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Evaluation of auxiliary tone based MAC scheme for wireless ad hoc networks with directional antennas

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***Abstract*—This Paper presents an analytical evaluation of auxiliary tone based MAC scheme that has been proposed to mitigate the directional antenna utilization problems in wireless ad hoc networks. We conducted a comparison study between two different Markov models for auxiliary tone based MAC scheme. In the proposed model in addition to the idle, success, and fail states, also the defer state has been considered that is more realistic. Results show that the proposed scheme outperforms the RTS/CTS based MAC scheme not only in high density networks but also in networks with low probability of transmission and low density networks.**

Keywords*- *ATB-DMAC; Directional Antennas; Medium Access Control; Ad Hoc Networks

I. INTRODUCTION

One of the most important issues in wireless ad hoc networks is how to exploit directional antenna benefits while avoiding the MAC layer problems like directional hidden node, directional exposed node, and the deafness problems [1]. Various MAC schemes have been proposed to make a satisfactory trade off between benefits and drawbacks of utilizing directional antennas. In [2] Deng et al. introduced Dual Busy Tone Multiple Access (DBTMA) which uses busy tones to prevent the omni-directional hidden node and deafness problems. In [3] the DBTMA has been extended to the nodes equipped with directional antennas for transmitting the busy tones. In [1] the deafness problem has been introduced and a busy tone based scheme has been proposed to mitigate it by informing the neighbors about end of the data transmission. The auxiliary tone based directional MAC scheme (ATB-DMAC) [4] is a useful MAC scheme that has been proposed to exploit the benefits provided by directional antennas in wireless ad hoc networks while attempting to mitigate the hidden node, exposed node, and deafness problems. One of the essential characteristic of ATB-DMAC scheme is its tone based neighbor discovery at the beginning of each packet transmission that can make it more suitable for mobile ad hoc networks with random movements. In [4] performance of this scheme has been evaluated based on the three states discrete Markov model and show that ATB-DMAC outperforms RTS/CTS based directional MAC only in dense networks and in networks with high probability of transmission. In this paper we conducted a comparison evaluation based on the Markov model with four states in which the idle, success, fail, and defer states have been considered and show through analysis how ATB-DMAC can help to increase throughput also in networks with low probability of transmission and low number of network nodes.

The rest of the paper is outlined as follows. Section II reviews the ATB-DMAC scheme. In section III the performance analysis is presented. Section IV includes the numerical results. We conclude the paper in section V.

II. ATB-DMAC SCHEME

As mentioned in [4], each node is equipped with an M=360/θ (where θ is beam-width) elements switched beam antenna that can be used in Tone-Antenna (TA) and Packet-Antenna (PA) modes for transmitting tone and control/data packets, respectively. Adopting two-way ground model for transmission and signal-to-noise-plus-interference-ratio (*SNIR*) as successful reception criterion, we must have $SNIR = (P_t / P_k) = (R_k^4 / R_t^4) \geq \sigma$. In which $\sigma = (R_i^4 / R_t^4)$ is the *SNIR* threshold, R_t, R_k and R_i are transmission range, interferer-receiver distance and interference range, respectively.

Each node with ATB-DMAC scheme uses following out-of-band tones to inform the neighbor nodes about its situation.

- Transmitter Direction Tone (TDT)
- Receiver Direction Tone (RDT)
- Other-direction Busy Tone (OBT)
- Same-direction Busy Tone (SBT)
- Desired Direction Tone (DDT)
- Collision Occurrence Tone (COT)
- RTS Collision Occurrence Tone (RCOT)

As noted before, nodes with ATB-DMAC scheme obtain the neighbor location information at the beginning of each packet transmission. Fig. 1 shows a comprehensive example that is set such that the application of each tone be considered. Suppose that in Fig. 1.1 nodes A and F want to send data to nodes B and E, respectively. They start with TDT tone transmission on all M beams sequentially, to inform the neighbors about packet transmission and its own direction and also obtaining their neighbors' location information. Fig. 1.2 shows that nodes B and G are idle and sense no tone but TDT tone, therefore they reply with the RDT tone to inform their existence/presence and their accessibility on that beam. Nodes C and D are communicating with each other, thus reply with

