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[1] ***Abstract*— We develop a new kind of fully distributed random backoff algorithm which completely removes collisions in a single channel carrier-sense multiple access based network without any assistance from a centralized coordination function. Based on carefully chosen design objectives, three principles are established to contribute to the design of the zero-collision achieving random backoff algorithm, which is dubbed as ZeroCollision. To find non-colliding access slots, a station learns from its past transmission history and from neighbors' activities. By building sufficient statistics for its access decision, the station is guaranteed to avoid collisions.**

By preventing collisions, the network performance is enhanced in terms of primary performance metrics such as throughput and transmission delay in comparison to the generic exponential backoff algorithm. We also analyze the VoIP capacity on top of the IEEE 802.11b PHY/MAC and show that the ZeroCollision algorithm supports maximally 54 users which is approximately 400 percent larger than the exponential backoff algorithm.

I. INTRODUCTION

Carrier-sense multiple-access(CSMA) in conjunction with Exponential Random Backoff severely suffers from collision frequency increase, high transmission delay, and low network throughput as the network size increases. This performance degradation is mainly induced by two intrinsic components of the multiple access and the random backoff algorithm under use: collision and random backoff delay. For decades since the nativity of the multiple access networking, a variety of random backoff algorithm has been designed and proposed to lessen the performance degradation in CSMA networks. Though many of them have showed possibility to mitigate the degradation either by modifying the delay function or by introducing an alternative one, the pathological symptom stated above is still pervasive.

Is the severe performance degradation unavoidable price to pay for using CSMA? In fact, if the network utilizes the central coordinator such as Point Coordination Function (PCF) in IEEE 802.11 [1], the scheduling is dictated by a single server and all the stations in the network can access the single channel without any collision. Our objective is to design a fully distributed random backoff channel access algorithm achieving zero collision probability on top of CSMA without any help from a central coordination function.

In this paper we propose a new distributed random backoff algorithm for shared resource access which eliminates collisions throughout most of the network operation period. For the focused algorithm development and analysis, we assume a single collision domain network under infrastructure mode with a base station and $M-1$ subscriber stations, no fading channel, no capture effect and perfect carrier-sensing. Time synchronization between stations is not assumed in general. A successful transmission is confirmed by the corresponding acknowledgement from the receiver. An unsuccessful transmission is caused only by collisions which occur when more than one station start to access the channel at the same time. The network topology under consideration is illustrated in Fig. 1. Less strict assumptions will be discussed at the end of this paper.

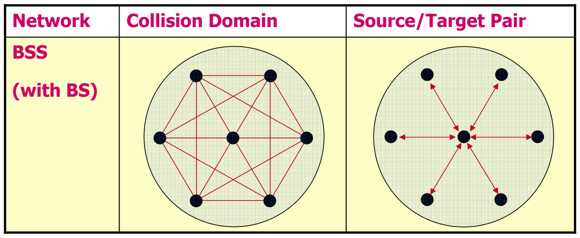

Fig. 1. Network configuration

A. Design Objectives

We adopt the following objectives to design a new channel access algorithm.

1) Distributed: Medium access decisions should be done in a fully distributed and dynamic manner. Both predefined scheduling and reservation request-confirmation message exchange with a central coordinator should be avoided. Each station should be autonomous in its own decision of channel access.
2) Scalability: The network throughput should not decrease as the network size increases. The computational complexity required at each station should be maintained of the order of $O(n)$. The memory size required to manage the transmission history should be minimized.
3) Efficiency: Maximum network throughput should be achieved without regard to the network size. This ob-

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jective reflects the effort to avoid the underutilization symptom of Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA) under bursty traffic model. In those cases, while collisions can be avoided by orthogonal resource allocation (by a central coordinator), momentary absence of traffic or active transmitters directly leads to the underutilization of the available channel resource. The algorithm should be efficient for any type of traffic pattern.
4) Fairness: The shares of the channel resource should be almost equal among all stations.
5) Asymmetry: While the base station in a network with $M-1$ active stations requires statistically $M-1$ times more channel access that a subscriber station, CSMA with exponential backoff usually does not allow the base station to have more frequent access, easily making the base station the bottleneck. Therefore we require a rigid and systematic frame on top of which the base station may enjoy the asymmetry in accessing the channel to enhance the overall network performance.
6) Backward-Compatibility: The protocol must be able to support stations that use the conventional CSMA MAC protocol.
7) Generality: The proposed algorithm should be modular enough so that it can be implemented on top of, but not limited to, existing IEEE 802.11 PHY family.
8) Performance: Performance of the proposed protocol should be lower bounded by that of IEEE802.11 MAC protocol.

