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A Novel Multi-Channel Based Scheme for Multi-Hop IEEE 802.11 Ad Hoc Networks

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Abstract: The most popular MAC protocol for mobile ad Hoc networks is IEEE 802.11 MAC specification which allows practical use of eight channels in 802.11a and three in 802.11b. In order to improve network throughput several multi-channel MAC protocols which allow multiple channels operation have been proposed for IEEE 802.11 Ad Hoc networks. However, simultaneous multiple channels operation is still not allowed because there is only one wireless transceiver per node in above schemes. This study introduces a novel multi-channel based scheme for multi-hop 802.11 Ad Hoc networks of which each node has multiple transceivers, which can resolve exposed terminals problem, hidden terminals problem and intruding terminals problem effectively. The MAC protocol in the scheme is also provided. Numerical results show that network throughput is significantly improved with more transceivers per node.

Key words: Mobile Ad Hoc networks (MANETs), IEEE 802.11, multi-transceiver based MAC protocol (MTMAC)

INTRODUCTION

A mobile wireless Ad Hoc network (MANET) comprises of a set of nodes equipped with wireless transceiver, thus the nodes can communicate with each other without any fixed infrastructure relay[1]. The Medium Access Control (MAC) protocol is one of the key techniques for Ad Hoc networks. The most popular MAC protocol supporting mobile Ad Hoc networks is the IEEE 802.11 MAC specification[2]. Mobile nodes in Ad Hoc mode can communicate directly with their neighboring nodes by exchanging RTS-CTS-DATA-ACK. Currently, IEEE 802.11 supports the use of multiple channels; frequency bands that can be used simultaneously without any interference with each other. For example, in IEEE 802.11b, nodes can use up to three channels and in IEEE 802.11a, up to eight channels can be used. In contrast to access points with multi-channel capability in infrastructure mode, mobile nodes in Ad Hoc mode are assumed to use only one channel in the current standard.

To utilize multiple channels in Ad Hoc networks several MAC protocols have been proposed. A modified IEEE 802.11 MAC protocol for multi-channel multi-hop Ad Hoc networks was proposed in[3]. A novel multi-channel MAC protocol was reported in[4] for IEEE 802.11 Ad Hoc networks. The simulation results show that performance improvement is remarkable in both papers. In[5], Adaptive Acquisition Collision Avoidance multiple access (AACA) protocol was proposed mobile Ad Hoc networks. The AACA protocol was based on combination of multiplechannels and random reservation. The common feature of above protocols is that there is only one wireless transceiver per node in MANETs, so the node just has half-duplex communication capability. At a given time instant, a node can communicate with only one node in the case of unicast, so the performance improvement of network is still limited.

In this study, a novel multi-channel based scheme as well as the MAC protocol named as MTMAC was proposed for IEEE 802.11 Ad Hoc networks. In the scheme there are multiple sub-nodes equipped with independent wireless transceiver (IEEE 802.11 wireless card). One of the available IEEE 802.11 channels is served as common channel for control packets transfer; the others are served as traffic channels for data packet transfer. Every sub-node dynamically reserves an idle traffic channel by RTS/CTS dialogue on the common channel that enable a node to perform parallel communications with other nodes. Fast packet switching is enabled between sub-nodes within the same node. The MTMAC protocol is expected to outperform the single-transceiver based protocols for IEEE 802.11 Ad Hoc networks. The main drawback of multi-transceiver based schemes is that the cost and energy consumption is increased, which is not a big problem for vehicle-mounted tactical systems.

MULTI-CHANNEL BASED SCHEME

Consider a MANET in which N nodes are randomly distributed in a predefined quadrate area. Each node has

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M sub-nodes and a different identifier (ID), say 1, 2, ..., N. Each sub-node has a wireless card (IEEE 802.11a or b) operating in half-duplex mode and a buffer for sending/receiving. The number of available channels is Nch, and then Nch is 8 when 802.11a transceiver is used or 3 when 802.11b is used. Two nodes within a fixed transmission range R can directly communicate with each other by their sub-nodes. One of the channels is served as common channel for reservation packet transfer and others is used as traffic channels for data packet transfer. When a sub-node has no data packet to transmit or receive, it senses the common channel. Let t_{PKT} , t_{RTS} , t_{CTS},. t_{SACK} and t_{ACK} be the transmission time of data packet, RTS packet, CTS packet, SACK and ACK packet, respectively. Transmission delay τ includes signal propagation delay t_p, RX_TX turn-around time trt, and carrier detection time t_d (i.e., $\tau = t_{rt}+t_p+t_d$). Suppose Distributed Inter-frame Space (DIFS) is the shortest time interval from the time that a sub-node senses the common channel is idle to that the sub-node begins to transmit. SIFS is short inter-frame space. Every sub-node dynamically reserves an idle traffic channel by RTS/CTS dialogue on the common channel that enable a node to perform parallel communications with other nodes.