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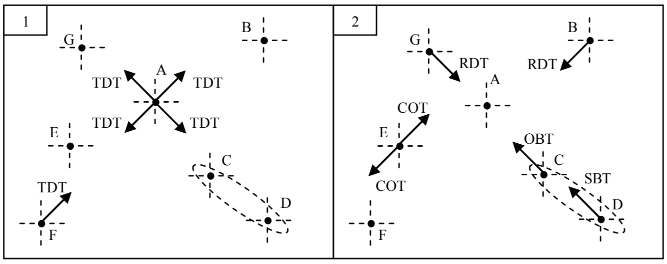
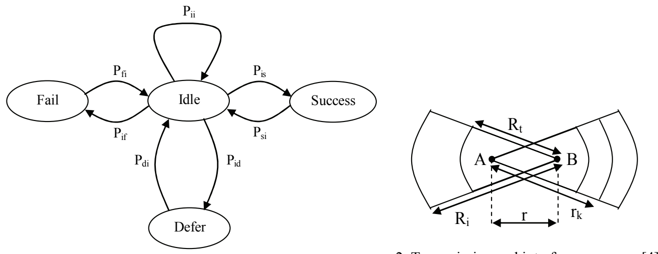


Figure 1. Node reactions in a network based on the ATB-DMAC scheme



1. Four state Markov model for steady-state probabilities 2. Transmission and interference ranges [4]

Figure 2. The Markov model and ranges for ATB-DMAC scheme.

OBT (to prevent the deafness by informing about involving in a connection in another direction, which prevents more try and increased back-off time) and SBT (to prevent the hidden node problem by informing about involving in a connection in the same direction, which prevents any future interferences) tones, respectively. Node E senses TDT tone on two different beams and replies with COT tone to inform the transmitters about simultaneous TDT transmission and to prevent probable collision occurrence on this direction. Thereafter, node F receives the COT tone and goes to the TDT defer state, which is designed to prevent future simultaneous TDT transmissions. Node A only replies with RTS packets on the directions that RDT tones are received and does not send any signal to the directions which the OBT, SBT, and COT tones have been received. Based on the destination address in RTS packet, since the received RTS packet is not related to the node G, it does not reply. In response to the successful RTS reception, node B transmits the DDT tone (to inform about intended node location) and CTS packet. Since the transmitter do not scans packet antenna for CTS packet but instead scans out of band frequencies using tone antenna, the DDT tone transmission can decrease the waiting time. When it detects the DDT tone selects the related packet beam. Finally, proper reception of data packet in receiver is acknowledged by ACK packet transmission. Due to node movements it is possible to have simultaneous RTS reception. The RTS collision occurrence is informed by RCOT tone transmission.

III. PERFORMANCE ANALYSIS

In [4], a three state discrete Markov model has been adopted for obtaining the saturation throughput. In the proposed model we adopt the four state Markov model shown in Fig. 2.1 which has been used in [7] for performance evaluations. In this case saturation throughput and transmission delay can be calculated as follows:

$$Throughput = \frac{P(S)T_{DATA}}{P(I)T_i + P(S)T_s + P(D)T_d + P(F)T_f} \quad (1)$$

$$Delay = T_s + (P(D)T_d + P(F)T_f + P(I)T_i)/P(S) \quad (2)$$

where *P(I), P(S), P(D),* and *P(F)* are the steady-state probability of Idle, Success, Defer, and Fail states, and their duration has been denoted by T_i, T_s, T_d, and T_f, respectively. T_{DATA} denotes the average data packet duration. Note that non-idle nodes will return to idle state after the corresponding duration with probability 1. Thus, assuming P_{xy} as probability of transition from *x* to *y*, we have: $P_{si}=P_{di}=P_{fi}=1$.

As depicted in Fig. 2.1 each node is in one of the before-mentioned four states, which implies:

$$P(I)+P(S)+P(D)+P(F)=1 \quad (3)$$

$$P(I) = P(I)P_{ii} + P(S)P_{si} + P(D)P_{di} + P(F)P_{fi} \quad (4)$$

Using (3) and (4), we obtain $P(I)=1/(2-P_{ii})$. Adopting Poisson distribution with density ρ for node locations over two dimensional plane, the probability of finding *k* nodes in an area of *A* is equal to: $P(k,A)=((\rho A)^k/k!).exp(-\rho A)$.