B. *Structure of This Paper*

This paper consists of several sections. On top of the design objectives, section II provides three design principles which embody the core ideas of the newly proposed random access algorithm, ZeroCollision. Section III introduces vector notations of the algorithm. Vector notations are useful in understanding and realizing the algorithm and will be helpful in future in-depth analysis. To be convinced about the realizability of ZeroCollision algorithm, we built two simulators and perform many experiments. Those empirical results are intensively discussed in section IV. Section VII presents more interesting research topics based on ZeroCollision by loosening strict assumptions used in this paper, and concludes the research.

II. PRINCIPLES OF ZEROCOLLISION ALGORITHM

With the previous section's objectives in mind as a set of design guidelines, we have three principles to exploit as core ideas of the new MAC algorithm, which is dubbed as ZeroCollision by reasons that become apparent in the following sections. The first principle is *the relaxation of the infinite soft capacity constraint*, the second is a *learning process* and finally the third one is the notion of *sufficient statistics for channel access decision*.

A. *Relaxation of the Infinite Soft Capacity Requirement*

For the fully distributed and uncoordinated multiple access two axioms have been generally accepted: random waiting after collision and statistical multiplexing. The combination of these two enable the infinite soft capacity. Here the capacity stands for the maximum number of stations that can access the shared resource and 'soft' implies that although the network does not have strict limitation on capacity, both network throughput and per-user throughput smoothly decrease as the network size increases.

These two notions were successfully incarnated and currently prevalent in many kinds of CSMA networks such as the IEEE 802.3 and IEEE 802.11 families, which are now the most popular Internet access technologies. In this research, however, we relax the infinite soft capacity constraint to realize the design objectives suggested in the previous section. This relaxation can be justified because

- Physical systems have hard capacity limits. Because of the implementation limitation, it is not possible to support an infinite number of stations in a network. As a typical example, the IEEE 802.11 MAC can only simultaneously support up to 2008 stations, since the maximum length of the Partial Virtual Bitmap of Traffic Indication Message in Beacon frame(from the base station) is limited to that number, where Partial Virtual Bitmap is used to wake up power-saving stations.
- Every network technology has its own coverage limit. For example, IEEE 802.3 100BASE-T and IEEE 802.3ab 1000BAST-T have limited cable distance up to 100m. Also, the typical operating ranges of IEEE 802.11b, 802.11g and 802.11a are 100m, 50m and 20m respectively. It is hardly natural that several hundreds of stations pack into the coverage of a single network.
- As the network size increases, severe performance degradation in terms of network throughput, per-user throughput, and transmission delay is induced. After a certain threshold of the network size, the performance becomes lower than the minimum required throughput/delay necessary to finish a single transaction of a user application. Therefore, infinite capacity loses its meaning at this point; a network cannot support more than a certain number of stations in reality.
- A wireless user's mobility is quasi-static. The best analogy to describe this is to think of a conference room in which users sporadically walk in or walk out. Whenever the station of a new user associates with the network, no extra association for a certain duration (more than a few minutes at least) is expected on average. We call this interval a quasi-static period.

Therefore, we deal with the design of a network with a hard capacity limit.

B. *Learning Process*

The second principle is that each station should learn some lesson from its past collision and successful transmission history. In this subsection, we relax the constraint of random waiting after collision. Typical but scalable random waiting algorithms are the *binary exponential random backoff algorithm* and the *truncated binary exponential random backoff algorithm*. In this paper we designate both as the exponential backoff algorithm. Exponential backoff algorithms are basically memoryless; whenever a successful transmission is detected, the contention window size is shrunk back (to the initial value in most cases) so that it repeats the process of collisions and exponential backoffs. While this memoryless feature of the backoff algorithms provides highly dynamic adaptation to the current network traffic condition under the elastic traffic model, it also causes unnecessary resource consumption that might be avoidable assuming the conditions are quasi-static and do not change extremely fast. Simply put, the learning process is based on the three following elements: learning one's own safe access slots, learning others' activities, and learning others' inactivities. They can be summarized as follows:

- The contention window size CW is fixed.
- If a station transmits its packet successfully by using a certain access slot, it keeps using that slot for future accesses until another collision is detected within that slot.
- Whenever a station detects the use of certain access slots by others, it marks those slots with a predefined recycle timer T_r, a non-negative integer, in its memory (that is later defined as Neighbor Access Vector), and avoid using them until T_r is expired. If a slot is marked, we call it *reserved*.
- Whenever a station's transmission collides, it randomly backoffs (jumps) to any non-reserved slot and uses it as the station's next access slot. To find the vacancy, the station refers to its memory.

