ACK/ATIM-RES) and if it wants to exchange data packets, it can transmit the DATA/ACK packets at the maximum transmission power P_{dmax} limited by Eq. 12.

Figs. 1(b) and (c) illustrate the regions of the neighboring node I. We use the ATIM-Acknowledgement (ACK)/ATIM-Reservation (RES) for the case of $R_{NT}(P_d) < R_{TR}(P_{max})$ and the longer ATIM-ACK (LATIM-ACK)/LATIM-RES for another case. Fig. 2 shows the timing of ATIM messages exchange. Since node S may not send ATIM-RES,

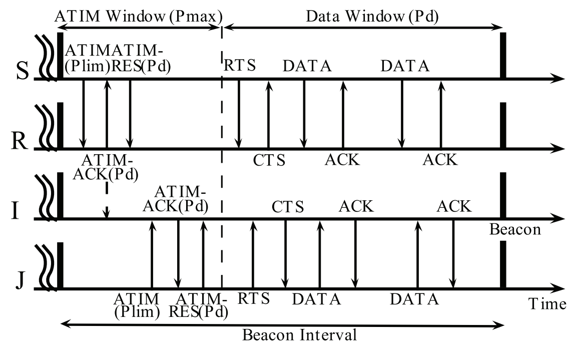

Fig. 3. The operation of STPC-MAC protocol.

the neighbor nodes set NAV(ATIM) until node S begins receiving ATIM-RES. Nodes R and S use LATIM-ACK/LATIM-RES to warn the nodes which are in the range $(R_{TR}(P_{max}), R_{NT}(P_{max}))$ with the estimated transmission power $P_d > (P_{max}.P_{Nthold})/P_{RXthold}$. The condition for the length of LATIM-ACK/LATIM-RES can be described as

$$T_{LATIM-ACK} < T_{ATIM-ACK} + SIFS + DIFS. \quad (13)$$

B. The operation of STPC-MAC protocol

Each node maintains a variable power limit P_{lim} which is updated by Algorithm 1. This value limits the maximum transmission power of each node in the current beacon.

All nodes have to listen to the channel during the ATIM window. Assume that node S has data packets for node R. We describe the procedure used in STPC-MAC protocol in details

1) Node S sends ATIM including its P_{lim} to node R at the maximum power P_{max}.
2) Based on the receiving power $P_r^{P_{\max}}$ of ATIM, node R estimates the required transmission power P_d for DATA transmission (Eq. 9). If P_d is less than P_{lim} of both nodes S and R, node R estimates the $R_{NT}(P_d)$ and sends ATIM-ACK(P_d) or LATIM-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) Upon receiving ATIM-ACK(P_d) or LATIM-ACK(P_d), node S confirms by sending ATIM-RES(P_d) or LATIM-RES(P_d); otherwise, it does not send any ATIM-RES.
4) The neighbor nodes update their P_{lim} using Algorithm 1 based on the receiving power P_r of the overheard ATIM messages or the sensing power P_{sense}.
5) After the ATIM window, both sender and receiver exchange RTS/CTS followed by multiple DATA/ACK packets while the others go to doze mode to save energy.

The operation of STPC-MAC protocol is illustrated in Fig. 3. After nodes S and R exchange ATIM messages successfully, the neighbor nodes I and J now start exchanging their ATIM messages. If they also exchange the ATIM messages successfully, they can then transmit simultaneously with nodes S and R during the data window.

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

```
P_lim ← P_max /*At the start of each beacon*/
repeat
  if Receives (L)ATIM-ACK/(L)ATIM-RES(P_d) correctly then
    if P_r ≥ (P_max.P_Nthold)/P_d then
      P_lim ← 0 /*Node ∈ (0, R_NT(P_d))*/
    else
      P_lim ← P_d /*Node ∈ (R_NT(P_d), R_TR(P_max))*/
    end if
  else
    if P_sense < P_Nthold then
      P_lim ← P_max /*Node ∈ (R_NT(P_max), ∞)*/
    else if P_sense ≥ P_Nthold for duration > T_ATIM-ACK then
      P_lim ← 0 /*R_NT(P_d) > R_TR(P_max)*/
    else
      P_lim ← P_dmax /*R_NT(P_d) < R_TR(P_max)*/
    end if
  end if
until ATIM window ends P_lim = 0
```

TABLE I
SIMULATION'S PARAMETERS

Parameters	Value
Beacon Interval / ATIM window	100 ms / 5 ms
SIFS / DIFS / Slot time	16 μs / 34 μs / 9 μs
ATIM / ATIM-ACK / ATIM-RES	28 bytes / 16 bytes / 16 bytes
LATIM-ACK / LATIM-RES	20 bytes / 20 bytes
Basic rate / Data rate	1 Mbps / 2 Mbps
Data packet size	512 bytes
Path loss coefficient (α)	4
Maximum radio power	250 mW
$P_{RXthold}$ / P_{Nthold} / $SINR_{thold}$	-82 dBm / -95.78 dBm / 6 dB
Transmit/Receive power consumption	1.65 W / 1.4 W
Idle / Doze power consumption	1.15 W / 0.045 W

III. PERFORMANCE EVALUATION

In this section, we evaluate the TCP performance of our proposed STPC-MAC protocol compared with IEEE 802.11 [1], PCM [6], ARPC [5] in terms of the aggregate throughput, the average delay, the energy efficiency defined as the total successful received packets over the total energy consumption and the Jain's fairness index [13].