Let us denote the transmission probability of each node with *p,* the probability of transition from idle state to itself can be expressed as equation (5). From Fig. 2.1 we can see that the steady-state probability of different states and the idle state are related via equations $P(S)=P(I)P_{is}$, $P(F)=P(I)P_{if}$, and $P(D)=P(I)P_{id}$.

$$P_{ii} = \sum_{k=0}^{\infty} (1 - p\frac{\theta}{2\pi})^k (\frac{\rho A}{k!}) \exp(-\rho A) = \exp(-\rho p \frac{\theta}{2\pi} A) \quad (5)$$

We define interference areas for different durations according to depicted ranges in Fig. 2.2, as below:

$$A_0 = 0 \,,\; A_1 = R_t^2(\theta/2)$$

$$A_2 = \begin{cases} R_t^2(\theta/2) - r^2 \tan(\theta/2)/2 \\ \quad 0 \le r \le R_t \end{cases}$$

$$A_3 = \begin{cases} 0 & 0 \le r \le R_t/\sqrt[4]{\sigma} \\ \sqrt{\sigma} r^2(\theta/2) - R_t^2(\theta/2) & R_t/\sqrt[4]{\sigma} \le r \le R_t \end{cases} \quad (6)$$

Let us denote the probability of successful reception in first time slot, TDT, RDT, RTS-CTS-ACK, DDT, and DATA durations with P_1 to P_6, respectively.

Hence, we have:

