DEMAC: An Adaptive Power Control MAC Protocol for Ad-Hoc Networks

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Abstract- Transmit Power Control (TPC) protocols have been proposed to address the limited power supplies in ad hoc networks. However, most of the previous work minimizes the transmit power without considering both the energy wasted in collisions and the energy used to overcome the interference from all the interfering nodes existing in the network. Our previous work shows the optimal transmit power for the maximum throughput and per frame minimum consumed energy exists and occurs when the power level is sufficient to avoid the interference, and causes the least contention between nodes. In this paper, we propose a novel per-frame-based TPC protocol, DEMAC, in ad hoc networks using IEEE 802.11 at low PHY rate. To avoid interference, improve throughput, and save energy, DEMAC adaptively looks for the optimal transmit power based on the network interference and data payload. DEMAC is validated via simulations and is shown to outperform several existing TPC protocols.

Index Terms: Ad-Hoc Networks, IEEE 802.11, Transimit Power Control, Interference,

1 INTRODUCTION

A wireless node in an ad-hoc network has limited battery power; therefore, it is important to reduce its energy consumption. A wireless node has four modes: transmit, receive, idle, and doze. It consumes the most power in the transmit mode. In the idle mode, it needs to sense the medium and consumes a little less than in the receive mode. The doze mode consumes very little and can be ignored compared to the other modes [15]. To save energy, one direction is to force a node to enter the doze mode when it is not necessary to be awake [1,2]. The other direction is to apply a TPC (Transmit Power Control) protocol [3,4,5,6]. We focus on the second direction in this paper. TPC looks for the minimum required transmit power between the transmitter and the receiver. Most of the previous work minimizes the transmit power without considering both the energy consumed because of collisions and the energy used to overcome the interference from other nodes. Too much interference decreases the signal to interference ratio, which may prevent an acceptable bit error rate, thereby requiring retransmissions and consuming more power.

Our previous work has demonstrated that under maximum interference, there is an optimal power level that achieves the maximum throughput and per frame minimum energy consumption [14]. Furthermore, the maximum throughput and the minimum consumed energy is achieved when control and data frames are transmitted with the same power. The power level should be high enough to avoid the interference but no higher so that it will not create unnecessary contention between nodes. In this paper, based on our previous research, we propose a per-frame-based TPC protocol, DEMAC (adaptive energy efficient MAC). In DEMAC, transmit power of RTS is used to find the interference in the network. The receiver calculates the optimal transmit power for the data frame based on the data payload and the current interference. CTS, DATA, and ACK will be transmitted with this optimal transmit power. DEMAC effectively avoids interference, improves throughput, and saves the energy consumption. DEMAC is validated via simulations. Our results show that DEMAC outperforms several existing TPC protocols.

This paper is organized as follows. In Sections 2 and 3, we review the related work and provide the technical background. In Section 4, we review some of our previous work that leads to the design of DEMAC. The protocol and simulation results are presented in Section 5. We conclude with Section 6.

2 RELATED WORK

IEEE 802.11 [7] sends all the packets with the maximum transmit power, but does not solve the interfering nodes problem, since interference occurs at the receiver and comes from all transmitting nodes (they become interfering nodes if the sum of the transmitting signals is large enough to interrupt the transmitter's transmission). In [3,4,5] the authors propose to perform the RTS/CTS handshake at the highest initial power level to avoid packet collisions from the interfering nodes. Their protocol allows the sender and the receiver to negotiate a lower transmit power (the minimum required) level for sending the data frames. We refer to this scheme as the BASIC scheme in the rest of the paper. BASIC consumes less energy than 802.11, yet it does not solve the interfering nodes problem. Furthermore, BASIC does not consider the interference from all the transmitting nodes. Jung et al. [6] propose the Power Control MAC (PCM) that uses the BASIC scheme but periodically transmits a data frame with the maximum transmit power. PCM inherits IEEE 802.11's shortcomings except it consumes less energy. POWMAC [10] proposes to use an access window to allow for a series of RTS/CTS exchanges to take place before multiple data frame transmissions. However, it is difficult to implement synchronization between nodes during the access window. POWMAC does not solve the interfering nodes problem either. Wang et al. [11] model the performance of a wireless node using Markov Chains. However, they consider interference from nodes at the receiver side only. R. Hekmat et al. [8] develop a honey grid model to calculate the maximum interference in ad hoc networks. However, they do not propose any schemes to prevent interference. S. Gobriel et al. [12] analyze interference and collisions in an ad hoc network. However, they assume that the interference area is only at the receiver side. J. P. Ebert et al. [17] propose to choose the energy-saving transmit power based on the length of the packet, howerver, they ignore the effect of interference in designing the protocol.