A station's behavior is affected by followings: its own success, its own collision, neighbors' inactivity in a collective sense, and neighbors' channel access in a collective sense. The station does not care whether neighbors' transmission is successful or not. Note that if CW is fixed and each station is allowed to have at least a single access slot, the maximum capacity is limited to CW. This hard capacity limitation is justified due to the first principle.

C. Sufficient Statistics for Channel Access

To understand ZeroCollision random backoff algorithm, it is crucial to first understand the notion of *'Sufficient statistics of CSMA random backoff'*. Consider the IEEE 802.11 MAC algorithm as a typical combination of CSMA and random backoff. When a station has a new packet to send, it senses the channel first. If the channel is sensed to be idle for at least the Distributed Interframe Space (DIFS) period, it transmits the packet right away. Otherwise, it waits for the end of the current busy period. At the end of the busy period, it waits for another DIFS, rolls a dice whose faces are numbered from 1 to CW, gets a backoff number, and again waits for idle slots as many as backoff number while continuously monitoring the channel activity. If the channel is sensed to be busy during the backoff period, the backoff counting stops until the channel is released to be idle. At the end of the backoff, the station transmits the packet. If the collision is detected, the station doubles its CW, and repeats the process until the successful transmission or the maximum retransmission count is reached. A careful observation of this process reveals an interesting fact: from the perspective of each station, the sufficiently required information for a station to determine its channel access is only the idle slots and the DIFSs. Considering a DIFS as an elongated idle slot, we regard both as idle slots. Since the idle slots between transmissions form a random process through the random dice rolling and unknown frame sizes, they become sufficient statistics for channel access. Fig. 2 illustrates the graphical explanation of sufficient statistics. The notion of sufficient statistics is connected to the concept of ZeroCollision's fixed size CW. This is more clarified in the next section. From now on, we do not model and analyze the algorithm in time domain. We move our thought domain into the discrete sequence of idle slots.

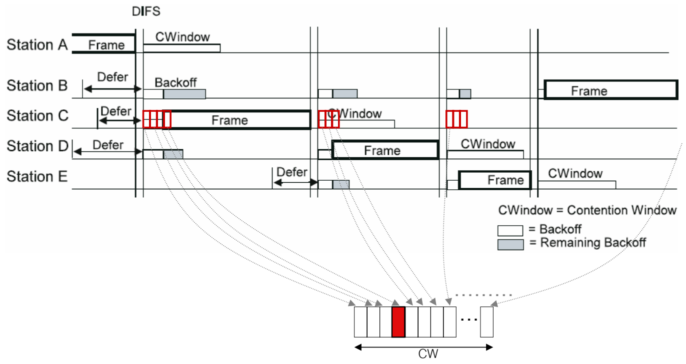


Fig. 2. Notion of sufficient statistics in channel access

III. ZEROCOLLISION ALGORITHM MODELING

Each station independently manages three row vectors of length CW: The Self Access Vector $\mathbf{S}$, the Neighbor Access Vector $\mathbf{N}$ and the Time Pointer Vector $\mathbf{P}$. CW is a network parameter and is assumed to be periodically broadcast within a beacon by the base station. The same CW is shared by all the stations which are associated/associating to the same base station. $\mathbf{P}$ has a single non-zero element whose value is typically one. The location of the non-zero element of $\mathbf{P}$ is called *time pointer*. Time pointer is cyclic-shifted to right hand side whenever an idle slot is detected. Similarly, each element of $\mathbf{S}$ and $\mathbf{N}$ stands for each slot time eligible for the access by stations. One should be cautious in understanding the notion of access slots; they are *not* physically consecutive but in fact intermittent (See Fig. 2) since a station may pause and resume carrier sensing according to the channel activities. Meanwhile, if we think of only the sufficient statistics defined in the third principle, intermittent slots form virtually consecutive accessible slots so that we can build vector notations. In vector notation, the cyclic-shift of the $\mathbf{P}$ at time k can be denoted as:

$$\mathbf{P}[k+1] = \mathbf{P}[k]\mathbf{C} \tag{1a}$$

$$\{\mathbf{C}\}_{ij} = \begin{cases} 1, & \text{if } j = i+1 \\ 1, & \text{if } j = 1, \text{ and } i = \text{CW} \\ 0, & \text{otherwise.} \end{cases} \tag{1b}$$