$$P_1 = \exp(-\rho p(\theta/2)A_1)$$

$$P_2 = P_3 = \exp(-\rho p(\theta/2)A_2(T_{Tone\_Collision} + 2))$$

$$P_4 = \exp(-\rho p(\theta/2)A_0(t_{RTS} + T_{CTS} + T_{ACK} + 3))$$

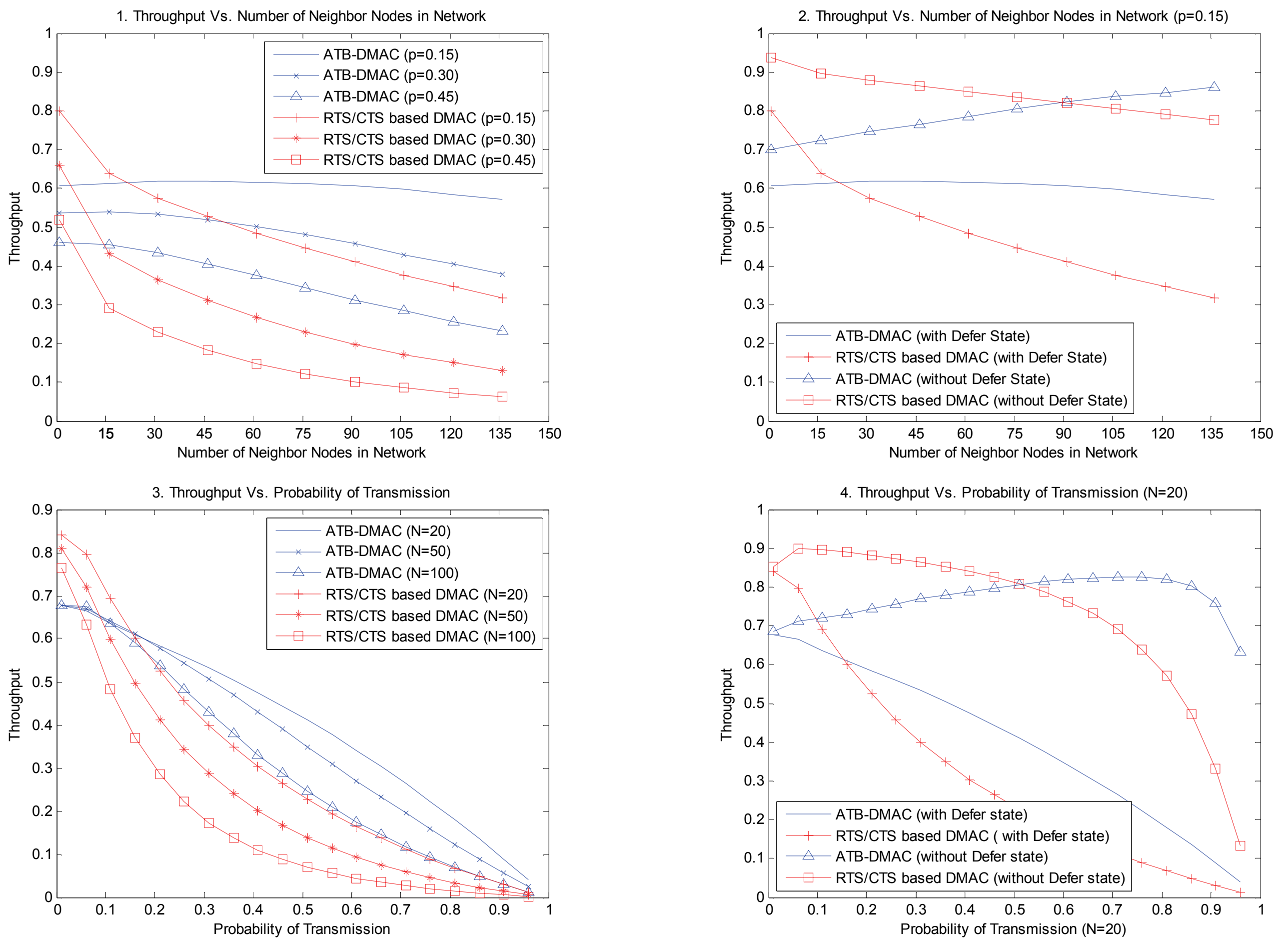


Figure 3. Analytical Comparison Results-Throughput

$$P_5 = \exp(-\rho p(\theta/2)A_3(T_{DDT}+2))$$
$$P_6 = \exp(-\rho p(\theta/2)A_0(T_{DATA}+2)) \qquad (7)$$

$$P_{is}(r) = \prod_{k=1}^{6} P_k,$$
$$P_{is} = p(1-p)\int P_{is}(r)f(r)dr, \qquad f(r) = 2r \qquad (8)$$

In which $T_{Tone\_Collision}$ is the mean waiting time for tone transmission on each beam.

Finally, we must obtain the idle, success, fail, and defer state durations. According to [5], we assume that T_f follows a truncated geometric distribution:

$$T_f = ((1-p)/(1-p^{T_2-T_1+1}))\sum_{k=0}^{T_2-T_1} p^k(T_1+k)$$
$$T_1 = T_{TDT}+1, \qquad T_2 = M(T_{TDT}+T_{RDT})+t_{RTS}+3 \qquad (9)$$

Where T_{TDT} and T_{RDT}, and are time durations of TDT, RDT tones transmission, respectively. T_{RTS} is time duration of RTS packet transmissions. The total RTS transmission time, can be derived as follows.

$$t_{RTS} = (M.P_{inp})T_{RTS}, \; P_{inp} = \sum_{k=0}^{\infty}((\rho A)^k/k!)\exp(-\rho A) \qquad (10)$$

In which P_{inp} is the probability that at least one idle node presents in the transmission area A of intended node. For simplicity, we assume T_i=*1* and T_s =T_d=

$$T_{TDT}+T_{RDT}+t_{RTS}+T_{DDT}+T_{CTS}+T_{DATA}+T_{ACK}+7 \qquad (11)$$

The transmission probability of each node in the next time slot, given that channel is idle, have been obtained in [6]. A transmission can be successful or not. Also, when a node receives a packet from higher layer and senses the channel busy or does not receive any data from physical/higher layer it will not transmit. Hence,

$$P_{if} = p - P_{is}, \qquad P_{id} = (1-p) - P_{ii} \qquad (12)$$

For evaluating the ATB-DMAC σχημε using new model we conducted throughput and delay comparison with the RTS/CTS based DMAC scheme proposed in [5]. Since in