MTMAC PROTOCOL

The proposed MAC (MTMAC) protocol is illustrated in Fig. 1. Each node maintains a channel state table by monitoring the common channel via its sub-nodes. All the sub-nodes within a node share the same channel state table. The channel state table stores the channel-related information for all of the traffic channels. As shown in Table 1, the available channel number is from 1 to Nch-1, channel number 0 represents the common channel. The CAV (Channel Allocation Vector) stores the status of all traffic channels. The CAV is similar to a NAV (Network Allocation Vector) in IEEE 802.11, indicating the time reserved for data transmission over the channel. Each traffic channel has a timer in CAV table and the timer is set according to the packet length value contained in the CTS/SACK dialogue packet for the indicated channel, and is decremented at each time unit. When the m-th sub-node of node i (i.e., i.m) wants to communicate with the n-th sub-node of node j (i.e., j.n), i.m will transmit an RTS packet to j.n after a DIFS, In the packet, the sender (i.m) designates multiple idle channels (at most Nch-1 channels) by retrieving the list of available channels from its channel table. The receiver (j.n) will randomly choose one idle channel from these channels by consulting its own channel state table and return a CTS packet to inform i.m and other neighbors (sub-nodes) of its choice. Then i.m will broadcast their transmission channel number to its neighboring sub-nodes by sending acknowledgement (SACK) packet. Every sub-node overhearing the CTS or SACK packet will know that RTS/CTS packets have been exchanged successfully and packet transmission will occur on the negotiated channel. These sub-nodes will not arrange any transmissions on that channel until ACK packet has been transmitted successfully. If i.m does not send SACK packet, its neighbors still record these channels as idle state. Every sub-node that receives the CTS packet will set a timer with interval $(t_{SACK}+t_{PKT} +t_{ACK}-t_{RTS}-t_{CTS})$ for the corresponding channel in CAV table, every sub-node that receives the SACK packet will set a timer or update the timer with interval $(t_{PKT}+t_{ACK}-t_{RTS}- t_{CTS}-SIFS)$ for the corresponding channel in CAV table. In order to reduce the collision probability of RTS packet, the contention window and the exponential back off scheme specified in IEEE 802.11 DCF is also exploited in MTMAC protocol.

Table 1: Channel number is from 1 to Nch-1

Channel number	Channel allocation vector
1	2 unit
2	0 unit
...	...
Nch-1	4 unit

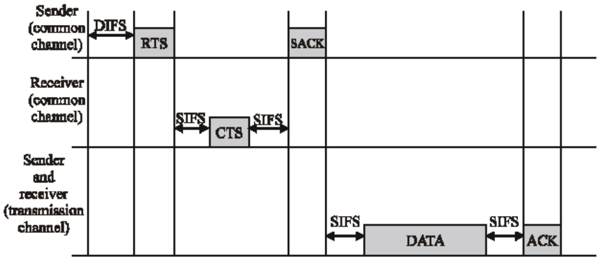

Fig. 1: MTMAC protocol

By separating the traffic channels from common control channel, MTMAC protocol can achieve collision avoidance and resolve exposed terminals problem, hidden terminals problem and intruding terminals problem effectively.

THROUGHPUT ANALYSIS OF MTMAC PROTOCOL

Throughput is defined as the average number of successful data packet transmissions over a given period. For simplicity, we assume that there are no transmission errors and each sub-node in each node receives a data packet from upper layer based on independent Poisson arrival process. Set the total packets arrival rate is λ per node, and then the arrival rate is λ/M

per sub-node. Every node sends its traffic packets to its neighboring nodes with equal probability. The receiving node chooses one of its sub-nodes to receive with equal probability too. Therefore the transmission traffic from i.m to j.n is $\lambda_{i.m-i.n} = \lambda/(M^2.Deg_i)$ where *Degi* is the number of neighbors of node I.