A. Simulation Model

The network consists of 36 nodes placed randomly in a 500m x 500m area. Each node generates and transmits constant-bit-rate traffic to its destination which is in its transmission range. Both transmitter and receiver have 1.5 m height antennas with the gain of 1 dBi. The other simulation parameters are listed in Table I. The carrier sense threshold $P_{CSthold}$ is the same as the noise power threshold P_{Nthold}. We simulated 20 different topologies (scenarios).

B. Simulation Result

The aggregate throughput, packet delivery ratio and packet loss of different protocols are shown in Figs. 4(a), (b) and (c), respectively. The power control algorithm in the PCM and ARPC is to save energy while keeping the throughput not decrease, not to improve the spatial reuse of the wireless

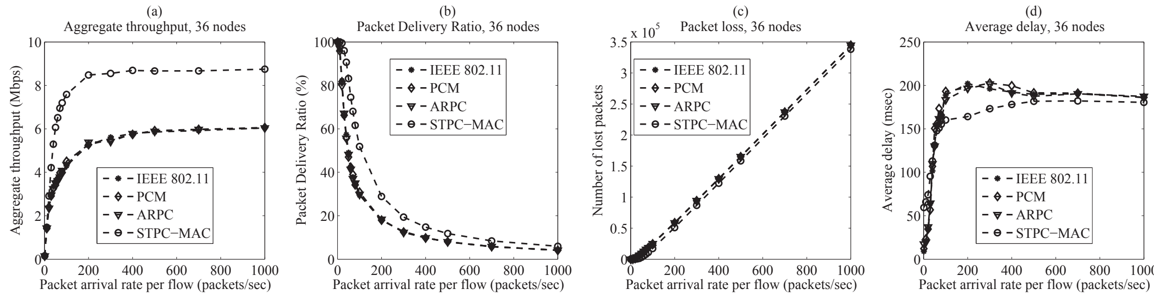

Fig. 4. Performance comparisons of different protocols.

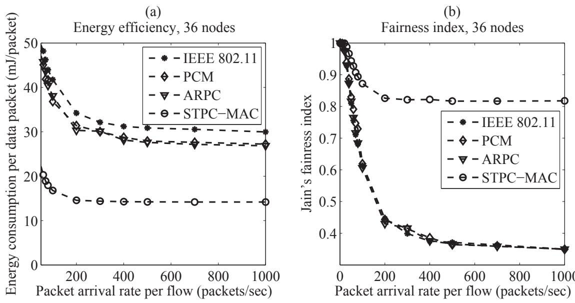

Fig. 5. Energy efficiency and fairness index of different protocols.

network. The STPC-MAC has 5% overhead for the ATIM window where only the ATIM/ATIM-ACK/ATIM-RES transmissions are allowed, but it reduces the overhead of the RTS/CTS during the data window. Besides that, when nodes exchange the ATIM messages successfully, they can use the channel for the entire data window regardless of the number of data packets in their buffers. 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 aggregate throughput of the STPC-MAC is higher as the network load grows to near saturation.

The packet delay includes the queue delay time at the sender, the transmission delay and the propagation time. The average delay is the ratio of the total packet delay and the number of successful packets. The average delay increases as the network load increases as shown in Fig. 4(d). Since the 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 the STPC-MAC is little bit higher than that of other protocols. However, when the packet arrival rate is high, the 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 as shown in Fig. 5(a). Although the transmitting nodes adjust their transmission power in the 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 when there is no need for data exchange with a much smaller doze power consumption of 0.045W than the idle power consumption. Therefore, the total energy consumption of the STPC-MAC is less than other protocols. Having the higher throughput and less energy consumption, the STPC-MAC protocol has better energy efficiency than the others.

By using beacon interval with the ATIM window and the data window, the STPC-MAC avoids the long-term starvation problem. The spatial reuse improvement also helps increase fairness index of the STPC-MAC. Fig. 4(b) shows that the STPC-MAC has a higher fairness index compared to others.

IV. Conclusions

In this paper, we have presented a new power control MAC protocol for ad hoc networks, named STPC-MAC, which improves the spatial reuse of wireless channels and the energy efficiency for the wireless nodes. Since the nodes which are within the carrier sensing range of another node can transmit simultaneously while they guarantee the interference below the threshold at the neighboring node, the STPC-MAC protocol has more concurrent transmissions than others. Simulation results prove that the STPC-MAC protocol has a better performance compared to other protocols.

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