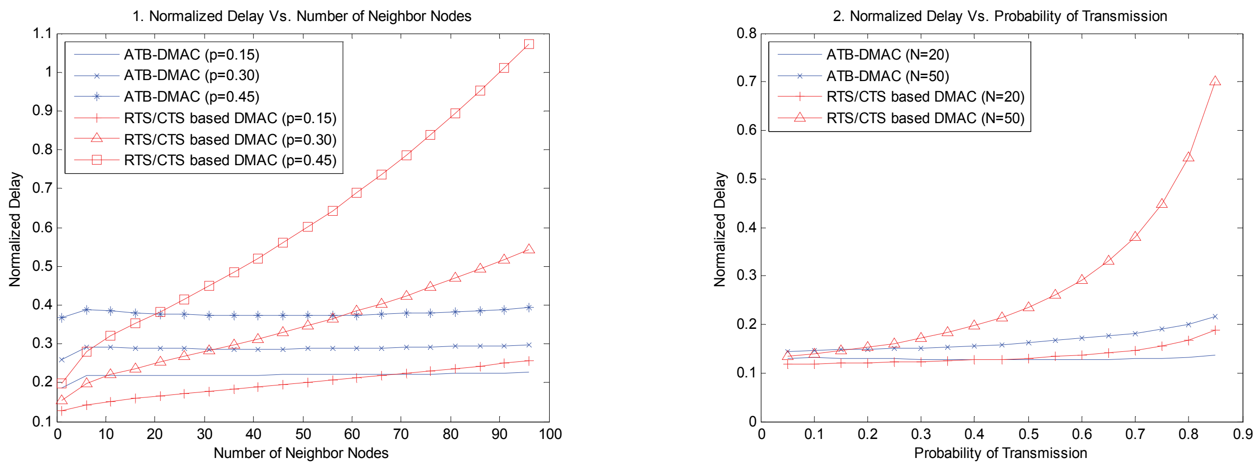


Figure 4. Analytical Comparison Results-Delay

RTS/CTS based DMAC nodes transmit all packets directionally and do not inform neighbor nodes before packet transmission, we must substitute A_0 with A_3, and in P_2 replace the $T_{Tone\text{-}Collision}$ with T_{RTS}. Also, $T_1=T_{RTS}+1$, and $T_2=T_{RTS}+T_{CTS}+T_{DATA}+T_{ACK}+4$.

IV. Numerical Results

In order to evaluate the above schemes we set parameters as follows: $\sigma=10$, $\theta=\pi/8$, $T_{TDT}= T_{RDT}= T_{DDT}=1$, $T_{RTS}=20$, $T_{ACK}= T_{CTS}=14$ and $T_{DATA}=1024$.

Fig. 3.1 shows that when number of neighbor nodes is increased the ATB-DMAC outperforms the RTS/CTS based DMAC, *e.g.* in networks with $p=0.15$, $p=0.30$ and $p=0.45$ for nodes with more than 20, 8, and 5 neighbor nodes, respectively. The results in Fig. 3.2 show that, with four state Markov model, the ATB-DMAC scheme gives better throughput than RTS/CTS based DMAC for wider range of network densities in comparison with the three state Markov model. Fig. 3.3 shows that in a network with certain nodes ATB-DMAC gives better performance for increasing in the probability of transmission. Also Fig. 3.4 shows that based on the four and three state model throughput of nodes with 20 neighbor nodes for proposed scheme outperforms RTS/CTS based scheme for $0.2<p<1$ and $0.5<p<1$, respectively, which means that the new scheme can outperforms in wider range than that have been proposed by the three state Markov model. Although, in Fig. 3.2 and 3.4 the three state model throughput is higher than that for the new model, but it must be noticed that the defer state (also exponential back-off times [6] which has been considered in new model and can decrease the throughput severely) has not been considered. As shown in Fig. 4.1 due to neighbor discovery duration, with low number of neighbor nodes the proposed scheme's delay is higher than that for other scheme. For higher numbers, its delay increases slightly while it increases dramatically for latter scheme. Also, Fig. 4.2 depicts that with same number of neighbor nodes for higher probability of transmission the proposed scheme's delay is much better than that for the RTS/CTS based scheme.

V. Conclusion

In this paper we reviewed the ATB-DMAC scheme and proposed a four states Markov model for performance evaluation in which also the defer state has been considered. The comparison evaluations are performed for the proposed scheme and RTS/CTS based MAC scheme based on the new analytical model. Numerical results show that the proposed MAC scheme outperforms the RTS/CTS based MAC scheme not only in high density networks but also in networks with low probability of transmission and in low density networks. Results confirm the reasonable performance of proposed ATB-DMAC scheme.

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