An Energy Efficient Multi-channel MAC Protocol for Wireless Ad hoc Networks

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***Abstract*—The IEEE 802.11 [1] provides multiple channels for wireless communications at the Physical Layer, but the Medium Access Control (MAC) protocol is only designed for a single channel. If the multiple channels can be exploited by multi-channel MAC protocol, there can be multiple transmissions on different channels. Besides that, the power control algorithm can improve the spatial reuse of wireless channels. In this paper, we combine the multi-channel MAC protocol and the power control algorithm together to exploit multiple channels and improve frequency reuse. The main idea of our proposal is to use IEEE 802.11 Power Saving Scheme (PSM) with different transmission power levels in the ATIM window and the data window. All nodes transmit ATIM/ATIM-ACK/ATIM-RES messages with the maximum power while contending the data channel during the ATIM window, and use the minimum required transmission power in the data window on their negotiated channels. The simulation results show that the proposed E-MMAC improve the performance of the network: aggregate throughput, average delay and energy efficiency.**

***Index Terms*—Energy Efficiency, Power Control, Multi-channel, MAC protocol, Ad hoc networks.**

I. INTRODUCTION

There are 3 non-overlapping channels in the IEEE 802.11b,g and 12 non-overlapping channels in the IEEE 802.11a. If the multiple channels can be exploited, the network throughput will be increased. However, it is not easy to design the MAC protocol that can exploit multiple channels with a single half-duplex transceiver. The transceiver can switch channel radio dynamically, but it cannot sense all channels simultaneously. So, it may lose the channel reservation messages from its neighbors on another channel. This leads to the new type of hidden terminal problem in a multi-channel environment, which we refer to as *multi-channel hidden terminal problem* [5].

Besides addressing the multi-channel hidden terminal problem, the designed MAC protocol has to solve the energy problem. The wireless nodes are usually powered by battery 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. Another way to save energy is to use power control schemes which allow wireless nodes to vary power level to transmit packets. In addition to providing energy conservation, power control can improve spatial reuse of the wireless channel.

In this paper, we propose an Energy Efficient Multi-channel MAC (E-MMAC) Protocol to exploit the multiple channels and improve the spatial reuse of wireless channel.

The rest of the paper is organized as follows: Section II reviews the related work of Multi-channel MAC protocols and power control schemes in the ad hoc networks. In section III, our proposed protocol is described in detail. Section IV presents simulation results. Finally, we conclude our work in section V.

II. RELATED WORK

The major challenges of multi-channel transmission are to negotiate a data channel while also trying to decrease the collision and control packets overhead. There are four approaches for multi-channel MAC protocol [2]: Dedicated Control Channel, Common Hopping, Split Phase and Mc-MAC.

In Dedicated Control Channel approach, each node has two radios: one radio is tuned to the channel dedicated to control packets and another one can switch to any other channels for data transmission. In Fig. 1(a), when the nodes have data to exchange, they perform RTS/CTS handshake in the control channel, and then exchange the data packets on the negotiated data channel. The representative of this approach is Dynamic Channel Allocation (DCA) [3]. By bringing power control scheme to Multi-channel MAC, Dynamic Channel Assignment with Power Control (DCA-PC) [4] is an improvement to DCA. In DCA-PC, all control packets RTS/CTS/RES are transmitted using the maximum power on the control channel, while DATA/ACK packets are transmitted with the minimum required power on the data channel. This approach does not require time synchronization but requires two radios, thereby increasing the cost of device.

Differ from that approach, each node has only one radio in Split Phase approach. Time is divided into alternating sequence of control interval or contention interval and data transmission interval, as shown in Fig. 1(b). During the control interval, all nodes have to switch to control channel and try to reserve data channels for their data transmissions. In the data interval, they switch to an agreed data channel to exchange data packets. MMAC [5] is an example of this approach. Since all nodes are on the control channel while the other data channels are free, the control interval affects the performance of the network. Traffic Aware Multi-channel

