An Enhanced Transmission Power Controlled MAC Protocol for Ad Hoc Networks

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Abstract—In mobile ad hoc networks (MANETs), every node overhears every data transmission occurring in its vicinity and thus consumes energy unnecessarily. Although lots of research has been done on energy efficiency remains it is an open problem. However, transmission power control (TPC) has been extensively used not only to save energy, but also to improve the network throughput. In this paper, we propose an enhanced transmission power controlled protocol, ETPMAC, which can improve the network throughput significantly using a single channel and a single transceiver. ETPMAC can enable several concurrent transmissions without interfering with each other by controlling the transmission power. Moreover, it does not introduce any additional control overhead. We show by simulation that ETPMAC can improve the network throughput by up to 71% compared to IEEE 802.11 in a random topology.

Key words –Component; Mobile ad hoc networks; MAC protocols; transmission power control

I. INTRODUCTION

A Mobile Ad hoc Networks (MANETs) is a networks where mobile nodes communicate with each other via wireless medium directly or indirectly with the help of other nodes. In MANETs, all the nodes share the wireless channel, and hence a medium access control (MAC) protocol is needed to coordinate their transmission and reduce the collision. IEEE 802.11(DCF) with optional use of RTS/CTS is now widely used as MAC protocol in MANETs.

However, several drawback of IEEE 802.11 have been identified in the past several years. IEEE 802.11 MAC uses the same transmission power regardless of the distance between the transmitter and receiver. This gives inefficient use of energy, since a successful communication between the nodes with small distance is possible with less power. According to IEEE 802.11 MAC, when node transmitting, the other nodes in its vicinity should keep silence to avoid interference. Therefore, the spatial reuse of network is very low. Many protocols are proposed to save the power consumption, like those in [3],[4],[5]. In these protocols, nodes transmit RTS/CTS with maximum power, and transmit DATA/ACK with minimum power needed for successful transmission. By doing this transmission power can be saved. Nevertheless, the spatial reuse is very low, and many collisions happen between control and data packets due to different carrier sensing range. Thus, the network throughput cannot be improved. In this paper, we propose a new enhanced transmission power controlled MAC protocol (ETPMAC), which simultaneously improve the network throughput and yield energy saving. The rest of the paper is organized as follows. Section II details of related works. In section III, we briefly introduce the operation of IEEE 802.11 DCF protocol and the power propagations model. Section IV details of our proposed ETPMAC protocol. Some simulation results are shown in Section V. We finally conclude this paper in section VI.

II. RELATED WORK

In some papers focusing throughput enhancement [6] [7] propose two channels and two transceivers, to improve the network throughput. However, the use of multichannel and multi-transceiver introduces additional hardware cost and implementation complexity. Recently [1] [2] propose DEMAC to improve the network throughput. However, it could achieve only limited improvement and need of power adjustment for each pocket. It works as the IEEE 802.11 MAC, achieve only limited improvement. Muquattash and Krunz [8] also propose in a throughput oriented MAC protocol utilizing single channel and single transceiver called POWMAC, different from the above protocols. In this, when one node overhears others nodes' transmission, it is still allowed to carry out its own DATA transmission as long as it does not interfere with ongoing ones. Thus, according to POWMAC, several transmissions can happen concurrently.

However, POWMAC cannot gain dramatic improvement on network throughput due to the following two reasons. First, several concurrent data transmissions may not take place if they are not synchronized due to existence of propagation delay. Second, it does not address mobility issue and hidden terminal problem still exists. In this paper, we propose an enhanced transmission power controlled MAC protocol, called ETPMAC, to increase the network throughput using single channel and a single transceiver. However, it does not incur any additional signaling overhead, i.e., only one RTS/CTS exchange for N (N>1) concurrent transmissions.

