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Ad Hoc网络中基于拓扑透明特性的混合MAC协议*

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Topology-Transparent Hybrid MAC Protocol for Ad Hoc Networks

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Abstract: A topology-transparent protocol, called topology-transparent hybrid MAC (TTHM) protocol is proposed for ad hoc networks. The proposed protocol is based on a protocol threading technique which is the basis of the threaded time spread multiple access (T-TSMA) protocol and a hybrid channel access strategy. According to the current network topology and traffic load, the proposed TTHM protocol can control each node to utilize its assigned slots and its non-assigned slots effectively. TTHM protocol is suitable for distributed application since it keeps the advantage of the topology transparency and eliminates the maximum nodal degree constraint. After the TTHM protocol is presented, its performance is analyzed. Simulation results show that the proposed TTHM protocol is better than the T-TSMA protocol.
Key words: ad hoc network; topology-transparent; hybrid channel access; time spread multiple access

摘 要: 针对ad hoc网络,提出了基于拓扑透明特性的混合MAC协议——TTHM协议(topology-transparent hybrid MAC protocol).TTHM协议在T-TSMA(threaded time spread multiple access protocol)协议所提出的螺纹协议机制的基础上引入了混合接入策略,能够根据当前的网络拓扑与业务负载,有效利用节点的分配与未分配时隙来进行报文传输.由于 TTHM 协议具有拓扑透明特性且克服了最大节点密度限制,因此便于分布式应用.仿真结果表明,TTHM协议比T-TSMA协议表现出更好的性能优势.
关键词: 自组织网络;拓扑透明;混合接入;扩时多址接入
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1 Introduction

Ad hoc network requires no infrastructure so that the nodes of the network are free to enter, leave or move inside the network without prior configuration. Controlling access to the shared wireless channel, generally known

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as multiple access control (MAC) protocol, has a fundamental impact on the overall efficiency of the ad hoc network. It is possible to categorize the MAC protocols into two different categories according to the channel access strategy employed.

The first category refers to contention-based MAC protocols that use the random access strategy to contend the shared wireless channel. These MAC protocols tend to perform well when there is little collision and degrade as the collision is increased. The IEEE 802.11 MAC protocol[1] which is based on the carrier sense multiple access/collision avoidance (CSMA/CA) is a very well-known first category protocol. Although it is widely used, its contention-based nature makes it difficult to reserve bandwidth which is desired by real-time multimedia traffic.

The second category refers to schedule-based MAC protocols that use the scheduling access strategy to assign each node a finite transmission schedule that maps a certain set of conflict-free slots in which the node is allowed to transmit, such as time division multiple access (TDMA) protocol. Therefore, the schedule-based nature is potentially better suited to meet the quality of service (QoS) requirement. However, it is hard to produce the optimal transmission schedule even with accurate, global information[2]. Thus, some distributed protocols which only require local information are proposed[3−7]. Unfortunately, these protocols depend critically on the network topology. When nodes are moving, the burden due to control message increases and may end up using most of the available bandwidth. Consequently, overheads increase with the network topology dynamically changing.

Chlamtac and Farago[8] have proposed a schedule-based topology transparency protocol called time spread multiple access (TSMA) protocol. In TSMA protocol, each node is assigned a unique scheduling slot set that deterministically specifies in which slot the node is assigned the transmission right and no scheduling overheads are needed when network topology changes. Collisions in the assigned slots are not excluded, but due to the special scheduling method, each node is guaranteed a successful transmission to every neighboring node within each frame. Though independent of the detailed topology of the network, TSMA protocol depends on the maximum nodal degree of the network. In order to overcome this shortage, Chlamtac and Farago introduced the T-TSMA protocol and a protocol threading technique[9] that relieves the TSMA protocol from the need to account for the maximum nodal degree.

However, both protocols employ a deterministic policy for the utilization of the assigned slots and fail to utilize the collided ones among its assigned slots and its non-assigned slots that would result in successful transmissions. In this paper we introduce the TTHM protocol that utilizes the slots effectively with the combination of the protocol threading technique and hybrid channel access strategy to achieve a better performance than the T-TSMA protocol.