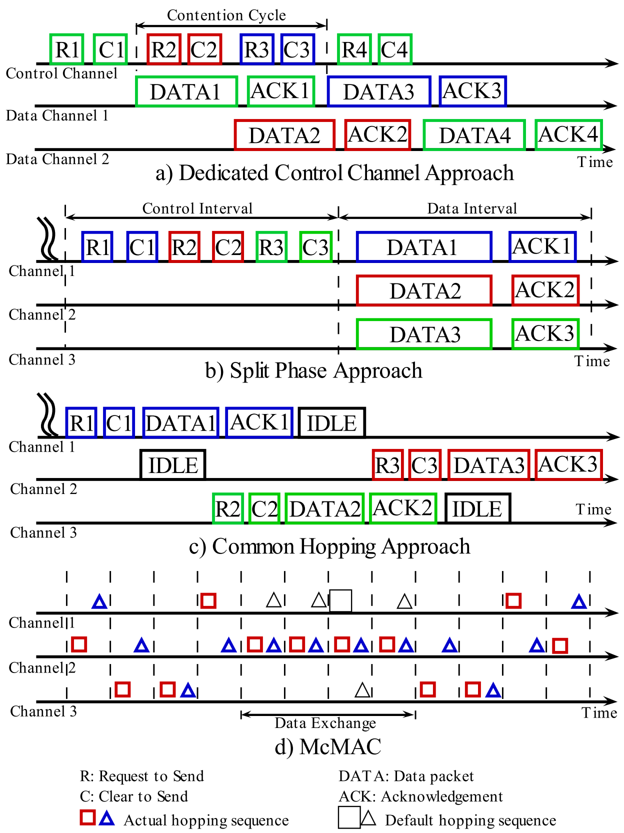

Fig. 1. Four approaches for multi-channel MAC protocol.[2]

MAC (TAMMAC) [6] proposed a mechanism to adjust the control interval dynamically according to the traffic of the network. H-MMAC [7] is an enhancement of MMAC. H-MMAC utilizes almost all of the entire channel resources to improve the network performance by allowing nodes to transmit data during the ATIM window.

Also, in Common Hopping approach, the nodes need only one radio. Nodes that do not exchange data hop through all channels synchronously. As shown in Fig. 1(c), the hopping pattern cycles through channel 1, 2 and 3. Now, all nodes are in channel 1, and node A wants to send data packets to node B. If nodes A and B perform RTS/CTS handshake successfully, they pause hopping and remain on channel 1 during data transmission. The other idle nodes continue hopping to channel 2. After the data transmission is over, nodes A and B rejoin the Common Hopping sequence with the other idle nodes. This approach requires all the nodes hoping frequently and tight time-synchronization. Since the channel switching time is 224 μs in IEEE 802.11, the switching time cannot be negligible. Channel Hoping Multiple Access (CHMA) [8] is an example of this approach. Pipelining Multi-channel MAC (π-Mc) [9] is similar to pipeline technique. The transmission task is divided into many subtasks. All of the subtasks are transmitted on different channel sequentially. All nodes which have data to transmit should contend to transmit first subtask on the first channel. If the first subtask is transmitted successfully, all the other subtasks also succeed in transmission.

The last approach is McMAC [10] displayed in Fig. 1(d), each node picks a seed to generate a different pseudo random hopping sequence. Idle node follows it ”home” hopping sequence. Each node puts its seed in every packet that it sends, so its neighbors eventually learn its hopping sequence. When node A has data to send to node B, A flips a coin and transmits with some probability p during each time slot. If it decides to transmit, it tunes to the current channel of node B and sends RTS. If node B replies with a CTS, both nodes A and B stop hopping to exchange data. Data transmission may takes place over some time slots. After the data transmission is over, nodes A and B return to their original hopping sequences.

The power control has an important role in energy saving and frequency reuse [4], [11]-[17]. Simple power control schemes are proposed in [4], [13]. In these schemes, RTS/CTS are sent at the maximum power while DATA/ACK 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 [14]. The receiver's interference range depends on the sender's transmission power. In [15], an Adaptive Range-based Power Control (ARPC) MAC protocol is proposed to avoid POINT problem.

In other power control schemes, a node is allowed to periodically increase the transmission power during data transmission in order to inform other nodes in the carrier sensing range of its transmission [16], [17]. These schemes can save the energy but they cannot improve the spatial reuse because node periodically uses P_{dmax} during its transmission. These schemes also cannot avoid the POINT problem.

Since we use the ATIM window to exchange the transmission power information, our proposal is not affected by POINT problem. In the next section, we describe our proposed protocol in detail.