Define the connectivity parameter as follows:

$$C(i, j) = \begin{cases} 1 \text{ if node I and j are 1-hop apart from each other} \\ 0 \text{ otherwise} \end{cases}$$

Define hidden terminal parameter of network as follows:

H (I, j) {1 if node I and j are hidden terminals ,0 otherwise

Define the distance parameter as follows:

$$Hop(I,j) = \begin{cases} k \text{ if node I and j are k-hop apart from each} \\ \text{other } 0 \text{ otherwise} \end{cases}$$

Define function $F_{hop}(i, k)$ as follows:

Fhop (I, k) = { 1 if Hope(i, k) = hop 0 otherwise

The successful transmission time Ts of MTMAC protocol on the common channel is given as:

$$T_s = DIFS+\tau+t_{RTS}+2SIFS+t_{CTS}+t_{SACK} \quad (1)$$

Consider the case where sub-node i.m starts a transmission of a data packet to j.n at time t. The transmission will be successful only if the following conditions are satisfied.

- Sub-node j.n is not transmitting on the same channel at the same time.
- At least an idle channel can be designated between i.m and j.n via RTS/CTS dialogue.
- The sub-nodes which one-hop apart from i.m and j.n do not transmit during the interval $(t-\tau, t+\tau)$.
- The sub-nodes which is one-hop apart from j.n and are HTs of sub-node i.m do not transmit any data packet during the interval $(t-\tau-t_{RTS}, t+\tau+t_{RTS})$.

For convenience we do not exploit the similar Markov model used in[6] to compute the probability that i.m is sending to j.n at time t. According to equal probability principle, the probability that i.m is sending packet to j.n is

$$[\lambda/(M^2\cdot Deg_i)]/[\lambda(Deg_i+1)] = 1/[M^2De_gi(Deg_i+1)] \quad (2)$$

The probability that sub-node j.n is transmitting is $(\lambda/M)/[\lambda(Deg_i+1)]$, then the probability that sub-node j.n is not transmitting is

$$\left[1-\frac{1}{M\cdot(Deg_i+1)}\right]$$

because the data packet is generated on Poisson arrival process, the probability that sub-node j.n does not generate a data packet is $\exp(-(\lambda/M)\cdot T_s)$. So the condition 1 can be described as follows:

$$P_{i,mj.n} = \frac{1}{M^2(Deg_i(Deg_i+1)}.\left[1\frac{1}{M^2(Deg_i+1)}\right]\cdot exp(-\lambda/M)T_s) \quad (3)$$

Condition 2 can be represented as

$$P_{idle}(i.m, j.n) = \sum_{k=1}^{Nch-1}\sum_{k=1}^{Nch-1}\begin{bmatrix} P(_{node\,i.m\,can\,designate\,k\,idle\,channels}). \\ P(_{node\,j.n\,has\,l\,idle\,channels}). \\ P(_{node\,j.n\,atleast\,has\,one\,idle\,channels\,belong\,to\,i.m's\,idle\,channels\,set\,node\,i.m\,can\,designate\,k\,idle\,channels\,and\,node\,j.n\,has\,i\,dle\,channels}). \end{bmatrix} \quad (4)$$

where

$$P(_{node\,j.n\,atleast\,has\,one\,idle\,channel\,belong\,to\,i.m's\,idle\,channel\,set\,node\,i.m\,can\,designate\,k\,idle\,channels\,and\,node\,j.n\,has\,l\,idle\,channels}).$$
$$= \begin{Bmatrix} 1-\dfrac{C^1_{Nch-1-k}}{C^1_{Nch-1}}, & k+1 \le N_{ch}-1 \\ 1, & k+1 > N_{ch}-1 \end{Bmatrix} \quad (5)$$

According to the Erlang=s formula of queue theory, P(i.m has k idle channels) and P(j.n has *l* idle channels) can be expressed as

$$\begin{aligned} &P(_{i.m\,has\,k\,idle\,channels}) \\ &= P(_{there\,are\,Nch-1-k\,busy\,channels\,for\,mod\,e\,i.m}) \\ &= \begin{Bmatrix} p_0(\dfrac{\lambda_{c-i.m}}{\mu})^{Nch-1-k}\left[\dfrac{1}{(N_{ch}-1-k)!}\right], & 0\le k\le Nch-1 \\ & otherise \end{Bmatrix} \end{aligned} \quad (6)$$

