A High-throughput MAC Protocol for Wireless Ad Hoc Networks

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Abstract

One way to improve the throughput of a wireless ad hoc network at the media access (MAC) layer is to allow concurrent transmission among neighboring nodes as much as possible. In this paper, we present a novel high-throughput MAC protocol, called CTMAC, that supports concurrent transmission while letting the MANET enjoy the simple design with a single channel, single transceiver, and single transmission power architecture. CTMAC inserts additional control gap between the transmission of control packets (RTS/CTS) and data packet (DATA/ACK), which allows a serious of RTS/CTS exchanges to take place before the possible multiple, concurrent data transmissions. To ensure that concurrent data transmission finishes correctly, the collision avoidance information is included in control packets, and used by neighboring nodes to determine whether begin their transmissions or not. Simulation results show that a significant gain in throughput can be obtained by CTMAC protocol compared with the IEEE 802.11 MAC protocol.

1. Introduction

Due to its characteristics of infrastructureless, mobility and robustness, the MANETs (Mobile Ad hoc NETworks) have gained significant attentions recently. The deployment and rerouting of traffics are flexible in MANETs, while how to utilize the scarce shared wireless radio channel efficiently remains one great challenge in practice.

IEEE 802.11 DCF [1] has been regarded as the basic Media Access Control (MAC) protocol for MANETs for its simplicity. Despite its simplicity, the IEEE 802.11 DCF can be overly restrictive. It prohibits any concurrent transmission between neighboring nodes even when the transmission is possible. This motivates the endeavor of exploiting potential concurrent transmissions between neighboring nodes in MANETs, which is the main topic of this paper. We concentrate on scheduling concurrent transmissions without the help of transmission power control (TPC).

CTMAC achieves concurrent transmission through the combination of three mechanisms. First, additional control gap is inserted between the transmission of control packets (RTS/CTS) and data packet (DATA/ACK). Second, to assure the correctness of concurrent transmissions, the collision avoidance information is included in control packets. Last, the ACK packets of different transmissions are sequenced.

The proposed CTMAC protocol is a distributed, asynchronous and adaptive media access protocol. It requires a very simple standard IEEE 802.11 circuitry, and works on the single channel and single transmission power architecture.

The rest of the paper is organized as follows. In Section 2 we present and analyze related works. The assumptions we make when designing the CTMAC is listed in Section 3. The proposed CTMAC is detailed in Section 4, followed by simulation results and discussions in Section 5. Finally, in Section 6, we draw our main conclusions with a list of future work.

2. Background and Related Work

Effort has been made on enhancing the throughput of MANETs through concurrent scheduling at the MAC layer. The existing works can be divided into two main classes. In the first class, transmission power control is used per-packet to increase the spatial

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channel reuse. TPC-based schemas can further be divided into two sub-categories: single-channel based or multi-channel based.

However, as pointed out in [2], single-channel based TPC can degrade the network throughput. Even optimized by periodically increasing the transmit power during the DATA transmission to inform the nodes in the carrier sensing zone, the power controlled MAC proposed in [2] at best can give comparable throughput to that of 802.11 scheme. The real throughput enhancement through TPC is obtained in multi-channel based TPC schemas [3, 4].

Although the simulations results in [3, 4] indicate impressive improvements in throughput over the 802.11 scheme, there are some major design problems with these schemes, such as how to deal with the huge latency introduced by TPC [5], the unrealistic assumption of same channel gain for both the control channel and data channel, the hardware complexity for the wireless communication node to be equipped with two transceivers, and incompatible with existing standards and hardware.

In the second class, the approach to improve throughput is to insert additional control gaps between RTS/CTS and DATA packets for successfully scheduled transmission, such as the MACA-P[6]. POWMAC [7] is a single-channel and single-transceiver protocol, which combines the approach of additional control gap and TPC. Besides the problems introduced by TPC, POWMAC protocol adds the control packet for all nodes which is not always necessary.

3. Preliminaries

In designing CTMAC, we assume that each node is equipped with basic IEEE 802.11-compliant hardware. For most of existing products follow the specification of IEEE 802.11, this assumption is widely supported.