III. PRELIMINARIES

A. *IEEE 802.11 MAC*

The fundamental access method of the IEEE 802.11 MAC is a DCF (Distributed Coordination Function) known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) with an option of RTS/CTS. The four-way handshake procedure (RTS/CTS/DATA/ACK), which is used to deal with the hidden terminal problem, is as follows. Before a node begins to transmit, it should first sense the channel to determine whether there is any ongoing transmission. If the channel is busy, the node shall defer until the channel is sensed idle for a period of DIFS. Then the node randomly chooses a backoff period according to the contention window and starts a backoff timer to backoff. The backoff timer decreases by 1 after the channel is idle for the duration of a slot. If the channel is sensed busy during any slot in the backoff interval, the backoff timer will be suspended. It can be resumed only after the channel is idle for a period of DIFS again. After the backoff timer reduces to 0, the sender transmits a RTS omnidirectionally. After correctly receiving the RTS, the receiver responses with a CTS after a period of SIFS. Similarly, after correctly receiving the CTS, the sender begins to transmit the data a period of SIFS later. This transmission ends after the receiver correctly receives the data and responses with an ACK. All four kinds of frames contain an estimated duration of the rest time of the transmission. Other nodes that receive these frames update their NAVs (Network Allocation Vector) with the duration. Every NAV decreases by 1 after a time slot. Those nodes are only allowed to transmit after they sense the channel idle for a period of DIFS after their NAVs expire.

B. *Power Propagation Models*

The power propagation models are used to predict the received signal strength. A general model [10] is given as follows:

$$\mathrm{P_r(d)} = \mathrm{P_t h}\,(\mathrm{G_t}, \mathrm{G_r}, \mathrm{h_t}, \mathrm{h_r}, \mathrm{L}, \lambda)\,\frac{1}{\mathrm{d}^{\gamma}} \qquad (1)$$

where Pt and Pr are the transmitted power and the received power, respectively, Gt and Gr are the gain factors for the transmitter antenna and the receiver antenna, respectively, ht and hr are the antenna heights of the transmitter and the receiver, respectively, d is the distance between transmitter and receiver, L is the system loss factor not related to propagation $(\mathrm{L} \geq 1)$, λ is the wavelength, h(.) is a function, and γ is the path loss exponent.

IV. THE PROPOSED MAC PROTOCOL: ETPMAC

According to IEEE 802.11 MAC protocol, every node has to carry out the physical carrier sensing before transmitting RTS, CTS, or DATA packets (but not ACK packets). If the channel is sensed to be busy, then the nodes cannot transmit those packets. As a result, the spatial reuse is low because each time only one pair of transmitter and receiver can use the channel, even though some other transmissions may not interrupt the ongoing transmission. The exposed terminal problem can be such an example. In this paper, we propose a single-radio, single-channel, and single-rate MAC protocol to improve the spatial reuse by controlling the transmission power so that several transmissions can be allowed at the same time without interfering with each other. This is an enhanced transmission power control MAC protocol, which we call ETPMAC. The idea here is that a new transmission can still be allowed as long as it does not interfere with the ongoing transmission.

ETPMAC does not use any new control packets other than RTS and CTS. Neither does it incur any other signalling overhead than one RTS/CTS handshake before a DATA transmission. Instead, one RTS/CTS handshake can be followed by several concurrent DATA transmissions, which do not interfere with each other.

Specifically, in ETPMAC, the nodes that overhear RTS or CTS can make a decision on whether they can transmit DATA packets to their intended receivers based on some useful information carried by RTS/CTS.

A. A Table Maintained by Each Node

As shown in Table I, each node maintains a table to keep some information of their neighboring nodes. "Node ID" is the MAC address of a neighboring node. "Min Power", denoted by Pmn, is the minimum transmission power required to successfully send a packet to that neighboring node when it does not suffer from any other interferences. "Max Power", denoted by Pmx, is the maximum transmission power allowed for the current node keeping this table to transmit packets when that neighboring node is engaged in one transmission. "NAV" is the time that the neighboring node will finish its ongoing transmission. Each time a node overhears a packet from one of its neighboring nodes, it updates this table. The details will be introduced later.

TABLE I. SOME INFORMATION OF NEIGHBORING NODES.