The remainder of this paper is organized as follows. In section 2, we introduce the TTHM protocol. In section 3, we provide the performance analysis. Section 4 presents the simulation results and section 5 concludes this paper.

2 Protocol Description

2.1 TSMA and threaded TSMA (T-TSMA)

TSMA protocol is based on some properties of finite (Galois) fields. Time is divided into frames, each frame being subdivided in q subframes, where q is the power of a prime number. Moreover, each subframe is subdivided into q slots and each node is assigned exactly one slot per subframe.

TSMA protocol assigns each node a unique polynomial of degree $\le K$ over the finite field $GF(q)$ which determines the transmissions schedule. Overlap of slot sets corresponds to common roots of the polynomial associated to different nodes. Hence, the degree K determines the maximum number of possible collisions that a node can cause its neighbor during one frame. Therefore, we conclude that the number of possible collisions in each frame for any two nodes is between 0 and K and this number of possible collisions depends on the degree of their difference polynomial. In order to guarantee that each node has at least one successful transmission to any neighbor during one frame, the non-covering condition can be expressed as[8]:

$$q \geq KD+1 \tag{1}$$

where D is the maximum nodal degree.

On the other hand, polynomials must be uniquely assigned, so that the following condition must hold as well:

$$Q^{K+1} \geq N \tag{2}$$

where N is the total number of nodes in the network.

We consider an ad hoc network with N nodes with changing topology. As described above, the TSMA protocol cannot efficiently handle the case when the maximum nodal degrees cannot be easily estimated. Intuitively, the maximum nodal degree may be as high as $N-1$ in the network. Therefore, the TSMA protocol is required to be adaptive to all the possible maximum nodal degrees, while using the same predetermined transmission schedule without changing itself. Although satisfying the above requirement looks difficult to achieve, it can be done using protocol threading technique[9].

Here, we shortly review the operation and basic concepts of the T-TSMA protocol[9]. In T-TSMA, it considers M protocols $P_1,P_2,\ldots,P_M$. The first $M-1$ of them are TSMA protocols, $P_j(1\leq j\leq M-1)$ chooses a prime parameter q_j and an integer K_j, with $q_j^{K_j+1} \geq N$ and $q_j^2 \leq N$. Moreover, T-TSMA contains a parameter α that controls how fast the q_j parameter grows and q_j is chosen as the smallest prime number with $q_j \geq \alpha q_{j-1}$.

It is designed so that the relation $q_1^2 \leq q_2^2 \leq \ldots \leq q_{M-1}^2 \leq N$ is satisfied. The last protocol P_M is a simple TDMA protocol with frame length N, i.e., in P_M each node has a unique dedicated slot as a degenerated case of TSMA. The role of the protocol P_M is to handle the case when the network may, at some points of time, get fully connected, as in this extreme case a TDMA protocol is the only reasonable protocol with a guaranteed delay bound.

The M protocols are combined in a time-sharing mode. The principle is illustrated in the Fig.1 by showing the threading of two protocols[9]. The general case is described as follows. Starting from a globally accepted initial time slot t=0, each node independently decides its transmission right in slot t by protocol P_j if the current time slot t satisfies $j=t(\text{mod } M)$. In other words, each protocol P_j is used once in every M slot.

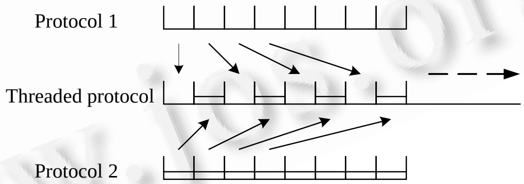

Fig.1 Schematic illustration of the protocol threading

2.2 Topology-Transparent Hybrid MAC protocol (TTHM)

As described above, the T-TSMA protocol includes M protocols and does not efficiently utilize the collided ones among its assigned slots and its non-assigned slots that would lead to successful transmissions. Intuitively, if these slots could be utilized effectively, in order to be adaptive to all the possible maximum nodal degrees, there is only need a TSMA protocol and an evolutionary-dynamic TDMA slot assignment protocol (E-DTSAP)[11] to be threaded. Our proposed TTHM protocol shows that a careful choice of the threaded protocols and hybrid channel access strategy could achieve a better performance than the T-TSMA protocol.