In DEMAC, we consider the effect of interfering nodes in the network, and on each of a node state transitions. It adaptively finds the optimal transmit power that avoids interference, minimizes consumed energy, and maximizes the throughput.

3 BACKGROUND

IEEE 802.11 is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Carrier sensing is performed using both physical carrier sensing (by air interface) and virtual carrier sensing. The effect of physical carrier sensing is determined by the transmit power of the sender. Virtual carrier sensing is performed by including the duration of the packet transmission in the header of RTS, CTS and DATA frames.

In a wireless network, a frame is considered to be successfully received if the Bit Error Rate (BER) is acceptable. Additive white gaussian noise (AWGN) is used to model the noise at the receivers, which is used to calculate the SNR (signal to noise ratio). The interference is expressed in the SIR (signal to interference ratio). Note that, a low SIR causes a high BER. Let SIR_{min} denote the minimum required SIR to successfully receive a frame. Since RTS is short, the BER of the RTS is very small when the $SIR \geq SIR_{min}$. However, SIR_{min} cannot guarantee that the DATA frame is successfully received: since the data frame is longer, the BER of the frame may also be large. We assume AWGN is fixed in this paper. If no interference exists, a high SNR can produce the target BER. If interference exists, then SNR and SIR are not sufficient to determine an acceptable BER.

A term related to the wireless radio is *Interference Range*, which is centered at the receiver and represents the range within which the other nodes are capable of interfering with the reception of frames at the receiver. The interference comes from all the transmitting nodes except the transmitter. Since the effects of interference are cumulative, a sufficient number of low interference causing nodes will disrupt the reception of a frame. The interference from a node depends on its transmission power, distance and the path loss.

RTS/CTS handshake effectively avoids interference from nodes inside the CCA (*Clear Channel Assessment*) busy range of a transmitting node and the transmission range of a receiving node (see details in [14]). However, the handshake can not avoid interference from interfering nodes. Therefore, RTS/CTS handshake can not guarantee a successful transmission.

4 THROUGHPUT AND CONSUMED ENERGY

In order to calculate theoretical results for the throughput and the energy consumed in the network, we use the Markov Chain model and the Honey grid network derived in [14]. Due to space constraints, we omit the details, but present the main points in the following sections.

4.1Node State Transition

We use a Markov Chain model to describe a wireless node's state transitions. The difference between our model and [11, 12] is: 1) we consider the interference from the entire system; 2) we consider the effect of interfering nodes on each of a node state transitions.

Let S_i, S_t, S_r, S_c, S_d, and S_a denote the steady-state probabilities of the node state: idle, transmit, RTS with collisions, CTS with collisions, DATA with collisions, and ACK with collisions.

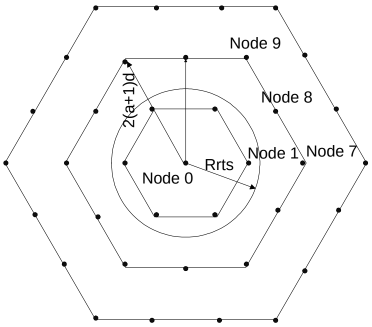

Figure 1 Honey Grid Model

Let T_{ii}, T_{it}, T_{ir}, T_{ic}, T_{id}, and T_{ia} denote the during of a transition to the new state: from idle to idle, from idle to transmit, from idle to RTS with collisions, from idle to CTS with collisions, from idle to DATA with collisions, and from idle to ACK with collisions.

The transmit state limiting probability, τ_t, represents the percentage of time the node is successfully transmitting, i.e., it is the ratio of the successful transmission time to the total transmission time (including both successful transmission time and collision time). As for a successfully transmitted payload, it is the payload of the DATA frame, and is given by (see details in [14]):

$$\tau_t = \frac{S_t L_{DATA}}{S_i T_{ii} + S_t T_{it} + S_r T_{ir} + S_c T_{ic} + S_d T_{id} + S_a T_{ia}} \qquad (1)$$

The throughput of the network is nothing but $\tau_t \times \lambda$, where λ is the packet arrival rate. In the next section, we derive λ.

4.2 Throughput and Consumed Energy

We calculate a node's throughput and consumed energy with maximum interference. To model maximum interference, we use a honey grid model [8].