Node ID	**Min Power (Pmn)**	**Max Power (Pmx)**	**NAV**

B. Overhearing CTS

In this subsection, we introduce how ETPMAC works when a node overhears CTS. When a receiver j receives RTS from a transmitter i, it can detect the reception power P_r^i, and obtain the transmission power P_t^i which is a new field we add in RTS frames. According to the power propagation model in (1), we have

$$P_r^i = C.\frac{P_t^i}{d_{ij}^{\gamma}}, \qquad (2)$$

where d_{ij} is the distance between node i and node j, and C is a constant.

Denote the receiver sensitivity by RXth. Then, by assuming the physical channel is symmetric, the minimum power required for the receiver j to successfully transmit a packet to the transmitter i, i.e., P_{mn}^i as mentioned before, satisfies

$$RX_{th} = C.\frac{P_{mn}^i}{d_{ij}^{\gamma}} \qquad (3)$$

From (2) and (3), we can get

$$P_{mn}^i = \frac{P_j^i.RX_{th}}{P_r^i} \qquad (4)$$

After obtaining P_{mn}^i receiver j should check in Table I to find those active neighboring nodes denoted by set S, i.e.,

$$S = \left\{\{k\}\middle|NAV^k > t_{now}\right\}$$

where NAV^k is the time that neighboring node k will finish its ongoing transmission, and tnow is the current time. Then, the maximum allowed transmission power of the receiver j, denoted by P_{aw}^j is

$$P_{aw}^j = \begin{cases} \min_{k\in s}\{P_{mx}^k\} & \text{if } S \neq \emptyset \\ P_{MAX} & \text{if } S = \emptyset \end{cases} \qquad (5)$$

Where P_{mx}^k is the maximum transmission power of node j at which j’s transmission will not interfere with k’s, $\emptyset$ stands for the empty set, and Pmx is the maximum allowed transmission power of the nodes. If P_{aw}^j is less than P_{mn}^i, then the receiver j is not allowed to reply with CTS because this CTS will definitely not received by the transmitter. Otherwise, CTS is transmitted after a period of SIFS with the transmission power P_{aw}^j .Thus, this CTS transmission will not interfere with j's active neighboring nodes' transmissions, and it is possible that this CTS could be correctly received. The same as RTS frame, our CTS frame also contains its transmission power. Since the CTS frame defined in IEEE 802.11 standard only has the MAC address of the frame's receiver, we add a new field called "Transmitter Address" in our CTS frame to put in the MAC address of the frame's transmitter. By doing this, other nodes overhearing CTS from the receiver j can update their information about j kept in Table I. Besides, we also add another new field called "Interference Level" in our CTS frame, which is the maximum average interference level each neighboring node is allowed to generate to receiver j. Denote "Interference Level" by $\mathrm{P}^{\mathrm{j}}_{\mathrm{inter\,f}}$. We can obtain

$$\mathrm{P}^{\mathrm{j}}_{\mathrm{inter\,f}} = \frac{\frac{\mathrm{P}^{\mathrm{i}}_{\mathrm{r}}}{\mathrm{SINR}} - \mathrm{P}_{\mathrm{noise}}}{\mathrm{N}.(1+\beta)} \quad = \frac{\mathrm{P}^{\mathrm{i}}_{\mathrm{r}} - \mathrm{SINR}.\mathrm{P}_{\mathrm{noise}}}{\mathrm{N}.(1+\beta).\mathrm{SINR}} \qquad (6)$$

where SINR is the signal-to-interference and noise ratio required to support a certain data rate (SINR is a constant since we do not consider rate adaptation here). N is the number of the neighboring nodes of the receiver j, which can be obtained by checking the number of nodes in Table I, and $\beta(\beta > 0)$ indicates the interference caused by the nodes out of the transmission range, which is about 0.5 for the two-ray propagation model and uniformly distributed terminals [11]. After a CTS is sent out, some neighboring nodes of the receiver j may overhear it and hence can update their information about node j. $\mathrm{P}^{\mathrm{i}}_{\mathrm{mn}}$ is calculated similar to (4), i.e.,

