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A throughput aware with collision-free MAC for wireless LANs

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Dear editor,

The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) hybrid with the resource reservation approach from Time Division Multiple Address (TDMA) has been emerged as a promising method to solve collision problems in wireless LANs [1–6]. In the hybrid method, a TDMA circle contains multiple slots for nodes to contend for the channel. Furthermore, it allows a node to reuse the same slot in continuous TDMA circles so that it can achieve collision-free state.

The AAB [3] modified the backoff value based on the number of acks received and idle slots sensed after last successful transmission. Due to this scheme, the protocol did not work without collisions when some nodes always had packages to send. In SRB [4], UCFA [5], they used a deterministic backoff value instead of Binary Exponentially Backoff (BEB) to achieve collision-free state. However, they took a long time to enter collision-free state and left a lot of idle slots in TDMA circles. In BCCA [6], successful node chose the same slot in a TDMA circle, and unsuccessful nodes were forced to choose from idle slots. All these methods aim to solve collision problems with TDMA fashion. None of them solve the collision problem while making full use of TDMA slots. Compressing idle slots and collision-free (CSCF) MAC are proposed by idle slots compression and collision avoidance in this research. We notice that each node is able to know the successful transmissions of other nodes in a single hop network. The nodes choose the numbers in the same order as the successful transmissions orders in last TDMA circle as their transmission order in the current TDMA circle. The order of successful transmission is unique because there cannot be two successful transmissions in the same slot. This order of each node is a deterministic value when all nodes keep transmitting, and it can also be varied when some nodes quit or fail in transmission. Therefore, we can keep the successful nodes at the head of the TDMA circle to prevent further collisions, and keep all idle slots at the end of the TDMA circle. We can com-

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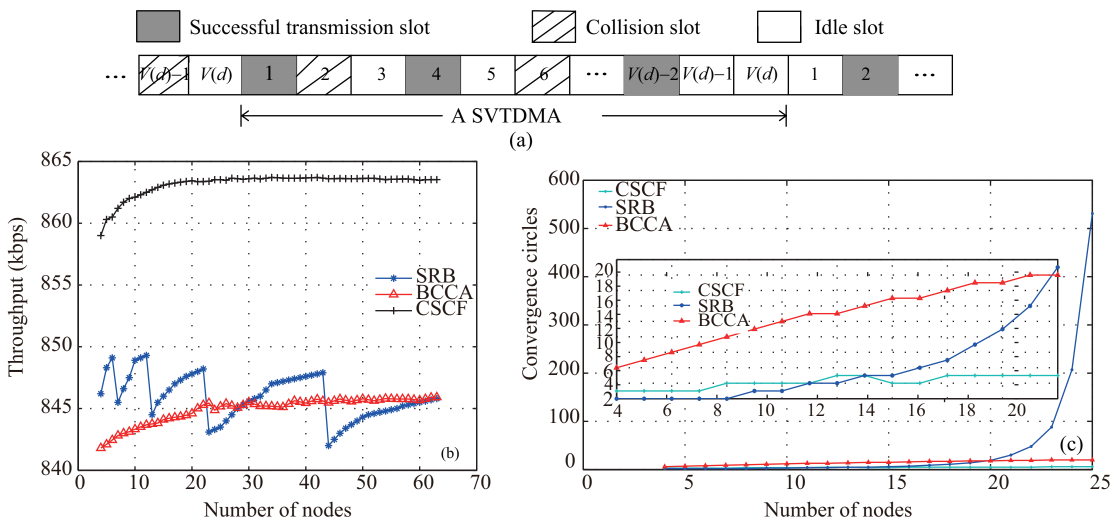

Figure 1 (Color online) Example of SVTDMA and results of the experiment. (a) An example of SVTDMA; (b) convergence circle comparison; (c) the comparison of throughput between SRB-MAC, CSCF-MAC and BCCA.

press idle slots when the network is stable.

Figure 1(a) shows an example of a self-adaptive virtual TDMA circle (SVTDMA) which contains $V(d)$ slots, being labeled from 1 to $V(d)$. In an SVTDMA, each node in a single hop network can get $N_{\rm s}$ successful transmissions, $N_{\rm c}$ collisions, $N_{\rm i}$ idle slots, and $V(d) = N_{\rm s} + N_{\rm i} + N_{\rm c}$. The initial $V(d)$ is $CW_{\min}$. We will double $V(d)$ if $N_{\rm Est}$ is larger than the $V(d)$, where $N_{\rm Est}$ is an estimated number of nodes in the network, as shown by

$$N_{\rm Est} = N_{\rm s} + C_{\rm N} \times N_{\rm c}, \tag{1}$$

$C_{\rm N}$ stands for the number of nodes in a collision. We get an appropriate value $C_{\rm N} = 3$ from simulations.

Nodes need three steps to reach collision-free state and compress idle slots in SVTDMA. In the first step, every node randomly selects a slot i from $[1, V(d)]$ at the initialization of the network and contends for the channel. Every node records $N_{\rm s}$, $N_{\rm c}$, and $N_{\rm i}$ in each SVTDMA. Successful nodes should record their numbers in the same order as the successful transmissions orders in the current SVTDMA.