Honey grid model: In a honey grid, the nodes are uniformly distributed and form concentric hexagons, called rings around a transmitting node. Based on such a model, we can obtain an upper bound on the interference experienced by a node without considering the node's moving patterns and its exact location. The model allows us to analyze how the maximum interference affects either a multi-hop or a single-hop ad hoc network's performance. A sample honey grid is shown in Figure 1. The jth ring has $6 \times j$ nodes. We consider the interference from both control and data frames, and assume that transmit power for DATA and ACK is the same. Similarly, transmit power for RTS and CTS is the same. A node's reach, *a*, is defined as the number of rings covered by its transmission range. *k* is the total number of rings in the network. *d* is the distance between two consecutive rings. The maximum packet arrival rate, λ_{max}, to a node, is (See details in [14]):

$$\lambda_{max} = -\frac{1}{H}\ln\left(1 - \frac{G P'_{data}\, d_{data}^{-\alpha}\, \Pi}{3 SIR_{min}(a+1)^{-(\alpha-1)} d^{-\alpha} \sum_{j=1}^{int(k/(a+1))} j^{-(\alpha-1)}}\right) \qquad (2)$$

where $\Pi = T_{it} / (P_{data}(L_{DATA} + L_{ACK}) + P_{rts}(L_{RTS} + L_{CTS}))$.

Here, G is processing gain [7] (10.4dB in IEEE 802.11 DSSS); P'_{data} is the power of the signal at the receiver; d_{data} is the distance from the transmitter to the receiver; SIR_{min} is the minimum required signal to interference ratio; α is the path loss exponent; P_{data} and P_{rts} denote the transmit power of the data and control frames, respectively; $\overline{H}$ is the average hop count.

Throughput: Let S be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit data payload without causing a collision, and is given by: $S = \lambda_{max}\tau_t$ (3)

Consumed Energy: We consider the energy consumed in all six possible states at a randomly given slot time. When the node state is at successful transmission, S_t, we also consider the energy consumed in receiving the transmissions. The six states already consider the energy consumed in retransmissions (which is caused by collisions). The energy consumed in the network, E, is the sum of the energy consumed by each hop:

$$\begin{aligned} E = \overline{H}(&S_{ii}e_{ii}\sigma + S_{it}(e_{rts}L_{RTS} + e_{cts}L_{CTS} + e_{data}L_{DATA} + e_{ack}L_{ACK} \\ &+ e_{r\text{-rts}}L_{RTS} + e_{\text{r-cts}}L_{CTS} + e_{\text{r-data}}L_{DATA} + e_{\text{r-ack}}L_{ACL}) + S_{ir}e_{rts}L_{RTS} \\ &+ S_{ic}(e_{rts}L_{RTS} + e_{cts}L_{CTS}) + S_{id}(e_{rts}L_{RTS} + e_{cts}L_{CTS} + e_{data}L_{DATA}) \\ &+ S_{ia}(e_{rts}L_{RTS} + e_{cts}L_{CTS} + e_{data}L_{DATA} + e_{ack}L_{ACK})) \end{aligned} \tag{4}$$

where e_{ii} represents the energy consumed in idle state; e_{rts}, e_{cts}, e_{data}, and e_{ack} represent the energy consumed in transmitting RTS, CTS, DATA and ACK respectively; $e_{r\text{-}rts}$, $e_{r\text{-}cts}$, $e_{r\text{-}data}$, and $e_{r\text{-}ack}$ represent the energy consumed in receiving RTS, CTS, DATA and ACK respectively.

Numerical Result: To investigate a node's performance with the maximum interference, we generate a honey grid ad hoc network, which has 20 rings, 1260 nodes, and the distance between two rings of 30 meters. min_R_{data} denotes the minimum required R_{data} and is 40m. TX power denotes transmit power. Table 1 is the parameters we used [7]. SIR_{min} is set according to 2.4GHz Lucent WaveLAN DSSS radio interface.

Table 1: Network Parameters

Parameter	Symbol	Value
RTS Length	L_{RTS}	160 bits
CTS Length	L_{CTS}	112 bits
DATA Length	L_{DATA}	4096 bits
ACK Length	L_{ACK}	112 bits
SIFS	SIFS	10 μs
DIFS	DIFS	50 μs
channel B/W	bw	2 Mbps
Header (MAC+PHY)	H	416 bits
Processing Gain	G	10.4 dB
Path loss factor	α	2
Contention Window	CW	31
SIR Threshold	SIR_{min}	10 dB