III. The Proposed E-MMAC Protocol

First, we summarize our assumptions as follows:

- There are N non-overlapping channels which can be used. The beacon interval is divided into the ATIM window and the data window. One channel is defined as a default channel (CH1) during the ATIM window.
- Each node has a single half-duplex transceiver which is capable of switching its channel dynamically.
- All nodes are synchronized, so that they begin their beacon interval at the same time.
- Since other interfering nodes are far away and contributes a smaller interference than the first tier interfering nodes, we ignore them in SINR calculation.
- The transmission power consumption is proportional to the radio transmission power. Node consumes the 1.65W when its maximum radio power is 250mW.

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}.

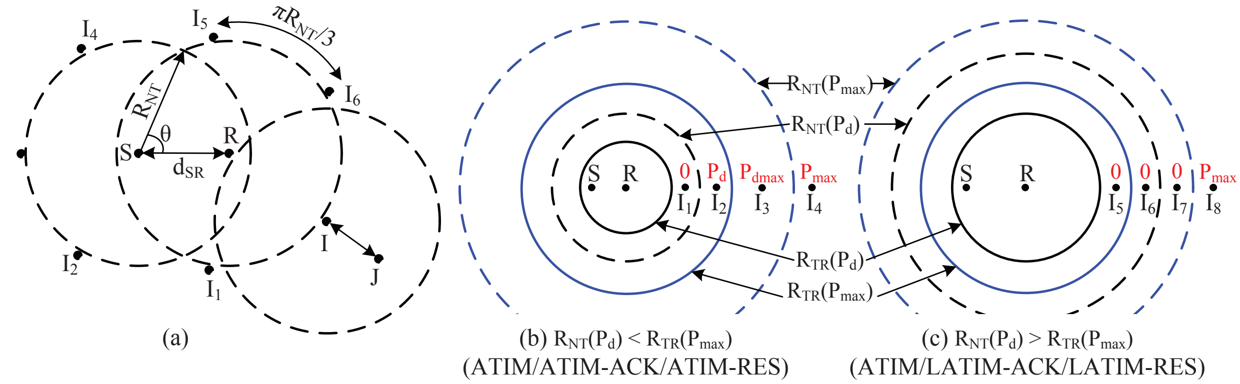

Fig. 2. The interference model.

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 [18], the receiving power P_r^S is calculated from the following formula

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

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;
L	other losses, assume $L = 1$ then c is constant;
α	path loss coefficient with range of 2-4.

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

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

where $P_r^i(R)$ is the interference caused by the interfering node i, 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.

When nodes R and S include the transmission power P_d information in the ATIM-ACK/ATIM-RES message. Only neighbors which are outside the noise threshold range of P_d can transmit simultaneously with nodes S and R. We have to find out how many interfering nodes at the first tier affect the transmission between nodes S and R and the maximum interference level in the worst case. The circumference C of the noise threshold range of nodes S and R (Fig. 2(a)) can be calculated easily

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

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

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

In case of $No\_Int = 7$ nodes, the maximum interference is $4.869 \cdot P_{Nthold}$. But, the maximum total interference in the worst case is $6 \cdot P_{Nthold}$ when nodes S and R are very close to each other, and there are 6 interference nodes contribute interference to them.

Next, we find the value of P_{Nthold} by using the 2 conditions of successfully and correctly reception above

$$P_{Nthold} \leq \frac{P_{RXthold}}{6.SINR_{thold}}. \quad (5)$$

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

$$P_d = \frac{P_{\max} P_{RXthold}}{P_r^{P_{\max}}}. \quad (6)$$

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

$$\frac{c.P_{max}}{R_{TR}^\alpha(P_{max})} \geq P_{RXthold}. \quad (7)$$

Next, 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} while keeping the its interference less than the threshold P_{Nthold} to node R (Fig. 2(b)).

$$P_{dmax} \leq \frac{P_{Nthold}.P_{max}}{P_{RXthold}} \leq \frac{P_{max}}{6.SINR_{thold}}. \quad (8)$$

It implies that when a node overhears the ATIM messages and if it wants to exchange data packets, it can transmit DATA/ACK packets at the maximum transmission power P_{dmax} that is limited by Eq. 8.