Here, we consider the TTHM protocol in more detail. An ad hoc network with N nodes can be viewed as a time varying multihop network and can be represented by a graph $G(V,E)$ where V and E are the set of all nodes and edges respectively[10]. Let S_u denote the set of neighbors of node $u(\forall u\in V)$. $D_u=|S_u|$ is the number of nodes in S_u which is called the degree of node u. The maximum nodal degree D in network is $\max_{u\in V}|S_u|$. Collisions are considered to be the only reason for failed transmissions. For a particular transmission $u\rightarrow v$ $(\forall u\in V,\forall v\in S_u)$ in slot i, collisions will happen only if v or any neighbor of v (except for u) also transmits in slot i. Since the destination node v and its neighbors are those who may interfere with node u's transmission in slot i, we call them interfering nodes to node u in slot i. Therefore, for a particular transmission $u\rightarrow v$, the interfering node set which results in the failure of $u\rightarrow v$ is $S_v\cup\{v\}-\{u\}$ where $|S_v\cup\{v\}-\{u\}|=D_v\le D$.

As described above, TTHM considers a TSMA protocol P_1 and the E-DTSAP P_2 to be threaded. According to Eqs.(1) and (2), when $D^2\ge N$, the frame length of TSMA protocol will exceed N, which is even worse for the TDMA protocol. Thus, we notice that the TSMA protocol should be utilized only when D is not large. Meanwhile, the TSMA protocol can be adaptive to a larger D as the q is increasing. Consequently, the TSMA protocol P_1 should have a polynomial degree of K=1 and subframe length of q which is the greatest prime number with $q^2\le N$.

Figure 2 shows the threading principle and frame structure of node u under the TTHM protocol. Here the sets of slots assigned to node u in one frame of the TSMA protocol P_1 and E-DTSAP P_2 are denoted by $\Omega_1^{(u)}$ and $\Omega_2^{(u)}$ where $|\Omega_1^{(u)}|=q$ and $|\Omega_2^{(u)}|=1$. The sets of slots not assigned to node u in one frame of protocol P_1 and P_2 are denoted by $R_1^{(u)}$ and $R_2^{(u)}$ respectively where $|R_1^{(u)}|=q^2-q$ and $|R_2^{(u)}|=F-1$.

In order to utilize the assigned slots and the non-assigned slots effectively, we propose a hybrid channel access strategy and subdivide each slot into four intervals: priority, contention, DATA and ACK interval. Generally, each minislot in the priority and contention intervals can be further divided into two control fields, namely, *RTS* (request to send) and *CTS* (clear to send) fields. The hybrid channel access strategy handshaking process is similar to the ADAPT protocol handshaking process[12]. For simplicity, we only explain the process of hybrid channel access strategy under the TSMA protocol P_1.