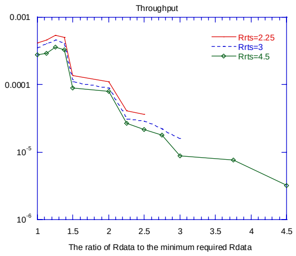

Figure 2 Throughput

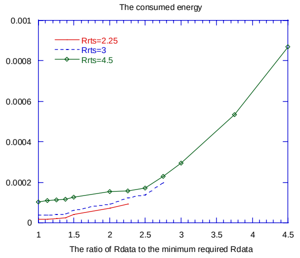

Figure 3 Consumed Energy

Figure 2 shows how the R_{data} (the transmission radius of DATA frame) and R_{rts} (the transmission radius of RTS) affect the throughput. The x-axis is the ratio of R_{data} to min_R_{data}. It increases from one to 4.5 times min_R_{data} (transmit power increases from 0.001mW to 0.0758 mW). The y-axis is the throughput. The three plots in Figure 3 represent throughput with three different R_{rts}, shown as multiples of min_R_{data}: 2.25, 3, and 4.5. For a fixed R_{rts}, the throughput is maximized when R_{data} is equal to 1.25 times the minimum required transmit power for data frame. We call this the *optimal transmit power* for a data frame. The throughput increases until this optimal value is reached. This is because with the increase of R_{data}, the number of interfering nodes is reduced. When R_{data} exceeds the optimal value, the throughput decreases. This is because more nodes will be covered in the transmitter's transmission range and the contention between nodes is increased. With smaller but sufficient R_{data}, these nodes can transmit yet not interfere with the transmitter's transmissions. For the same reason, a longer R_{rts} results in lower throughput.

Figure 3 shows the relation between the consumed energy and R_{rts}. The y-axis is the energy consumed in the network. As shown in Figure 3, with a fixed value of R_{rts}, energy consumption increases at about the same rate as R_{data}. The reasons are: 1) a higher R_{data} means a higher TX power; 2) a higher TX power causes more interference between nodes, causing more collisions. As a result, energy consumption due to retransmissions increases. Varying R_{rts}, we see that a larger R_{rts} consumes more energy. The reason is the same as explained above. The minimum energy consumption per frame, which is calculated by dividing throughput by energy consumption, is achieved at the optimal R_{data}. Although min_R_{data} consumes the least total energy, transmission with optimal R_{data} achieves the maximum throughput, yet consumes just a little more energy than min_R_{data}.

We also calculate the throughput and consumed energy with R_{data}=R_{rts}=40m (not shown). The throughput and consumed energy are 0.000553178bps and 1.49-05e joules respectively. The maximum throughput of 0.00055467bps is achieved at R_{rts}=100m; however, the consumed energy is 1.8e-05j. The per frame consumed energy at R_{data}=R_{rts}=40m is much less than the per frame consumed energy with the optimal value at R_{rts}=100m. From the previous numerical results, we have shown the throughput is reduced and consumed energy is increased with increased R_{rts}. So, the optimal TX power at min_R_{data} of 40m is at R_{data}=R_{rts}=40m. In [14], we also show the maximum throughput is achieved at R_{data}=R_{rts} with the increase of min_R_{data}. Therefore, the TX power of control frame and data frame should be equal to achieve the maximum throughput and the per frame minimum consumed energy. However, since the data payload of a data frame is usually much longer than that of a control frame, it may need to be transmitted with a higher TX power to achieve an acceptable BER. Obviously, the TX power of the control frame should not be less than the TX power of the data frame. Thus, the optimal value for throughput and consumed energy occurs when the control frame and data frame are transmitted with the same power level, and the power level is high enough for transmitting the data frame. This causes the least contention between nodes, and avoids interference.

Based on these findings, we propose a per-frame-based TPC protocol, DEMAC, in the next section.

5 DEMAC

DEMAC (adaptive energy-efficient MAC) is a per-frame-based TPC protocol, which heuristically determines the optimal transmit power in an ad hoc network. Note that DEMAC works under any level of interference, not just the maximum. The frames are transmitted at either 1Mbps or 2Mbps according to IEEE 802.11 DSSS PHY [7]. We do not consider the higher required SIR caused by the higher PHY rate, although the analysis of the previous section is applicable and DEMAC can be adapted to the higher rate.

In DEMAC, nodes use discrete TX power levels and exchange this information in the RTS/CTS handshake so that the optimal level can be determined. The transmit power of RTS is used to find the interference from the entire network. The receiver determines the optimal TX power based on the interference and data payload. CTS, DATA, and ACK are then transmitted with this optimal TX power. Next, we present DEMAC in more detail.

5.1 Table Creation

In DEMAC, each transmitting node maintains two tables. The first table, called Recording Table (RT), keeps the most recent TX power for each communicating node. If the transmitter can find the receiver's record from the RT, then the transmitter transmits to the receiver using the power level in that record. Otherwise, the transmitter uses a second table, called Checking Table (CT), to determine RTS power.