Since the region between the transmission range and noise threshold range of P_{max} is too large, we can improve the spatial reuse by allowing nodes in this region to transmit simultaneously with the interference constraint. We define the longer LATIM-ACK and LATIM-RES messages to help neighbor nodes distinguish the case of $R_{NT}(P_d) > R_{TR}(P_{max})$. As shown in Figs. 2(b) and (c), ATIM/ATIM-ACK/ATIM-RES are used when $R_{NT}(P_d) < R_{TR}(P_{max})$, and ATIM/LATIM-ACK/LATIM-RES are used when $R_{NT}(P_d) > R_{TR}(P_{max})$.

Algorithm 1 Choose the "best" data channel CH

$delta \leftarrow 0$;
$CH \leftarrow 0$;
for i = 1 to N **do**
  if $P_d \leq PCL_S[i].P_{lim} \&\& P_d \leq PCL_R[i].P_{lim}$ **then**
    $temp \leftarrow min\{PCL_S[i].P_{lim}, PCL_R[i].P_{lim}\} - P_d$;
    if $delta < temp$ **then**
      $delta \leftarrow temp$;
      $CH \leftarrow i$;
    end if
  end if
end for

Algorithm 2 Algorithm to update P_{lim}^{ch} in each beacon

$P_{lim}^{ch} \leftarrow P_{max}$ /*At the start of each beacon*/
repeat
  if Receives (L)ATIM-ACK/(L)ATIM-RES(P_d) correctly **then**
    if $P_r \geq \frac{P_{max} \cdot P_{Nthold}}{P_d}$ **then**
      $P_{lim}^{ch} \leftarrow 0$ /*Node I_1, I_5 in Fig. 2*/
    else
      $P_{lim}^{ch} \leftarrow min(P_{lim}^{ch}, P_d)$ /*Node I_2 in Fig. 2*/
    end if
  else if $P_{sense} \geq P_{Nthold}$ for $duration > T_{ATIM-ACK}$ **then**
    $P_{lim}^{ch} \leftarrow 0$ /*Node I_6, I_7 in Fig. 2*/
  else if $P_{sense} \geq P_{Nthold}$ for $duration = T_{ATIM-ACK}$ **then**
    $P_{lim}^{ch} \leftarrow min(P_{lim}^{ch}, P_{dmax})$ /*Node I_3 in Fig. 2*/
  end if
until ATIM window ends **or** $P_{lim}^{ch} = 0$

B. Preferable Channel List (PCL)

Each node maintains the data structure call Preferable Channel List (PCL). In PCL, each entry stores the transmission power limit P_{lim} for each channel as shown in Table I. This value limits the maximum transmission power of each node in the current beacon. At the beginning of each beacon, P_{lim} is set to P_{max}. All nodes have to listen to the default channel during the ATIM window, and update the P_{lim} for a corresponding channel by Alg. 2 according to the overheard ATIM messages or the sensing power. Figs. 2(b) and (c) show 2 scenarios to to update the P_{lim}.

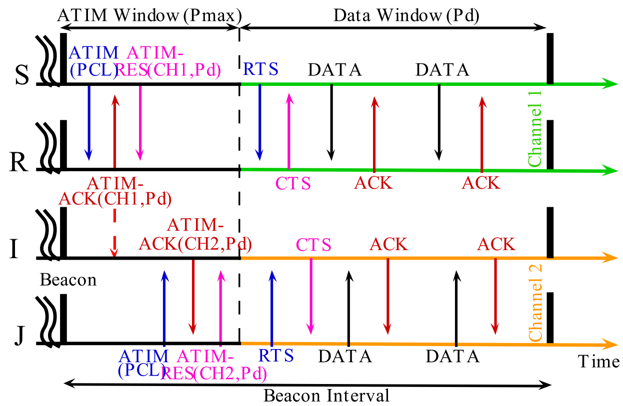

Fig. 3. The operation of E-MMAC protocol.