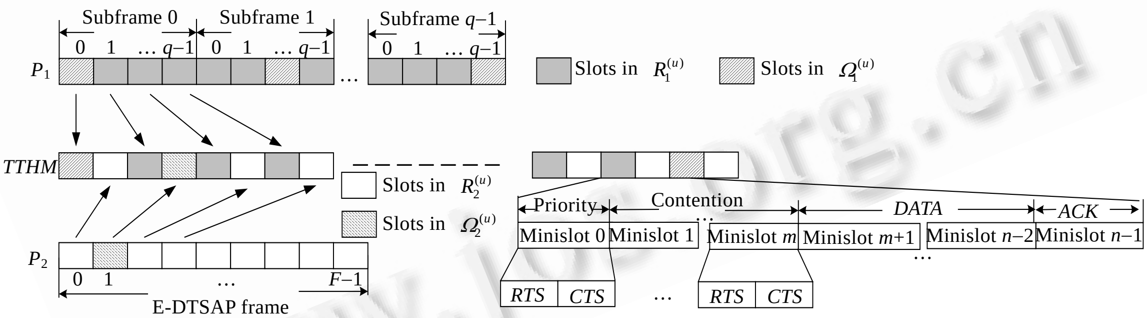

Fig.2 Schematic illustration of the TTHM protocol

Under the TSMA protocol P_1 in TTHM, each node has q assigned slots in each frame. For a particular transmission $u\rightarrow v$, in order to secure the assigned slots ownership, node u sends a *RTS* packet to node v for the slot reservation during the *RTS* field in the priority interval of slot $i\in\Omega_1^{(u)}$. Once node v has received the *RTS* packet, it will reply a *CTS* packet to node u during the *CTS* field in the priority interval of slot i.

Once the *RTS*/*CTS* handshake is completed, node u is free to transmit a data packet to node v during the whole contention and DATA intervals and will receive a ACK packet from node v in the ACK interval of slot i successfully. If node u reserves unsuccessfully in the priority interval, it means the *RTS* transmission is corrupted by its interfering nodes in $S_v\cup\{v\}-\{u\}$. However, in order to utilize this collided assigned slot, node u should contend to reserve slot i again during one of the minislot in the contention interval with probability $p_1^{(u)}$. Moreover, node u

should stop the reservation when it senses the channel is not idle during the current minislot *CTS* field in the contention interval. Obviously, if node u completes the *RTS*/*CTS* handshake during the current minislot in the contention interval, it has a collision-free transmission in the following section of contention and DATA intervals. As a result, the TSMA protocol P_1 can effectively utilize the assigned slots.

Meanwhile, node u must listen to the channel during the *CTS* field in the priority interval of slot i only if $i \in R_1^{(u)}$. If node u senses the channel idle during the *CTS* field in the priority interval of the current non-assigned slot i, it should contend to reserve this idle non-assigned slot in accordance with the process to reserve the collided assigned slots described above during the contention interval. It is obvious that if node u completes the *RTS*/*CTS* handshake during the current minislot in the contention interval, it is also free to transmit a data packet to node v in the following section of contention and DATA intervals. Consequently, the TSMA protocol P_1 can utilize the non-assigned slots effectively and improve the performance.

As described above, node u needs to use an effective probability $p_1^{(u)}$ to reserve the collided assigned slots and idle non-assigned slots that would result in successful transmissions during the contention interval. Regarding the network context in which the TTHM protocol operates, we make the following backoff operation.

Under the TSMA protocol P_1 in TTHM, node u maintains a backoff limit timer $m_1^{(u)}$ which is initialized to be 0. When node u reserves unsuccessfully in the contention interval, it increases the backoff limit timer $m_1^{(u)}$ (up to some maximum value) and generates a backoff timer $W_1^{(u)}$ which is randomly chosen between 1 and $2^{m_1^{(u)}}$. The backoff timer is decremented by 1 when node u senses the channel idle during the current minislot *CTS* field in the contention interval of the collided assigned slots or idle non-assigned slots. Once it reaches 0, node u is ready to reserve a collided assigned slot or idle non-assigned slot during the current minislot *RTS* field in the contention interval. If node u senses the channel is not idle during the current minislot *CTS* field in the contention interval, it holds the backoff timer and waits for the next slot. The only time node u reduces its backoff limit timer $m_1^{(u)}$ (down to 0) is when it reserves successfully in the contention interval. We emphasize that it is not a full-fledged design at this stage, but an appealing solution approach.

Obviously, under the hybrid channel access strategy, there are many collided assigned slots and idle non-assigned slots could produce successful transmissions. Though the *RTS*/*CTS* handshake process increases the overhead, the increased overhead is little due to the fact that the *RTS*/*CTS* packet is very short. Consequently, our proposed TTHM protocol can effectively utilize the assigned slots and the non-assigned slots.