$$\mathrm{P}^{\mathrm{j}}_{\mathrm{mn}} = \frac{\mathrm{P}^{\mathrm{j}}_{\mathrm{t}}.\mathrm{RX}_{\mathrm{th}}}{\mathrm{P}^{\mathrm{j}}_{\mathrm{r}}} \qquad (7)$$

then, next time when a neighboring node k wants to send packets to node j, it can carry out the transmission only if its maximum allowed transmission power, $\mathrm{P}^{\mathrm{k}}_{\mathrm{aw}}$, is no smaller than $\mathrm{P}^{\mathrm{j}}_{\mathrm{mn}}$.Since this CTS contains the transmission power of receiver j, denoted by $\mathrm{P}^{\mathrm{j}}_{\mathrm{t}}$, for a neighboring node k, we have

$$\mathrm{P}^{\mathrm{j}}_{\mathrm{r}} = \mathrm{C}.\frac{\mathrm{P}^{\mathrm{j}}_{\mathrm{t}}}{\mathrm{d}^{\gamma}_{\mathrm{jk}}} \qquad (8)$$

$$\mathrm{C}.\frac{\mathrm{P}^{\mathrm{j}}_{\mathrm{mx}}}{\mathrm{d}^{\gamma}_{\mathrm{jk}}} \qquad (9)$$

where d_{jk} denotes the distance, between receiver j and the neighboring node k, and $\mathrm{P}^{\mathrm{j}}_{\mathrm{mx}}$ is the maximum transmissior power allowed for node k to transmit packets without affecting the reception of the following DATA packets at receiver j From (8) and (9), we obtain

$$\mathrm{P}^{\mathrm{j}}_{\mathrm{mx}} = \mathrm{C}.\frac{\mathrm{P}_{\mathrm{inter\,f.}\ \mathrm{P}^{\mathrm{j}}_{\mathrm{t}}}}{\mathrm{P}^{\mathrm{j}}_{\mathrm{r}}} \qquad (10)$$

After successfully overhearing the CTS from node j, neighboring node k will update the NAV field in Table I for node j. If node k does not want to send out any packets, it does not set its NAV. With $\mathrm{P}^{\mathrm{j}}_{\mathrm{aw}}$ defined in (5), even later it he some packets to transmit, those transmissions will not interfere with j's reception. Or, if it has a DATA packet for node node k will set its NAV in the same way as that defined in IEEE 802.11 standard. If the neighboring node k has a DATA packet for some node l other than node j, it will also set it NAV if $\mathrm{P}^{\mathrm{k}}_{\mathrm{aw}} < \mathrm{P}^{\mathrm{l}}_{\mathrm{mn}}$. It can carry out the transmission period of SIFS later only if the maximum transmission power of node k is no smaller than the minimum transmission power required transmitting packets to node l. Thus, there is a good chance that some neighboring nodes of receiver j can transmit DATA packets at the same time as node i, and the spatial reuse can be highly improved.

For example, as shown in Figure. 1, node j is both in the transmission range of node i and in that of node k; node k is outside the transmission range, but within the carrier sensing range of node i; node l is within the transmission range of node k, and outside the carrier sensing range of node i. Assume there are two flows, one from node i to node j, and the other from node k to node l. According to IEEE 802.11, there can be only one transmission at a time. However, according to our proposed ETPMAC, these two flows may happen at the same time after node k overhears CTS from node j.

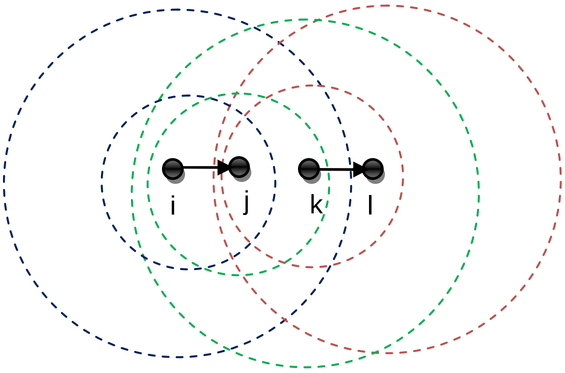


Figure. 1. An example that two concurrent transmissions happen after a CTS is overheard. The big circle is the carrier sensing range, and the small circle is the transmission range.