Table 2: Checking Table

level	TX power	transmission radius
1	1 mW	<=40 m
2	2 mW	<=60 m
3	3.25 mW	<=80 m
4	7.25 mW	<=100 m
5	15 mW	<=120 m
6	200 mW	120 m

CT, as shown in Table 2, is used to find the minimum required TX power for the current transmission. Note that, the transmitting node may not know the distance to the receiving node (due to node mobility), or the amount of interference in the network. CT is used when the transmitter can not find the current receiver's record in the RT, or, the RTS transmission with the TX power recorded in RT fails. If the transmitter cannot find the receiver in RT, it first transmits RTS with TX power given by the first level in CT. If there is no response, the transmitter increases the TX power to the next level in the CT.

In IEEE 802.11 [7] with PHY rate of 1Mbps and 2Mbps, the minimum TX power is 1mW and the maximum is 1W. The first entry in the CT will have TX power level of 1 mW. The number of recommended power levels is defined by *dot11NumberSupportedPowerLevels*. These static levels are recommended and provided by individual companies and are defined as *dot11TxPowerLevel1* through *dot11TxPowerLevel8*. One of these eight values will be set as the TX power during the system parameters setting, and will be used in 802.11. In DEMAC, we use that TX power as the maximum TX power (entry six) in CT. This value is chosen to be large enough to transmit the farthest required distance under the worst expected conditions. We assume the value is 200mW in Table 2. The number of power levels in CT is equal to *dot11ShortRetryLimit*. In this case, the limit is 6 [7]. The third column in CT corresponds to the maximum transmission radius with the given TX power. The values shown are based on a 2.4 GHz Lucent WaveLAN DSSS radio interface. The transmission radius in the fifth row is actually the maximum transmission radius. We calculate it to be 120 meters in Table 2. The second through fourth entries in CT are chosen to produce equal interval additions to the maximum transmission radius. Thus, CT can be used to find the minimum required TX power for RTS transmission. In Table 2, the maximum TX power is 200mW and transmission radius with this power is 120m. The first TX power level should be 1mW as we explained previously and corresponds to a radius of 40m. The gap between two neighboring transmission radius is 20 meters. Since the sixth time is the last chance, the frame will be retransmitted with the maximum TX power (200 mW). If the frame can not be transmitted after six tries, the frame will be discarded. Next, we explain how DEMAC is implemented.

5.2 DEMAC

In DEMAC, the transmitter and the receiver collaborate to find the optimal TX power level as shown in Figure 4. The receiver uses both the required SIR and the required BER to calculate the optimal TX power for the transmission.

Transmitter (Sender):

Case 1: The transmitter finds the receiver's record in the RT and sends RTS using the recorded TX power;

Case 2: The transmitter does not find the receiver's record in the RT and starts to send RTS using the minimum level TX power in CT.

The transmitter needs to include the TX power in RTS. In both cases, if the RTS has timed out, the transmitter finds the next higher TX power level in CT and retransmits the RTS using that TX power. The process will continue until the sender receives a CTS from the receiver. The reasons for the time out could be: 1) at least one other node inside the sender's transmission range transmits simultaneously; 2) the TX power is not high enough for the path loss; 3) a collision occurs at the RTS because of too much interference. To reduce the transmission delay time, we assume the cause was either of the last two. Once the transmitter receives the CTS from the receiver, it transmits the data frame using the TX power requested by the receiver (as included in the CTS) and writes it down in RT.

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Notations:
TX_count: the transmission times, which is initialed to 1;
$SIR_{min}$: the required minimum SIR (the units are dB);
tx_SIR: the increased SIR for satisfying the data payload and BER requirement, and the units are dB;
Algorithm:
Transmitter:
1.If the receiver's record is found in RT, then {transmit RTS with that TX power and include the TX power in RTS; TX_count=0;  go to 3}   else { go to 2;}
2.Sends RTS with TX power according to the TX_count (level) entry in CT, and  include the TX power in RTS;
3. If (the RTS timed out) {
        if  (TX_count=0) {find next higher TX power in CT;
              TX_count=the next higher TX power's level;}
        else   {TX_count++;}
        go to 2;}
    else { # CTS is received
        send the data frame using the TX  power indicated
         by the receiver in CTS and record in RT.}
Receiver:
1.After successfully receiving the RTS from the transmitter, find the data payload length, calculate the amount of interference based on current SIR;
2. $SIR=SIR_{min}+0.5$;
3. tx_SIR= int(data payload (octet)/228);
4. if (tx_SIR== data payload (octet)/228)
        $SIR = (SIR + (\text{tx\_SIR} \times 0.5))$;
    else
        $SIR = SIR + (\text{tx\_SIR} + 1) \times 0.5$;
5. calculate the respective TX power based on the SIR and the amount of interference;
6. send CTS using the TX power, including TX power in the CTS.
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Figure 4 DEMAC

Receiver:

Before we introduce how DEMAC is implemented by the receiver, we explain how the acceptable BER (Bit Error Rate) is determined. As shown in [13], for a fixed SNR, when SIR is more than 2 dB, the BER is below 1%; and, a 0.5 increase in SIR results in a small decrease in BER. We will use this result shortly. We assume the background noise, AWGN, is fixed.