3 Performance Analysis

We examine the performance of TTHM protocol by considering the throughput and transmission delay, where the throughput is defined as the average number of packets successfully transmitted by an arbitrarily chosen node u in one slot and the transmission delay is measured in the number of slots.

For the rest of this work, it will be assumed that node u transmits only toward node v in one frame and node v will be a node randomly picked from S_u[10]. Let λ_u be the probability that node u is busy, i.e., has a nonempty buffer, and N is the total number of nodes in the network. For tractability, we assume that the traffic load and the network topology are homogeneous. This enables us to replace time dependent value with “typical” constant value that represent the average attribute of the network, i.e., $\lambda=\lambda_u$, $p_1 = p_1^{(u)}$, $|S_u|=D$ for every $u\in V$.

Let us define the following notations[9]: $T_1(D,\lambda)$: throughput of the TSMA protocol P_1 in TTHM, the number of interfering nodes is D and any interfering node is busy with probability λ; $T_2(D,\lambda)$: throughput of the E-DTSAP P_2 in TTHM; $T(D,\lambda)$: throughput of TTHM; $L(D,\lambda)$: transmission delay of TTHM.

According to Ref.[8], for the TSMA protocol P_1, we assume the polynomial function of node u is

$$y = f^{(u)}(x) = a_0^{(u)} + a_1^{(u)} x \ (\mathrm{mod}\ q) \tag{3}$$

According to the TSMA protocol[8], the assigned slots in which the node u transmits packets in the frame are

$$\Omega_1^{(u)}(m) = mq + f^{(u)}(m),\ m = 0,1,...,q-1 \tag{4}$$

Now assume that node u has D interfering nodes, denoted by $I_1,I_2,\ldots,I_D$. According to Ref.[9], when node v covers node u's assigned slot $\Omega_1^{(u)}(m)$, we have

$$f^{(u)}(m) = f^{(v)}(m),\ m = \left\lfloor \Omega_1^{(u)}(m)/q \right\rfloor \tag{5}$$

Here $f^{(v)}(x) = a_0^{(v)} + a_1^{(v)} x\ (\mathrm{mod}\ q)$ is node v's polynomial function with $f^{(v)}(\cdot)\neq f^{(u)}(\cdot)$. According to Ref.[9], if we choose $a_1^{(v)}$ arbitrarily and $a_0^{(v)} = (f^{(u)}(m) - a_1^{(v)} m)\ (\mathrm{mod}\ q)$, Eq.(5) is satisfied. There are $q-1$ choices of the coefficient vector that are different from node u's vector. So there are at most $q-1$ interfering nodes collided with node u in slot $\Omega_1^{(u)}(m)$, even when $D>q-1$. Therefore, we call the interfering nodes collided with node u in slot $\Omega_1^{(u)}(m)$ covering nodes to node u in slot $\Omega_1^{(u)}(m)$.

To denote an arbitrary subset of the covering nodes, we use the notation $I_{d_1}, I_{d_2},...,I_{d_l},\ l \le \min(D, q-1)$. According to the above assumptions, these l nodes have l polynomials whose coefficients are chosen uniformly, with the only constraint that the coefficient vectors must be different from node u's and different from each other. Let us define the following notations:

$pc_m^{(u)}(l)$: Probability that node u collides with at least one covering node of $I_{d_1}, I_{d_2},...,I_{d_l}$ in slot $\Omega_1^{(u)}(m)$;

$pf_m^{(u)}(D-l)$: Probability that node u is not collided by the other $D-l$ interfering nodes in slot $\Omega_1^{(u)}(m)$;

$PC_m^{(u)}(D,\lambda)$: Probability that node u collides with at least one covering node in its assigned slot $\Omega_1^{(u)}(m)$;

$PF_m^{(u)}(D,\lambda)$: Probability that node u is not collided by the interfering nodes in its assigned slot $\Omega_1^{(u)}(m)$;

$T_F(D,\lambda)$: Throughput derived from the collision-free slots of the assigned slots of the TSMA protocol P_1 in TTHM;