In CTMAC, each node maintains a special data structure, Active Neighbor List (ANL), to record the knowledge about other active nodes(i.e., nodes that are receiving, transmitting, or scheduled to do so) in its vicinity. For every active node *u* in *i*'s vicinity, ANL(*i*) contains the following information:

$$\{U_{address}, G_{iu}, T_{data}^{(uv)}, T_{ack}^{(uv)}, T, R, P_{MTI}^{(u)}\}$$

where

- $U_{address}$: address of node *u*.
- G_{iu}: estimated channel gain G_{iu} between nodes *i* and *u*, computed as following: $G_{iu} = P_{rx}^{(u)} / P_{tx}$, $P_{rx}^{(u)}$ is the received signal power of node *u*'s control packet and P_{tx} is the transmission power.
- $T_{data}^{(uv)}$ and $T_{ack}^{(uv)}$:the start time of transmission *uv*'s DATA packet and ACK packet, according to the values advertised by node *u* in its RTS/CTS/ATS packet (the corresponding communication node of *u* is node *v*).
- *T:* transmitter tag. If the received packet is a RTS or ATS packet, then this node is a *T*-node and the *T* tag is set.
- *R:* receiver tag. If the received packet is a CTS packet, then this node is an *R*-node and the *R* tag is set.
- The maximum tolerable interference (MTI) of node u, denoted by $P_{MTI}^{(u)}$, if *u* is a *R*-node.

To distinguish different roles of transmissions, we introduce two notions for any successfully scheduled transmission: master transmission and slave transmission. If both the transmitter and the receiver have no transmitter or receiver of scheduled transmissions in their vicinity (its ANL is empty), then this one is a master transmission and the participators are called master transmitter and master receiver respectively. Other transmissions that must adjust their transmitting times of DATA or ACK packet according to overheard information of neighboring master transmissions, so they are slave transmissions. Note that the use of words "master" and "slave" does not imply any form of centralized control, for each node has equal chance to become a master node.

4. The Proposed CTMAC Protocol

We now describe the details of CTMAC protocol, which are divided into three main parts: packets exchange process, concurrent transmission control rules and adaptation mechanism of ACG.

4.1. Basic Operation of CTMAC

Considering the network topology with 4 nodes (ABCD) which are in the transmission ranges of each other, the basic operation of CTMAC is illustrated in Figure 1.

First, node A transmits an RTS packet to node B, including information such as the scheduled start times of A's DATA packet (T_{data}) and B's ACK packets (T_{ack}). To avoid the requirement of synchronized clocks, both values are specified relative to the receiving time of associated control packet. Node B replies with a CTS packet to node A, including similar information. After the RTS/CTS packets are exchanged, node A refrains from sending its data packet for the ACG duration. During this duration, C and D can exchange control packets and schedule their transmission if possible.

In CTMAC, the CTS packet of original IEEE 802.11 DCF is extended and classified into two types: normal CTS and negative CTS packet. Through normal CTS packet, the receiver tells the transmitter that it has get ready for the coming DATA transmission as in IEEE 802.11. However in CTMAC, the receiver may modify the value of T_{data} and T_{ack} declared by the transmitter in RTS packet and includes the new value in its CTS packet. If the slave receiver finds it is impossible for the slave transmission to continue according to the concurrent control rules, then it will send a negative CTS packet to notify the slave transmitter to cancel the proposed transmission.

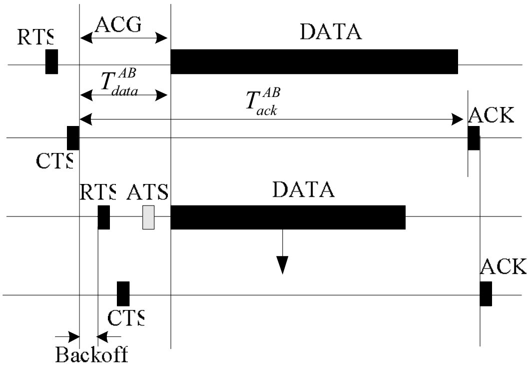

Figure 1. **Basic operation of CTMAC**

In CTMAC, the optional ATS (abrogate-to-send or adjust-to-send) packet for slave transmission is needed in two situations. First is that when the slave receiver modifies the values of T_{data} or T_{ack} scheduled by the slave transmitter, the slave transmitter uses ATS (adjust-to-send) to inform its neighbors of the adjustment.

Second is that when it is impossible for the slave receiver to receive the data packet, then it responds with a negative CTS packet, so the slave transmitter uses ATS (abrogate-to-send) to notify its neighbors to cancel the proposed schedule.

To make more transmissions concurrentable, we propose a novel ACK packet sequence mechanism. The ACK packets of one master transmission and all the slave transmissions synchronized to this master transmission are transmitted one by one in sequence. Thus, we eliminate the collisions between DATA and ACK packet or ACK packets of concurrent transmissions. The detail process is as following. When the salve transmission computes its T_{ack}, it postpones the starting time of its ACK packet to the ending of ACK packets of all scheduled transmissions in the vicinity of slave transmitter or receiver.