Since the data frame is much longer than the RTS, the receiver should look for the data payload length in the duration field of RTS to determine the TX power level needed to meet the BER requirement. In the IEEE 802.11 MAC, each data-type MPDU (MAC protocol data unit) consists of 24 octets MAC header and 4 octets FCS (Frame Check Sequence), and the length of the frame is in Frame body field, which is from 0 to 2304 octets. The PPDU (PLCP protocol data unit) format of the IEEE 802.11 PHY includes 144bits PLCP (physical layer convergence protocol) preamble, 48bits PLCP header, and the length of MPDU. Receiving the data frame with the same SIR as the RTS may result in higher BER, which will cause an unsuccessful transmission. This is because the FCS is fixed at 32 bits. With the longer MPDU, the probability of longer burst errors occurring increases and FCS can not correct them. So, we increment SIR by 0.5 dB for each 228 octets. Furthermore, the interference also will increase BER. Since the data frame is transmitted with the higher TX power, it will cause more interference to other nodes. In addition to the increased SIR for data payload, we increment SIR by another 0.5 dB to avoid interference.

After successfully receiving RTS, the receiver finds RTS TX power and data payload length from it. The receiver calculates the current amount of interference based on the current SIR and the RTS TX power. It finds the required SIR for data frame by first letting $SIR=SIR_{min}$ and increasing the SIR by 0.5 dB, and then increase the SIR by 0.5 dB for each 228 octets of data payload in MPDU. After finding the required SIR, the receiver calculates the required TX power. We call this calculated TX power the *optimal TX power.*

Finally, the maximum TX power will be limited by the initial maximum TX power. Based on our conclusions in section 3.2, transmitting a control frame with a higher TX power than the data frame neither improves throughput nor reduces consumed energy. Therefore, in DEMAC, CTS, DATA, and ACK frames are transmitted with the same optimal TX power. The receiver sends CTS to the transmitter at the optimal TX power. The expected TX power is also included in CTS frame. Even if the TX power used for transmitting RTS is higher than the optimal TX power, the receiver will adjust it and find the optimal TX power for the following frames. After receiving the CTS, the transmitter will record the TX power for the receiver in RT and send the data frame using the expected TX power. In the next section, we validate DEMAC via simulations.

6 SIMULATION

We use ns-2 (ns2.27) with the CMU wireless extension [16] to perform the simulations. In our simulations, we consider the interference from all the interfering nodes. We compare DEMAC with IEEE 802.11 [7], BASIC [5], and PCM [6]. The channel bit rate is 2 Mbps and CBR (constant Bit Rate) is used as the traffic generator. Our simulations are implemented with 50 nodes randomly located in two dimensional space, $1000m \times 1000m$. In each scenario, one node may communicate with another node directly or by relaying, depending on the transmit power. We use three metrics to evaluate 802.11, BASIC, PCM and DEMAC: 1) *Aggregate Throughput* which is the sum of the data frames correctly received by the receivers per time unit; 2) *Effective Data Delivered per Joule* which is the received effective data frames divided by the entire energy consumption; 3) *Data Frame Corruption Ratio* which is the portion of MAC layer frames interrupted by interfering nodes.

6.1 Simulation Results

We simulate the network with 1) a fixed data payload length of 512 octets, 2) varying data payloads, from 100 octets to 1200 octets, and 3) node mobility.