$I_1^{(u)}$: Average number of idle non-assigned slots sensed by node u in one frame of the TSMA protocol P_1;

$P_1^{(u)}$: Average probability that node u reserves successfully in the contention interval of the TSMA protocol P_1;

$c_1^{(u)}$: Average number of minislots used by node u to reserve slots in the contention interval of the protocol P_1;

$T_C(D,\lambda)$: Throughput derived from the shared slots of the assigned slots and the non-assigned slots of the TSMAprotocol P_1 in TTHM;

$I_2^{(u)}$: Average number of idle non-assigned slots sensed by node u in one frame of the E-DTSAP P_2;

$P_2^{(u)}$: Average probability that node u reserves successfully in the contention interval of the *E*-DTSAP P_2;

$c_2^{(u)}$: Average number of minislots used by node u to reserve slots in the contention interval of the E-DTSAP P_2;

F_u: Average frame length of node u in the E-DTSAP P_2.

For tractability, we calculate $T_F(D,\lambda)$ first. As covering nodes $I_{d_1}, I_{d_2},...,I_{d_l}$ require l different vectors, there are $(q-1)(q-2)\ldots(q-l)$ different choices. Thus

$$\begin{aligned} pc_m^{(u)}(l) &= P(\text{node } u \text{ collides with at least one node of } I_{d_1},...,I_{d_l} \text{ in } \Omega_1^{(u)}(m)) \\ &= P(\text{node } u \text{ is covered by } I_{d_1},...,I_{d_l} \text{ at } \Omega_1^{(u)}(m)) \times P(\text{not all of } I_{d_1},...,I_{d_l} \text{ are free at } \Omega_1^{(u)}(m)) \\ &= \frac{(q-1)(q-2)...(q-l)}{(q^2-1)(q^2-2)...(q^2-l)}(1-(1-\lambda)^l) \\ &= \left(\prod_{k=1}^{l} \frac{q-k}{q^2-k}\right)(1-(1-\lambda)^l),\ l \le \min(D, q-1) \end{aligned} \tag{6}$$

Note that node u has D interfering nodes, there also need D–l interfering nodes that are not covered with node u at slot $\Omega_1^{(u)}(m)$. Thus

$$\begin{aligned} pf_m^{(u)}(D-l) &= P(\text{node } u \text{ is not covered by the other } D-l \text{ interfering nodes at } \Omega_1^{(u)}(m)) \\ &= \frac{(q^2-q)(q^2-q-1)...(q^2-q-D+l+1)}{(q^2-l-1)(q^2-l-2)...(q^2-D)} \\ &= \prod_{k=1}^{D-l}\frac{q^2-q-k+1}{q^2-k-l},\ l \le \min(D,q-1) \end{aligned} \tag{7}$$

As described above, we define D' as min(D,q–1) and calculate $PC_m^{(u)}(D,\lambda)$ as follows:

$$\begin{aligned} PC_m^{(u)}(D,\lambda) &= P(\text{node } u \text{ collides with at least one covering node in } \Omega_1^{(u)}(m)) \\ &= \sum_{I_{d_1}} P(\text{node } u \text{ collides with } I_{d_1} \text{ in } \Omega_1^{(u)}(m)) \cdot \\ &\quad P(\text{node } u \text{ is not covered by the other } D-1 \text{ interfering nodes at } \Omega_1^{(u)}(m)) + \\ &\quad \sum_{I_{d_1},I_{d_2}} P(\text{node } u \text{ collides with at least one node of } I_{d_1},I_{d_2} \text{ in } \Omega_1^{(u)}(m)) \cdot \\ &\quad P(\text{node } u \text{ is not covered by the other } D-2 \text{ interfering nodes at } \Omega_1^{(u)}(m)) + ... + \\ &\quad \sum_{I_{d_1},...,I_{d_{D'}}} P(\text{node } u \text{ collides with at least one node of } I_{d_1},...,I_{d_{D'}} \text{ in } \Omega_1^{(u)}(m)) \cdot \\ &\quad P(\text{node } u \text{ is not covered by the other } D-D' \text{ interfering nodes at } \Omega_1^{(u)}(m)) \\ &= \binom{D}{1} pc_m^{(u)}(1)pf_m^{(u)}(D-1) + \binom{D}{2} pc_m^{(u)}(2)pf_m^{(u)}(D-2) + ... + \binom{D}{D'} pc_m^{(u)}(D')pf_m^{(u)}(D-D') \\ &= \sum_{l=1}^{D'}(1-(1-\lambda)^l)\binom{D}{l}\left(\prod_{k=1}^{l}\frac{q-k}{q^2-k}\right)\left(\prod_{k=1}^{D-l}\frac{q^2-q-k+1}{q^2-k-l}\right),\ D' = \min(D,q-1) \end{aligned} \tag{8}$$