TABLE I
NODE A'S PCL

Channel - CH	Tx Power Limit - P_{lim}
CH1	250
CH2	0
CH3	100

C. The operation of E-MMAC protocol

The operation of the proposed E-MMAC protocol is illustrated in Fig. 3. All nodes switch to the default channel during the ATIM window. We assume that node S has data packets for node R. The procedure of E-MMAC protocol is described as the follows:

1) Node S sends ATIM including its PCL 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. Based on the P_d and both PCLs of nodes S and R, node R choose the "best" data channel CH_i and the required transmission power P_d by Alg. 1. Then, node R sends ATIM-ACK(CH_i, P_d) to node S. Otherwise, node R sends ATIM-ACK($NULL, NULL$) to indicate that they cannot exchange data in this beacon.
3) If node S receives ATIM-ACK(CH_i, P_d), it confirms by sending ATIM-RES(CH_i, P_d); otherwise it does not send ATIM-RES.
4) The neighboring nodes update their PCLs by Alg. 2.
5) After 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.

In Fig. 3, after nodes S and R exchange ATIM messages successfully. If nodes I and J find that they can not transmit simultaneously with nodes S and R on channel 1, they have to choose another channel. And they decided to use channel 2 for their data transmission.

IV. PERFORMANCE EVALUATION

In this section, we have simulated IEEE 802.11, MMAC [5], DCA-PC [4] and our proposed E-MMAC protocol by our own developed tools in MATLAB [19].

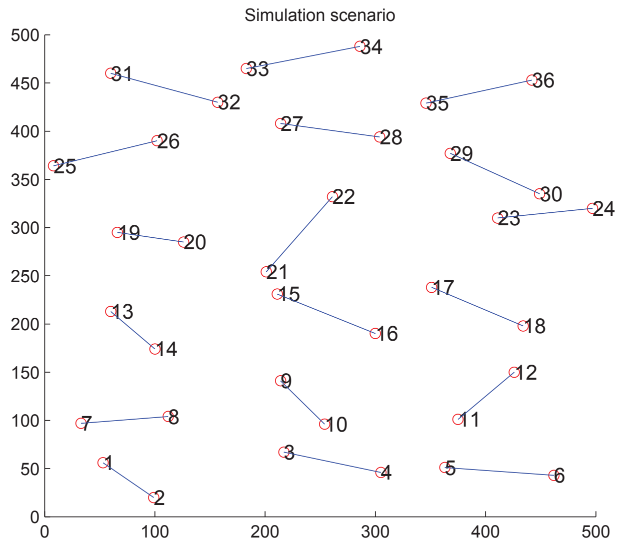

Fig. 4. An example of simulation scenarios.

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 transmitter-receiver pair. We simulated 20 different topologies (scenarios) which one of them is shown in Fig. 4. Each node generates and transmits constant-bit-rate (CBR) traffic to its destination. Both transmitter and receiver have 1.5m height antennas with the gain of 1dBi. The other simulation parameters in our simulations are listed in Table II. Each simulation was performed for 5 seconds and the simulation results are the average of 40 runs.

TABLE II
SIMULATION'S PARAMETERS

Parameters	Value
Number of channels	3 channels
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	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

In our simulation, we use the following metrics to evaluate the performance.

$$Throughput = \frac{Packet\_Size * No\_Successful\_Packets}{Total\_SimTime}$$

$$Average\_Delay = \frac{Total\_Packet\_Delay}{No\_Successful\_Packets}$$

$$Energy\_Efficiency = \frac{Total\_Energy\_Consumption}{No\_Successful\_Packets}$$

B. Simulation Result

Fig. 5 shows the performance comparison of different protocols as the network load increases. The network load becomes high when the packet arrival rate is large. The aggregate throughput of different protocols are shown in Fig. 5(a). The aggregate throughput of the multi-channel MAC protocols are higher than IEEE 802.11 MAC protocol designed for single channel. When the network load is high, the E-MMAC has higher aggregate throughput than MMAC and DCA-PC. DCA-PC uses one channel for control packets and 2 data channels for data transmissions. By using the separate control channel, DCA-PC with power control can achieve more than twice the throughput of IEEE 802.11. In both MMAC and E-MMAC, 5% of time interval is used for the ATIM window where only ATIM/ATIM-ACK/ATIM-RES transmissions are allowed. In E-MMAC, when nodes exchange ATIM messages successfully, they can use the channel exclusively during the entire data window regardless of the number of data packets in their buffers. When the packet arrival rate is low, they cannot fully utilize the data channel during the data window. Since some nodes within the carrier sensing range of P_{max} can transmit simultaneously, the E-MMAC has more concurrent transmissions in each data channel than the others. The nodes fully utilize the data channel during data window as the packet arrival rate increases. The aggregate throughput of E-MMAC is significantly higher then other protocols when the network load grows to near saturation.