Random Topologies with fixed data payload: Figure 5 shows the throughput in 50 random topologies. The x-axis is the sce-

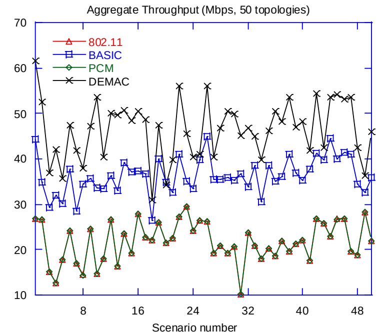

Figure 5 Throughput (fixed payload)

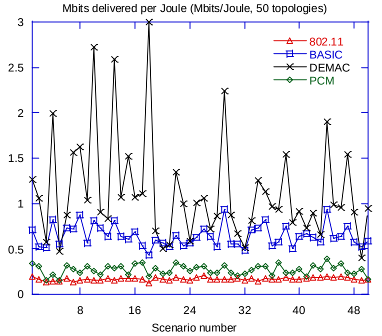

Figure 6 Data delivered per joule(fixed payload)

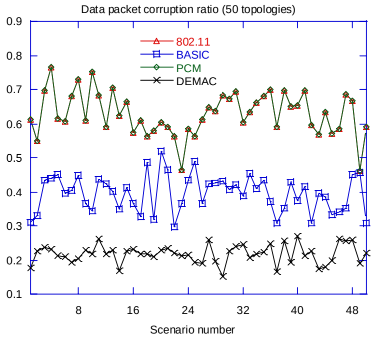

Figure 7 Corruption ratio(fixed payload)

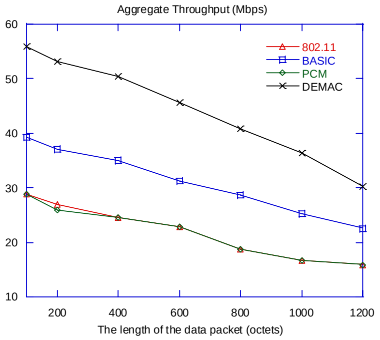

Figure 8 Throughput (varying payload)

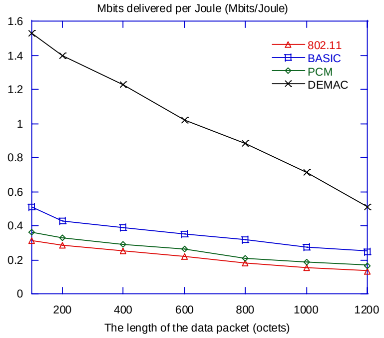

Figure 9 Data delivered per joule(varying payload)

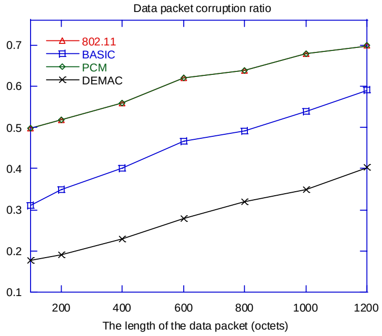

Figure 10 Corruption ratio(varying payload)

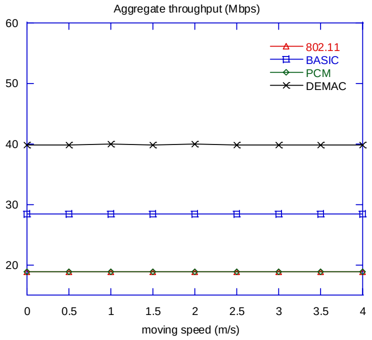

Figure 11 Throughput (varying mobility**)**

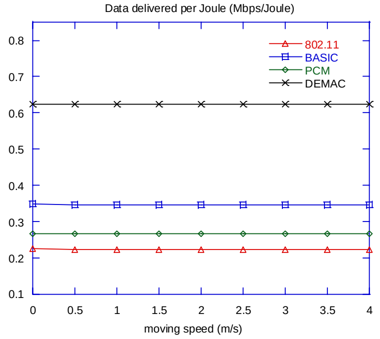

Figure 12 Data delivered per joule(varying mobility)

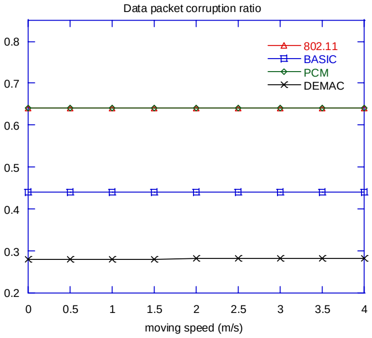

Figure 13 Corruption ratio(varying mobility)