C. *Overhearing RTS*

We add a new field in our ACK frames called "Transmission Power" to put in the transmission power P_t^j of the ACK packets. So, when node i receives an ACK from node j, it can obtain the reception power P_r^j, as well as the transmission power of the ACK packet.

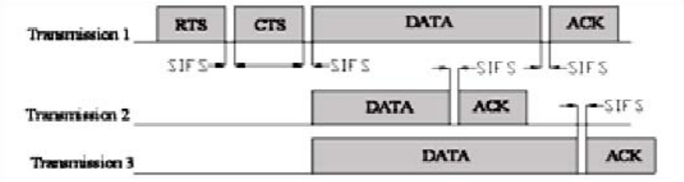


Figure. 2. An example that three concurrent transmissions have DATA packets of different lengths.

Thus, node i can calculate the maximum average interference level each neighboring node is allowed to node i, denoted by $P_{\mathrm{inter\,f}}^i$, in a way similar to (6), i.e.,

$$P_{\mathrm{inter\,f}}^j = \frac{P_r^j - \mathrm{SINR}.P_{\mathrm{noise}}}{\mathrm{N}.(1+\beta).\mathrm{SINR}}.$$

Besides, node i also updates P_{mn}^j in Table I according to (7). Next time, when node i has a RTS packet to transmit, it will put $P_t^j$and $P_{\mathrm{inter\,f}}^j$ in two new fields of the RTS frame, respectively, i.e., "Transmission Power" and "Interference Level". Any neighboring node that overhears this RTS will update their P_{mn}^i, P_{mx}^i and NAV^i in Table I accordingly. After successfully overhearing the RTS packet from node i, if a neighboring node k does not want to send out any packets, it will not set its NAV. Or, if it has a DATA packet for node i, node k will set its NAV in the same way as that defined in IEEE 802.11 standard. If the neighboring node k has a DATA packet for some node l other than node j, it will also set its NAV if $P_{aw}^k < P_{mn}^l$. It can carry out the transmission a period of 2 * SIFS+T_{CTS} later only if the maximum transmission power of node k is no lower than the minimum transmission power required to transmit packets to node l. Thus, there is a good chance that some neighboring nodes of transmitter i can transmit DATA packets at the same time as node i, and the spatial reuse can be highly improved.

For example, as shown in Figure. 3, node j and node l are both in the transmission range of node k; node i is in the transmission range of node j, but outside the carrier sensing range of node k; node l is in the transmission range of node k, but outside the carrier sensing range of node j. Assume there are two flows, one from node j to node i, and the other from node k to node l. According to IEEE 802.11, node j and node k will fairly contend with each other for the channel and there is only one transmission at a time. However, according to our proposed ETPMAC, two DATA transmissions from node j and node k, respectively, may happen at the same time after one node overhears a RTS from the other, and two ACKs from node i and node l, respectively, may also both be received successfully.

Furthermore, let us consider a special case when both overhearing a RTS and overhearing a CTS occur to the same node which plans to have a DATA transmission. Assume a node overhears a RTS packet and is allowed to carry out DATA transmission. If later this node overhears a CTS packet and is not allowed to carry out the transmission any more, then it does not carry out the transmission as planned and waits until the channel is idle without doubling its contention window. Again, this is for the fairness issue.

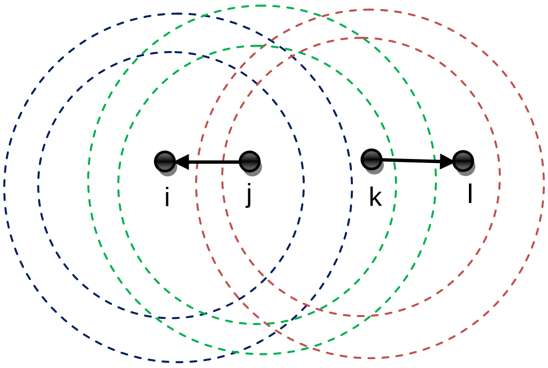


Figure. 3. An example that two concurrent transmissions happen after a RTS is overheard. The big circle is the carrier sensing range, and the small circle is the transmission range.