The sequencing of ACK packets isolates the DATA and ACK packets in time, which make more concurrent transmissions possible. On the other hand, it simplifies the CTMAC protocol greatly for we only need to consider the possible collisions between DATA packets.

4.2. The Concurrency Transmission Control

To exploit the potential concurrent character of the network, additional control gap (ACG) is inserted between the RTS/CTS/ATS packets and the DATA packet in CTMAC. Thus, after receiving control packets destined for other nodes, one node needn't to postpone its transmission immediately. However, it records necessary information in its ANL. Then, when the node whose ANL is not empty gains the chance to send control packets, it should first check its ANL. If the remaining time of scheduled transmission is long enough to complete the exchange of control packets, it can start transmitting control packet. If not, it should postpone its transmission.

ACG makes concurrent transmissions possible, but not ensure their success. So we need to add necessary power information (P_{MTI}) in the control packets. Now we explain how the receiver computes its P_{MTI}. Let $P_{rxThreshold}$ be the minimum reaching power for a node to decode the packet correctly, which is common to all nodes. $P_{rxThreshold}$ is determined by the hardware and denotes the property of hardware. We define $P_{total}^{(u)}$, the accumulated total interference power of current scheduled transmission of node *u*, as

$$P_{total}^{(u)} = \sum\nolimits_j G_{uj} * P_{tx} \ ,$$

Here, *j* is the *T*-node in node *u*'s ANL.

Then, the P_{MTI} of node *u* is:

$$P_{MTI}^{(u)} = \frac{P_{rx}^{(uv)} - SINR * \left(P_{rxThreshold} - P_{total}^{(u)}\right)}{SINR * N_{ACG}^{(u)} * \left(1+\alpha\right)}$$

$N_{ACG}^{(u)}$ is the number of AS in the ACG of node *u*, which will be detailed in Section 4.3.

α is ratio of the interference due to nodes outside the transmission range *vs.* the interference due to nodes inside the transmission range. α <1 is depends mainly on the propagation path loss factor and in practice, $\alpha \approx 0.5$ for the two ray model and uniformly distributed nodes.

In CTMAC, for any salve transmission to be scheduled, it should obey the following four rules of concurrent (RCs):

- RC0(requirement of time)：The remaining time of current master transmission's ACG is long enough for the salve transmission to finish its exchanging of control packets.
- RC1(for salve transmitter): the DATA packet of salve transmitter should not disturb any already

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scheduled transmission.

- RC2(for salve receiver): any already scheduled transmissions should not violate the salve receiver's receiving.
- RC3(for both salve transmitter and receiver): the salve node should postpone its ACK packet after the ACKs of all scheduled transmissions.

If one potential slave transmission has more than one master transmission in its vicinity, then this transmission is not allowed to be scheduled. All unschedulable transmissions should wait for the finish of master transmission before contending for the channel again. However, if the ANL of potential slave transmitter is empty while the ANL of potential slave receiver is not empty, the potential slave transmission is still schedulable and the slave receiver should send back CTS packet with new values of T_{data} and T_{ack}. To achieve this, we add an M tag in the RTS packet to indicate whether the ANL of its sender is empty or not.

4.3. Adaptation of N_{ACG}

The ACG offers the nodes in the vicinity of scheduled transmission the chance to exchange their own control packets, and thus improves the throughput of network. However, the additional waiting time introduced by ACG may also decrease the throughput, so the size of ACG has decisive effect on the performance of CTMAC. For given network topology and traffic, the potential concurrent is definite and the size of each node's ACG should be suitable for its current situation.

Obviously, the size of ACG should be adaptive according to the status of network to achieve better performance. We notice that, two kinds of nodes contribute to the cumulate interference of one node: nodes in its transmission range and out of its transmission range. Obviously, only the nodes in the transmission range of one node can receive its control packet and utilize its ACG to schedule concurrent transmissions. Fortunately, these nodes are recorded in the ANL, so we can tune the size of ACG based on the number of entries in the ANL adaptively.

In CTMAC, the ACG consists with adjustable number (N_{ACG}) of access slot durations (AS). Each slave transmission can occupy one AS and exchange its control packets. If successfully scheduled, this slave transmission can proceed with the master one at the same time. The duration of AS is fixed, which consists of the sum of the transmission durations of the RTS, CTS, and ATS packets, plus the maximum back-off time (when the CW value of IEEE 802.11 is minimum).