nario number and y-axis is the throughput. DEMAC outperforms IEEE 802.11, PCM and BASIC. This is because DEMAC adaptively finds the optimal transmit power to transmit frames. DEMAC effectively avoids interference, reduces the contention between nodes, and reduces the number of idle nodes. There are fewer nodes inside the transmitter's transmission range with the optimal TX power. The contention between the transmitter and the other nodes inside the transmitter's transmission range reduces. Some of those nodes still can transmit instead of keeping idle while not interrupting the transmitter's transmission. IEEE 802.11 achieves the same throughput as PCM. BASIC is better than IEEE 802.11 and PCM. This is because BASIC transmits data frames with the minimum required transmit power. So, compared with IEEE 802.11 and PCM, BASIC reduces the number of idle nodes during data frame's transmission. Figure 6 shows data delivered per joule with random topologies. The y-axis is the Mbits delivered per joule. In all 50 scenarios, DEMAC outperforms IEEE 802.11, PCM and BASIC. BASIC delivered more data per joule than PCM and IEEE 802.11. Figure 7 shows data frame corruption ratio with random topologies. DEMAC causes less corruption than the others. IEEE 802.11 causes the same percentage corruption as PCM. BASIC causes less corruption than IEEE 802.11 and PCM.

Random Topologies with Varying Data Payloads: We simulate random topologies with varying data payloads, ranging from 100 octets to 1200 octets. Each point in the plots is averaged over 50 random topologies.

Figure 8 shows the throughput with varying data payloads. The x-axis is the data payload, which is varying from 100 octets to 1200 octets. Throughput is reduced with increased data payload. As we explained in Section 5.2, the acceptable BER is reduced with a higher data payload. The longer data frame must be transmitted with a higher TX power, which will cause more interference to other nodes, more contention between nodes, and more idle nodes as previously explained. DEMAC has better throughput than all the others protocols. This is because DEMAC adaptively finds the optimal transmit power for the transmissions. IEEE 802.11 achieves the same throughput as PCM. BASIC outperforms IEEE 802.11 and PCM. This is because BASIC transmits data frames with the minimum required transmit power. Compared with IEEE 802.11 and PCM, it will cause less interference to other transmitting nodes and has fewer number of idle nodes.

Figure 9 shows data delivered per joule with varying data payloads. The delivered data per joule is reduced as data payload is increased. DEMAC delivers more data than all the others. BASIC is next, then PCM, and finally, IEEE 802.11. Figure 10 shows the data frame corruption ratio with varying data payloads. The corruption ratio is increased with the increased data payloads. DEMAC has the least corruption ratio among the four protocols. IEEE 802.11 has the same corruption ratio as PCM. BASIC has less corruption ratio than 802.11 and PCM.

Random Topologies with Varying Mobility: We simulate random topologies with varying mobility. Each point in the figures is averaged over 50 random topologies with a fixed data payload length of 1000 octets.

Figure 11 shows the aggregate throughput for random topologies with varying mobility. The simulated mobility patterns are specified by the nodes' moving speeds, which are 0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4m/s. The x-axis is the moving speeds of the nodes. The y-axis is the aggregate throughput. We assume that no multipath fading occurs. As shown in Figure 11, the protocols are not sensitive to node mobility. This is because the path loss condition (α in Equation 2) is the same for all the protocols. DEMAC outperforms the other three because it considers all the interference from interfering nodes and transmits frames using the optimal transmit power. IEEE 802.11 and PCM achieve the same throughput. BASIC achieves better performance than IEEE 802.11 and PCM. It is because BASIC transmits data frames using the minimum required transmit power. It causes less interference to other nodes and has fewer idle nodes than IEEE 802.11 and PCM.

Figure 12 shows data delivered per joule with varying mobility. The results show that each protocol delivers the same amount of data with varying mobility. The reason is the same as in aggregate throughput. DEMAC delivers more data than the other three protocols. Figure 13 shows the packet corruption ratio with varying mobility. The corruption ratio is not sensitivite to mobility of the nodes. DEMAC achieves the least corruption ratio among all protocols. BASIC has less corruption ratio than IEEE 802.11 and PCM. IEEE 802.11 and PCM have the same corruption ratio.

6.2 Summary

From the simulations, we verify that DEMAC has the following advantages: 1) DEMAC significantly outperforms existing protocols which do not consider all the interference in the network; 2) Increased SIR for finding optimal transmit power is very effective in improving the throughput and saving energy; 3) DEMAC still performs the best when nodes are mobile.

7 CONCLUSION

In this paper, we proposed a novel per-frame-based TPC protocol, DEMAC (adaptive energy efficient MAC) used with the low PHY rate. In DEMAC, transmit power of RTS is used to find the interference in the network. Based on the interference and data payload, the receiver determines the optimal transmit power for the following transmissions. CTS, DATA, and ACK are transmitted at this optimal transmit power. DEMAC is validated by simulations. DEMAC outperformed previous power control protocols, for example, BASIC and PCM. This is because the design of DEMAC is considered to avoid interference, improve throughput, and save energy. We will adapt DEMAC to 802.11 with high rate in the future.

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