Where

$$\mu=1/Ts,\ P_0 = \left[\sum_{K=1}^{N_{ch}-1}(\frac{\lambda_{c-i.m}}{\mu})^{Nch-1-k}\frac{1}{(N_{ch}-1-k)!}\right]^{-1} \quad (7)$$

and

$$\lambda_{c-i.m} = \lambda\left\{\sum_{k=1}^{N}F_2(k,i)\frac{1}{Deg_k}\sum_{l=1}^{N}[C(l,k)C(l,i)]+\sum_{k=1}^{N}C(i,k)\right\}$$

The different between P(j.n has l idle channels) and P(i.m has k idle channels) is that $\lambda_{c\text{-}i.m}$ is replaced by $\lambda_{c\text{-}j.n}$ in above Eq., i.e.,

$$\lambda_{c-j.n} = \lambda\left\{\sum_{k=1}^{N} F_2(k,j)\frac{1}{Deg_k}\sum_{l=1}^{N}[C(l,k)C(l,j)] + \sum_{k=1}^{N} C(j.k)\right\} \quad (9)$$

Condition 3 and 4 can be combined together as

$$P_s(i.m, j.n) = \exp\left\{\begin{matrix} -(\lambda/M)\left[\tau\cdot M\sum_{k=1}^{N} C(l,k)C(l,j) + 2(M-1)\right] \\ -(\lambda/M)\cdot t_{RTS}\cdot\left[M\sum_{k=1}^{N} H(k,i)C(k,j)\right]\end{matrix}\right\} \quad (10)$$

The channel state of random access systems can be divided into busy period B and idle period I. We can define the stable throughput from sub-node i.m to j.n on common channel as

$$S_c(i.m, j.n) = \frac{U(i.m, j.n}{B(i.m, j.n) + I(i.m, j.n)}, \quad (11)$$

Where B(i.m,j.n) and I(i.m,j.n) are the average busy and idle periods of transmission from sub-node i.m to j.n repectively. U(i.m,j.n) is the probability of that the sender transmit a packet successfully during a busy period and

$$U(i.m, j.n) = P_{i.m, j.n}\cdot P_{idle}(i.m, j.n)\cdot P_s(i.m, j.n) \quad (12)$$

I (i.m,j.n) is the average idle period of the Poisson data stream with arrival rate $(\lambda/M)\cdot[_{\text{the Number of sub-nodes related to transmission from i.m to j.n}}]$, i.e.,

$$I(i.m, j.n) = \frac{1}{\sum_{k=1}^{N}\lambda[C(k,i) + C(k,j) - C(k,i)C(k,j)]} \quad (13)$$

In order to get B(i.m, j.n), we define two random variables Y and Z which are respectively equal to the interval from the appearance of the first unsuccessful transmission packet to the appearance of the last unsuccessful transmission packet during busy interval $(0, \tau)$ and $(0, \tau + t_{RTS})$. Then the average time intervals of unsuccessful packet transmissions are

$$T_{cr} = \overline{Y} + \tau + DIFS + t_{RTS} \quad (14)$$

$$T_{CZ} = \overline{Z} + \tau + DIFS + t_{RTS} \quad (15)$$

Where $\overline{Y}$ and $\overline{Z}$ are the mean value of Y and Z respectively, as

$$\overline{Y} = \tau\text{-}[1\text{-}EXP(\text{-}E\tau G_y)]/G_y \quad (16)$$

$$\overline{Z} = \tau + t_{RTS}\text{-}\{1\text{-}\exp[\text{-}(\tau + t_{RTS})G_Z]/G_z\} \quad (17)$$

Where

$$G_Y = \sum_{k=1}^{N}(\lambda/M)\cdot[M\cdot C(k,i)C(k,j) + 2(M-1)] \quad (18)$$

$$G_Z = \sum_{k=1}^{N}(\lambda/M)\cdot[M\cdot H(k,i)C(k,j)] \quad (19)$$

Therefore the average busy period B(i.m,j.n) can be given as

$$\begin{aligned} B(i.m, j.n) &= P_S(i.m, j.n)\cdot T_S + \frac{G}{G_Y + G_Z}[1 - P_S(i.m, j.n)]\cdot T_{CY} \\ &+ \frac{G_2}{G_Y + G_Y}[1 - P_S(i.m, j.n)]\cdot T_{CZ} \end{aligned} \quad (20)$$

Finally, the overall throughput of the whole Ad Hoc network is expressed as

$$S = \sum_{i=1}^{N}\sum_{m=1}^{M}\sum_{\substack{j=1 \\ j\neq 1}}^{N}\sum_{n=1}^{M} Sc(i.m, j.n)\cdot C(i,j) \quad (21)$$

It can be proved that S is maximized with infinite M in the case of all the other network parameters are given.