Consequently, we calculate $PF_m^{(u)}(D,\lambda)$ as follows:

$$PF_m^{(u)}(D,\lambda) = 1 - PC_m^{(u)}(D,\lambda) \tag{9}$$

Observe that $PF_m^{(u)}(D,\lambda)$ is independent of $\Omega_1^{(u)}(m)$ and node u, for tractability, we may drop the upper and lower indices. Thus, we have

$$T_F(D,\lambda) = \frac{\lambda(n-2)}{2nq} PF(D,\lambda) \tag{10}$$

For node u to successfully reserve a non-assigned slot or a shared slot of the assigned slots, the following conditions must occur simultaneously. First, node u has a nonempty buffer with probability λ. Second, these slots occur with probability $(q(1-PF(D,\lambda))+I_1^{(u)})/q^2$. Finally, node u reserves successfully in the contention interval with probability $P_1^{(u)}$. Consequently, we can calculate $T_C(D,\lambda)$ as follows:

$$T_C(D,\lambda) = \frac{\lambda}{2N}\sum_{i=1}^{N}\frac{1}{q^2}\cdot\left((q(1-PF(D,\lambda))+I_1^{(i)})\cdot P_1^{(i)}\cdot\left(\frac{n-c_1^{(i)}-2}{n}\right)\right) \tag{11}$$

Combining Eqs.(10) and (11), we obtain the throughput of the TSMA protocol P_1 in TTHM:

$$T_1(D,\lambda)=T_F(D,\lambda)+T_C(D,\lambda) \tag{12}$$

Moreover, under the E-DTSAP P_2, each node has one unique assigned slot in each frame with the neighboring nodes up to two hops away. Similarly, the throughput of the E-DTSAP P_2 in TTHM can be calculated as follows:

$$T_2(D,\lambda) = \frac{\lambda}{2N}\sum_{i=1}^{N}\frac{1}{F_i}\cdot\left(\left(\frac{n-2}{n}\right)+I_2^{(i)}\cdot P_2^{(i)}\cdot\left(\frac{n-c_2^{(i)}-2}{n}\right)\right) \tag{13}$$

As described above, transmission delay represents the interval from the slot when a packet arrives at the top of the queue until the slot when the packet is transmitted successfully. Consequently, we have the throughput and transmission delay of TTHM as follows:

$$T(D,\lambda)=T_1(D,\lambda)+T_2(D,\lambda) \tag{14}$$

$$L(D,\lambda)=1/T(D,\lambda) \tag{15}$$

As described above, the performance of TTHM is dependent of some variants, i.e., F_u, $I_1^{(u)}$ and $I_2^{(u)}$. However, with the changes of the topology density of the network and the traffic load, these variants would change also. Thus, we would evaluate the performance of TTHM through simulations.

4 Evaluation Results

In this section, we show simulation results regarding performance evaluation of our proposed TTHM protocol. In the simulation experiments, we compare the performance of our proposed TTHM protocol with T-TSMA protocol for a variety of topologies.

For numerical demonstration we first choose two networks with sizes N=3000 and N=10000 respectively[9] and the range of the maximum nodal degree D is from 4 to 50. The optimal values of α and M were α=1.568 and M=7 for N=3000 and α=1.576 and M=8 for N=10000 respectively. Moreover, the maximum backoff limit timer is set to 10 and the parameters of minislot in one slot are set to n=16, m=4. Varying D and λ, we measured the throughput and transmission delay as a function of these parameters.