D. Tuning the Physical Carrier Sensing Threshold

IEEE 802.11 standard defines two important concepts: transmission range and physical carrier sensing range, which are determined by receiver sensitivity and physical carrier sensing threshold, respectively. Two nodes within the transmission range, of each other can communicate directly, and two nodes within the physical carrier sensing range of each other cannot transmit packets at the same time. As shown in [12], physical carrier sensing range has a great impact on the network throughput. On one hand, the increase of physical carrier sensing range can alleviate the hidden terminal problem, which helps increase the throughput. On the other hand, as physical carrier sensing range increases, the spatial reuse decreases, which impairs the throughput. As a result, there exists an optimal physical carrier sensing range with respect to a certain transmission range, which is usually larger than the transmission range.

Certainly, this is true for wireless networks using IEEE 802.11. However, with respect to our proposed ETPMAC, we contend that this is not necessarily the case. As shown in Figure. 1, if node k wins the contention with node i for the channel, it will start the four-way handshake (RTS/CTS/DATA/ACK) with node l. Since node j is in the carrier sensing range of node l, it will keep silent for a period of EIFS after the ACK from node l is received by node k. Thus, when node I attempts to send RTS to node j, it cannot respond with CTS, which is the receiver blocking problem. Due to this problem, ETPMAC cannot increase the throughput much because it relies on node j's CTS to schedule the concurrent transmissions.

To address this problem, we propose to set physical carrier sensing threshold equal to receiver sensitivity such that the carrier sensing range is the same as the transmission range. Thus, in Figure. 1, if node j successfully receives a RTS from node i, it can still reply with a CTS even if node l is transmitting an ACK to node k. Besides, we notice that node k becomes a hidden terminal to the transmission from node i to node j. However, if node k does not transmit RTS when node j is receiving RTS from node i, then node k will receive CTS from node j and begins to transmit DATA packet at the same time as node i. If node k transmits RTS when node j is receiving RTS from node i, its transmission will not interfere with node j's reception if node k is a little bit further away

Figure. 4. An example that two transmissions in Figure. 1 are partially overlapping.

from node j. In this case, the transmission from node i to node j and that from node k to node l can be partially overlapping, as shown in Figure. 4.

Moreover, there would be another problem if the physical carrier sensing range is larger than the transmission range. For example, as shown in Figure. 3, assume node k is within the carrier sensing range of node j. If node k wins the channel and transmits RTS to node j, node j can correctly receive this packet and plans to transmit DATA packet at the same time as node k. However, a period of SIFS later node j will overhear the CTS from node l, and hence will set its NAV with a length of EIFS after the CTS transmission is finished, which prevents it from transmitting DATA packet to node i. We call this problem the transmitter-blocking problem. Similarly, if node i is within the carrier sensing range of node k, node A; cannot transmit its DATA packet as it has planned after node k first receives RTS from node j, and then overhears CTS from node i. However, by setting the physical carrier sensing range to the same as the transmission range, this problem can be overcome.