The initial and minimum value of N_{ACG} for the master transmitter is 1, which allows one slave transmission to be scheduled. After initialization, the value of N_{ACG} is updated adaptively according to the recent information in the ANL. If the number of concurrent slave transmissions is larger than or equal to N_{ACG}, then the N_{ACG} is increased, else the N_{ACG} is decreased. To prevent the fluctuation, the step of increase or decrease is 1. However, it is not always better to choose larger value for the N_{ACG}. Waiting excessively due to the large value of N_{ACG} will overcome the performance gain through concurrent transmissions. In CTMAC, the maximum N_{ACG} is set to 3, which allows three slave transmissions to be scheduled concurrently with the master one.

5. Performance Evaluation

We now evaluate the performance of the CTMAC protocol by implement it in GloMoSim [8] simulator, and contrast it with the IEEE 802.11 scheme. For simplicity, data packets are assumed to be of fixed size of 2KB. We focus on one hop throughput, so the packet destination is restricted to one hop from the source. Table 1 list the various values for simulation parameters, which compatible with standard 802.11.

Table 1. Parameters used in the simulation

Propagation model	TwoRayGround
Data rate	2 Mbps
SINR	6 dB
Receive sensitivity	-94dBm
Receive threshold	-82dBm
Transmit power	30mW(15dBm)
Transmission range	400m
Carrier-sense range	800m

5.1. Random Grid Topologies

First we consider a random grid topology where nodes are placed within a square area of length 800 meters. The square is split into n*n small squares, one node is placed in the small square randomly. Assume there are m transmission pairs where the transmitter is saturated. The destination nodes of all transmissions are chosen randomly from nodes in the neighboring grids of corresponding transmitters. Since all the nodes are within the carrier sense range of each other, only one transmission can proceed at a time under IEEE 802.11 scheme.

The performance is demonstrated in Figure 2. From these figures, we can see that the density of nodes affects the network throughput greatly under CTMAC scheme. The higher the node density to be, the higher the achieved throughout to be. At any moment, the number of contending transmissions in the system also have impact on the throughput of the network, because there will be more potential concurrent transmissions if there are more contending transmissions.

5.2. Cluster Topologies

To generate a cluster topology, we consider an area of dimensions 400*400 (in meters). 16 nodes are split into 4 equal groups and each group occupies a 100*100 square in one of the corners of the whole area. For a given node, the destination is selected from another cluster with probability of p or from same cluster with probability $1-p$. We simulate the scenario of four transmissions in the network, with the packet generation rate of k packets per second for each transmitter. Part (a) of Figure 3 demonstrates the performance of CTMAC and IEEE 802.11 when $p=0.25$. With the increase the network traffic, the CTMAC can achieve about 70% increase in throughput over the IEEE 802.11 scheme. The result when $p=0$ is in part (b) of figure 3. In this case, CTMAC approaches its best performance, achieving about 150% increase over the IEEE 802.11 scheme.

6. Conclusions

In this paper, we have proposed the CTMAC, a concurrent transmission media access control protocol for MANETs. Our simulation results showed that the CTMAC can improve the network throughput by up to 150%. To the best of our knowledge, CTMAC is the first single-channel, single-transceiver and single-transmission power protocol that increase network throughput while preserving the collision avoidance property of the 802.11 scheme.

7. References

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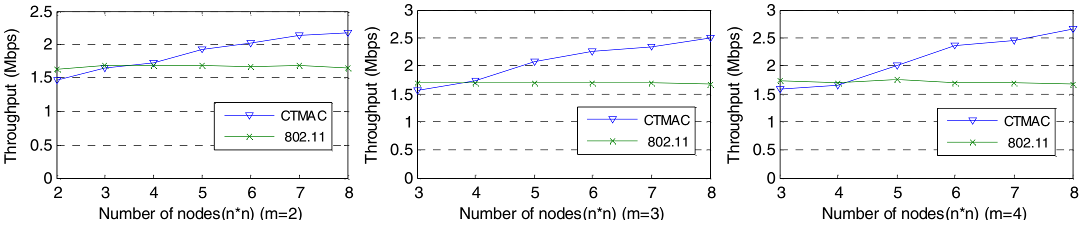
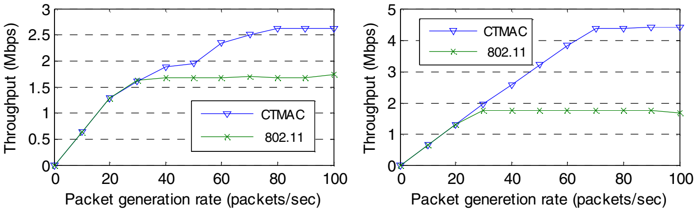


Figure 2. Performance of the CTMAC and the 802.11 protocols (random grid topology)



(a) p=0.25
(b) p=0

Figure 3. Performance of the CTMAC and the 802.11 protocols as function of *k*