Figures 3 and 4 show the lines of throughput with the maximum nodal degree D under different protocols. From Figs.3 and 4, we can see that our proposed TTHM protocol always performs better than the T-TSMA for all values of λ. In particular, for small values of the maximum nodal degree D, the throughput is much better than the T-TSMA. The curves also show that the throughput of TTHM protocol decreases smoothly as D increases and converges to T-TSMA, because more maximum nodal degree D will induce more interference.

The throughput of T-TSMA is low because it includes too many threaded protocols and does not efficiently utilize the collided ones among its assigned slots and its non-assigned slots. For the two cases of N=3000 and N=10000, both results show that the throughput is improved by our proposed TTHM protocol for all values of D and λ. Therefore, it can be concluded that our proposed TTHM protocol acquires stable high throughput.

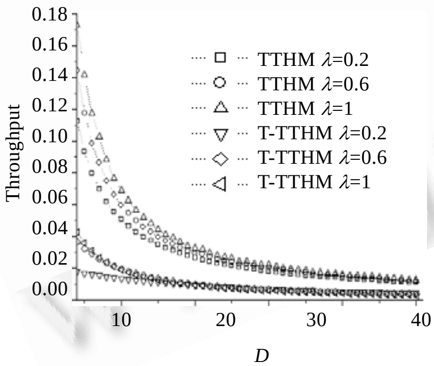

Fig.3 Throughput as a function of D for N=3000

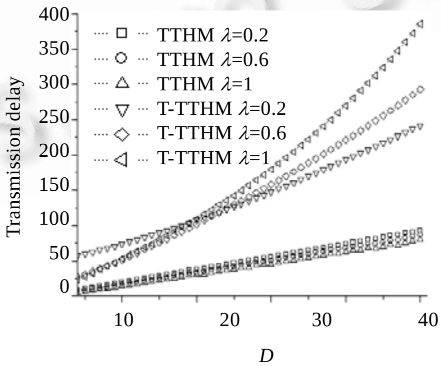

Fig.4 Transmission delay as a function of D for N=3000

From Figs.5 and 6, we can see the transmission delay increases almost linearly with D and our proposed TTHM protocol has the smallest transmission delay for all values of D and λ. The reason is the same as described above. Mobility impacts on the performance of our proposed TTHM protocol are not taken into account in this paper, and we will discuss it in future work.

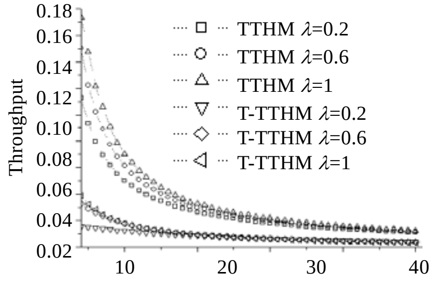

Fig.5 Throughput as a function of D for N=10000

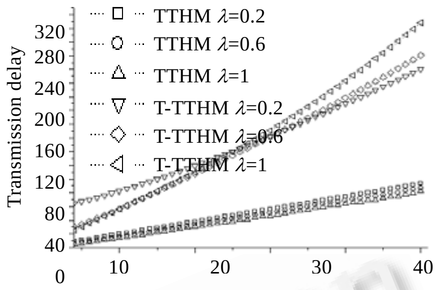

Fig.6 Transmission delay as a function of D for N=10000

5 Conclusion

This paper introduces the TTHM protocol based on the concept of protocol threading and hybrid channel access strategy. We present the protocol and analyze the performance of it. Simulation results show that our proposed TTHM protocol provides a significant improvement upon the T-TSMA protocol over a wide range of maximum nodal degrees and traffic loads. At the same time, TTHM protocol keeps the advantage of the topology transparency and eliminates the maximum nodal degree constraint. Thus, it is well-suited for a real ad hoc network.

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