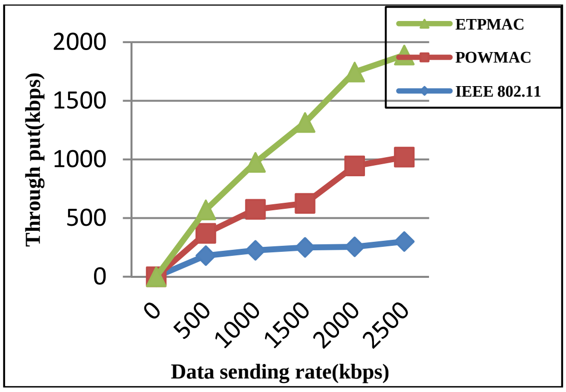
V. PERFORMANCE EVALUATION

In this section, we use NS2 (version 2.29) to evaluate the proposed ETPMAC protocol and compare its performance with POWMAC [8], and IEEE 802.11 MAC. We compare ETPMAC with POWMAC because the latter one is also a transmission power control MAC protocol based on a single-channel, single-transceiver design, and it shares some common features with ETPMAC. We do not compare ETPMAC with those protocols like [3] [4] because their main objective is to save energy and they can achieve comparable throughput to that of IEEE 802.11 MAC at best. Neither do we compare ETPMAC with those protocols with multi-channel and/or multi-transceivers [6] [7]. Some of our simulation parameters are shown in Table II.

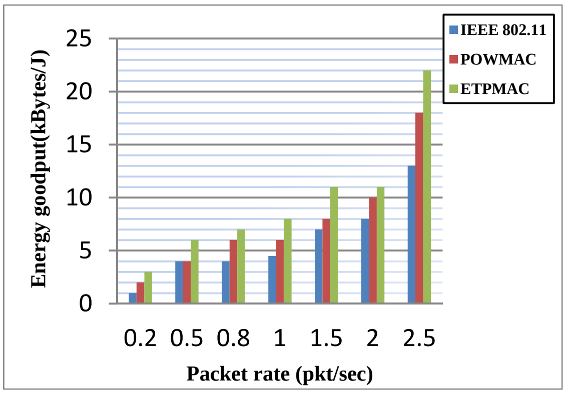
TABLE II. SIMULATION PARAMETERS.

Parameters	Value
Channel frequency	2.4 GHz
Data rate	2 Mbps
Basic rate	1 Mbps
SINR threshold	7 dB
Packet size	2000 bytes
Transmission range	250 meters
RTS retry limit	7

We evaluate the performance of ETPMAC, POWMAC, and IEEE 802.11 MAC in a multi-hop scenario. We use a 1000m x 1000m 2D topology where there are 50 randomly distributed nodes. Ten nodes are chosen to be CBR (Constant Bit Rate) sources and their destination nodes are randomly chosen, the network uses AODV (Ad Hoc On Demand Distance Vector Routing) routing protocol. Figure. 5 shows the simulation result with different parameters. We can see that ETPMAC can achieve up to 71% higher throughput than that of IEEE 802.11, and 32% higher throughput than that of POWMAC. This is because in multi-hop networks ETPMAC can make concurrent transmissions happen whenever possible without introducing any additional overhead, while POWMAC allows concurrent transmissions at the cost of more signaling overhead, i.e., N RTS/CTS exchanges for N concurrent transmissions. This overhead becomes more significant when the data rate increases and delay using ETPMAC is reduced compared to other MAC protocols. Therefore, the spatial reuse is very much increased.



(a)



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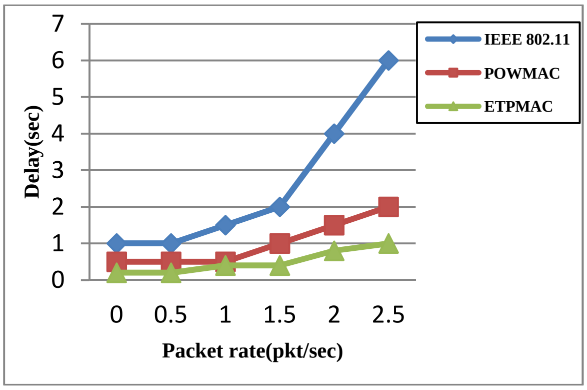

(c)

Figure 5. Performance of ETPMAC, POWMAC, and IEEE 802.11 MAC with different parameters

VI. CONCLUSION

In this paper, we propose a new adaptive transmission power controlled MAC protocol, known as ETPMAC, which can significantly improve the network throughput using a single channel and a single transceiver and consume less energy. Our simulations show that ETPMAC can improve the throughput by up to 71% compared to IEEE 802.11 MAC . We must realize that there are some limitations on ETPMAC. First, it does not address the mobility issue. Second, hidden terminal problems still exist. We will investigate these issues in the future.

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