Fig. 5(b) shows the average delay of different protocols against the packet arrival rate. The average delay increases as the network load increases. MMAC and E-MMAC have the overhead of the ATIM window and the ATIM window limits the number of nodes which can exchange data in the data window. When the network load is low, nodes cannot fully utilize the channel, the average delay of the MMAC and E-MMAC are higher than that of other protocols. The average delay of E-MMAC is higher than MMAC when the packet arrival rate is low because the number of nodes in data window is less than that of MMAC. The reason for this is the characteristic of E-MMAC: nodes use data channel exclusively in data window regardless of their packet arrival rate. When the packet arrival rate is high, all multi-channel MAC protocols have lower delay because they support more concurrent transmissions than IEEE 802.11. Since E-MMAC can improve the spatial reuse of wireless channel, it allows more data packets than the others. The higher the network load grows, the smaller the average delay of E-MMAC gets.

The energy efficiency is one of the benefits of the proposed E-MMAC protocol. The total energy consumption over the data packets transmitted successfully in the network of the different protocols are compared in Fig. 5(c). Although the transmitting nodes adjust their transmitting power in DCA-PC protocol, the idle nodes stay awake and consume the idle power of 1.15 W. The DCA-PC also consumes more power since each node is equipped with 2 transceivers. In both MMAC and E-MMAC, the PSM is adopted by using the ATIM

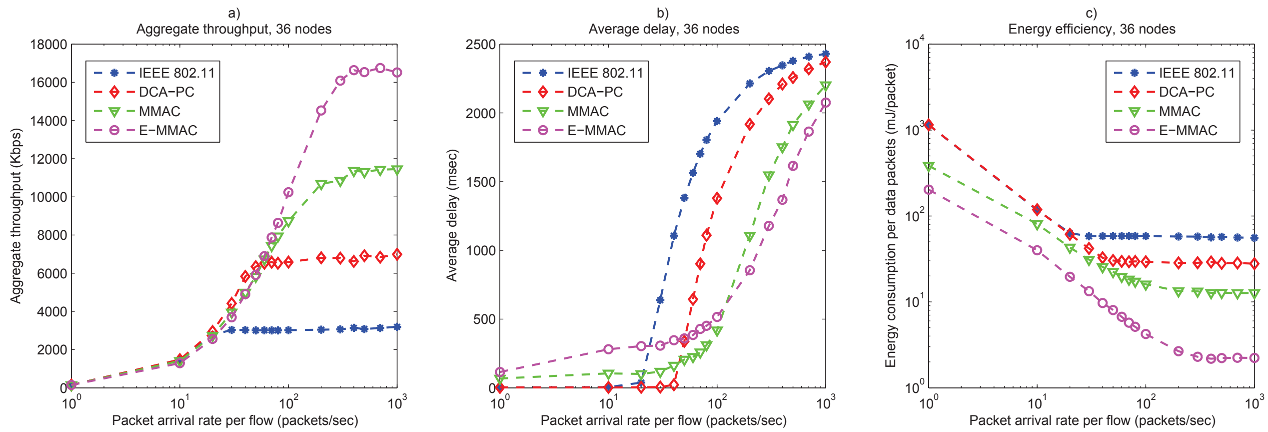

Fig. 5. Performance comparisons of different protocols.

window and the data window. It allows nodes to enter doze mode with a power consumption of 0.045 W when there is no need for data exchange. The doze power consumption is much smaller than the idle power consumption. With the appropriate power control mechanism, the E-MMAC can save the energy. Having the higher throughput and less energy consumption, the E-MMAC protocol has better energy consumption per data packet than the others.

V. Conclusion

Although a lot of multi-channel MAC protocols for ad hoc networks have been proposed, the design of an efficient enough multi-channel MAC is still a long way to go. In this paper, we proposed the new Multi-channel MAC protocol which improves the performance of the ad hoc networks. Our proposed E-MMAC required only one transceiver for each node resulting in less energy consumption than DCA-PC that requires two transceivers for each node. Moreover, by implementing the power control algorithm, the E-MMAC can exploit the multiple channels as well as increase the spatial reuse. Simulation results showed that E-MMAC protocol improves the network performance in terms of aggregate throughput, average delay and energy efficiency.

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