RESULTS

Consider N nodes of a MANET randomly located in the area of. We take the average throughput over 50 random network topologies for performance evaluation. The parameters of wireless network are set as follows. N = 50, R = 25, $t_{PKT} = 1$, $t_{RTS} = t_{CTS} = t_{ACK} = 0.02$, $t_{SACK} = 0.01$, $\tau = 0.002$, DIFS = 0.004, SIFS = 0.002. We suppose that whether a 802.11a channel or 802.11b channel has the same bandwidth. Nch is the number of available channels, Nch is eight when 802.11a is used and Nch=three when 802.11b is used. M is the number of transceivers per node. When there is no special explanation, we use the above parameters for the numerical analysis. We will compare

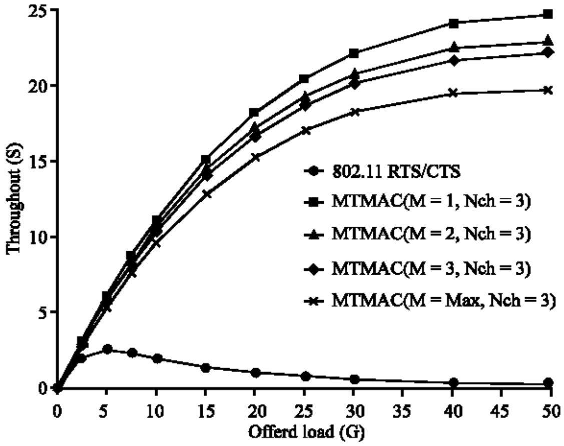

Fig. 2: Throughput versus offered load (Nch=3)

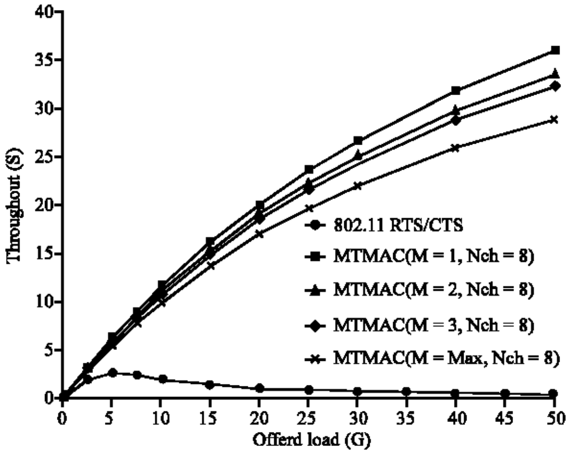

Fig. 3: Throughput versus offered load (Nch=8)

the performance of MTMAC protocol to that of IEEE 802.11 RTS/CTS protocol.

Throughput comparisons of the two protocols are shown in Fig. 2 (Nch = 3) and Fig. 3 (Nch = 8). The network performance of MTMAC protocol is much better than that of IEEE 802.11 RTS/CTS protocol. Numerical results show that network throughput is significantly improved with more transceivers per node. This is because multiple channels operation is allowed and there are two transceivers per node in case of M=2 thus increasing the density of network and enabling node to perform parallel communications. At the same time separating traffic channels from common reservation channel reduces the collision interval of data packet. Therefore the throughput of network is improved significantly.

CONCLUSIONS

This study presents a novel multi-channel based scheme as well as the MAC protocol for tactical Ad Hoc networks, which combines the concepts of multi-transceiver and multi-channel. Nodes in the novel multi-channel based scheme have the capability of full-duplex and parallel communications. The protocol can resolve the HTs problem, ETs problem and intruding terminals (ITs) problem in mobile multi-hop Ad Hoc networks effectively. Theoretically analysis and numerical results show that the MTMAC protocol greatly outperforms the regular IEEE 802.11 RTS/CTS MAC protocols. Another conclusion is that throughput is maximized when the number of transceivers per node tends to infinity. In future we will study the performance of proposed scheme via simulations extensively.

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