In the second step, at the beginning of a new SVTDMA, each node estimates the number of nodes by using formula (1). If $N_{\rm Est}$ is bigger than $V(d)$, $V(d)$ will be doubled to provide more slots for nodes. Then, the successful nodes select slot i to access the channel according to their successful transmissions order in the previous SVTDMA. The unsuccessful nodes randomly select slot i from $N_{\rm s}+1$ to $V(d)$. All nodes will run the second step until they select particular slots (a node matches a slot).

In the third step, nodes start to check whether the network reaches the collision-free state after they all chose particular slots. If the network maintains the same situation in two consecutive SVTDMAs without collisions and entrances of new nodes, it enters the collision-free state. Otherwise, all the nodes roll back to the step 2. Then we further shorten $V(d)$ and Inter Frame Spacing (IFS). $V(d)$ becomes $N_{\rm s}+2$, which reserves two idle slots for new nodes to prevent collision between new nodes and successful nodes. As for compressing IFS, nodes just sense a SIFS then start a new four-way handshake transmission.

A Markov chain is applied to demonstrate CSCF-MAC can reach the collision-free state in a single hop saturated network. $P_{ij}^{(N)}$ $(i, j \in [0, n], N \in Z^{+})$ stands for the Nth order probability of transition from state i to state j. State i represents that i nodes select particular slots in the current SVTDMA.

We use $P_{V(d),n}(k_1)$ and $P_{m,m+k_2}$ from [6] to calculate the transition probability $P_{ij}^{(1)}$. Among n nodes, the probability that there are exactly k_1 nodes that select particular slots from $V(d)$ idle slots is $P_{V(d),n}(k_1)$. Probability that there are m nodes that select particular slots in the current SVTDMA, with $V(d) - m$ idle slots left for other $n - m$ nodes is $P_{m,m+k_2}$. We can get Nth order transition matrix according to the Markov chain properties. $P_{k_3n}^{(1)}$ represents the probability of the nodes number with selected particular slots changing from k_3 to n after one step. So, $P_{k_3n}^{(N)}$ represents the probability of the nodes number changing from k_3 to n nodes after N steps. The total probability

P will be

$$P = \sum_{k_3=0}^{n} P_{V(d),n}(k_3) \times P_{k_3 n}^{(N)}. \quad (2)$$

The probability calculated in (2) is the sum of possibilities of all initial states turning into the collision-free state after N steps. Specially, $\lim_{N\to\infty} P_{in}^{N} = 1, i \in [0,n]$, and $\sum_{k_3=0}^{n} P_{V(d),n}(k_3) = 1$, $\exists \lim_{N\to\infty} P = 1$. Therefore, the network could reach the collision-free state finally.

We also get some simulation results in saturated modes. Figure 1(b) shows the comparison of convergence circle. To give a fair comparison, the BCCA runs its approaching process in every TDMA circle instead of receiving beacons, which performs better than the original protocol. The CSCF-MAC is smoother and better than both SRB and BCCA, which benefits from the slot determination method. SRB-MAC takes more circles to reach collision-free state because the closer the number of nodes to the size of TDMA circles, the lower probability that nodes can select idle slot. In BCCA, the approaching process can only eliminate idle slots that are detected in last TDMA circle between its front node and itself. If the front node changes transmission slot, the node will run approaching process to eliminate idle slots again. So, BCCA takes longer time than CSCF-MAC to reach final state.

From Figure 1(c), the throughput of the protocols other than SRB-MAC' will grow when the number of nodes gets bigger. The size of the service ring Ω is different in SRB-MAC. However, the larger $|\Omega|$ comparing to the number of nodes, the more idle slots may exist, which means the throughput will decrease when the number of idle slots increases. When the number of nodes gets bigger, the throughput of SRB-MAC will grow if $|\Omega|$ remains the same and sharply decreases if $|\Omega|$ is doubled because the number of nodes reaches the critical value. The throughput of BCCA is about 845 kbps because the periodic beacon frames take up the channel. CSCF-MAC's throughput is about 863 kbps when the number of nodes is bigger than 14. Even when the number of nodes is smaller than 14, CSCF-MAC will still keep the highest throughput of 860 kbps owing to compressing idle slots and IFS in the collision-free state.

In the letter, CSCF-MAC is proposed by using idle slot compression and collision avoidance to improve throughput. SVTDMA is designed to reduce the collision probability in collision state by increasing $V(d)$, and to reduce idle slots number in the collision-free state by decreasing $V(d)$. The backoff method on the SVTDMA can reduce collisions by keeping the unsuccessful nodes from competing with the successful nodes without extra cost. It also keeps the successful nodes at the head of the SVTDMA to guarantee $V(d)$ to be downsized in the collision-free state. Simulation results prove that CSCF-MAC outperforms other protocols in terms of throughput and convergence circle.

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