The initial $\mathbf{P}$ is $\mathbf{P}[0] = [1, 0, \cdots, 0]$ for every station. Because of cyclic-shift property, the following equality holds:

$$\mathbf{P}[k] = [0, \cdots, 0, 1, 0, \cdots, 0], \tag{2}$$

where 1 is the $[(k \bmod \text{CW}) + 1]^{th}$ element of $\mathbf{P}[k]$. The non-zero element of $\mathbf{S}$ stands for the station's eligible access slot. Whenever the time pointer has the same position as the non-zero element of $\mathbf{S}$, the station is allowed to transmit its packet. Otherwise, the transmission is not allowed. In vector notation, station j may transmit only if the inner product of $\mathbf{S}$ and $\mathbf{P}$ is positive.

$$\mathbf{S}_j^T \mathbf{P}_j > 0. \tag{3}$$

Typically every station has a single non-zero element in its $\mathbf{S}$. However multiple access slots per station are allowed for special purpose. For example, a base station is assumed to have $(M-1)$ times more traffic than any of its associated subscriber stations. Accordingly it may have $M-1$ non-zero elements in its $\mathbf{S}$ so that the overall network can easily achieve the maximum performance through the asymmetric resource allocation. Besides, multiple access slot allocation also enables Quality of Service in a CSMA network. This flexible and asymmetric resource allocation capability is another beauty of ZeroCollision algorithm.

On the other hand, $\mathbf{N}$ stands for neighbor stations' accessed slots in a collective sense. Whenever a station senses that another station accesses the channel, it marks the corresponding element of $\mathbf{N}$ with T_r. T_r indicates the freshness of neighbors' activity during that slot. As mentioned before, $\mathbf{N}$ is managed in a collective way. That is, the bookkeeping of $\mathbf{N}$ does not depend on which neighboring stations access the channel. Also, if a previously marked slot with positive freshness in $\mathbf{N}$ is sensed to be idle, the station decrements the freshness of that slot by one. Whenever the freshness reaches zero, it is regarded as unmarked, and is recycled for a new access slot selection process on collision detection. The slots with positive freshness are *reserved*, and those with zero freshness are *vacant*.

$$\mathbf{N}_j[k+1] = \begin{cases} \mathbf{N}_j[k] + \mathbf{P}_j[k], & \text{if slot is sensed busy} \\ \max(0, \mathbf{N}_j[k] - \mathbf{P}_j[k]), & \text{otherwise.} \end{cases} \tag{4}$$

If more than one station select the same access slot, that leads to a collision. On collision detection, a colliding station should give up the current access slot and randomly choose one of the non-reserved slots in its own $\mathbf{N}$, if it has at least one non-reserved slot. A subtle protocol understanding needs to be clarified here. From the perspective of a colliding station, the colliding access slot is not a reserved one. From the perspective of other stations, the colliding access slot is marked as a reserved one. This incongruity is deliberately allowed in order to guarantee each station's minimal operational complexity; otherwise, every station would have to keep track of acknowledgement packets for others as well to determine whether the transmission was successful or not, which is apparently bothersome. Note that this reselection rule allows the colliding station to reselect its previously colliding slot with non-zero probability. This might look strange at first glance. However, there are two beneficial aspects. First, it provides faster convergence to zero-collision status. Second, it provides the localization of the collisions in case of under-provisioning. In vector notation, a collision occurs at time k if and only if

$$\sum_{i \neq j}^{M} \mathbf{S}_i^T \mathbf{P}_i[k] \mathbf{S}_j^T \mathbf{P}_j[k] > 0, \tag{5}$$
$$\text{where } i, j \in \{1, 2, \cdots, M\}.$$

On detecting a collision, the station j randomly chooses $\mathbf{S}_j[k+1]$ such that

$$\mathbf{S}_j^T[k+1]\mathbf{N}_j[k] = 0. \tag{6}$$

If there is no solution to (6), station j sticks to use the previous access slot.

$$\mathbf{S}_j[k+1] = \mathbf{S}_j[k]. \tag{7}$$

There is a non-zero probability that there is no eligible non-reserved slots to reselect despite that M is less than CW. In this case one may wait until some slots' freshness reach zero again.

A. ZeroCollision Algorithm

Here we provide the ZeroCollision algorithm in a more compact, but generic way. A station randomly selects a slot from Self Access Vector and set a non-zero value in it. When a station is neither receiving, transmitting, nor sensing channel activity,

1) If the inner product of the Self Access Vector and the Timer Pointer Vector is nonzero, the station is allowed to access the channel.
2) If the station's packet collision is detected, clear the Self Access Vector, randomly choose one non-reserved slot from Neighbor Access Vector and set a non-zero value in it.
3) If an idle slot is detected, decrement the corresponding slot value in Neighbor Access Vector if it is positive, and shift Timer Pointer Vector to the right.
4) If an busy slot is detected, set the corresponding slot value to Recycle Timer in Neighbor Access Vector and wait until the channel becomes idle.

B. Convergence

This subsection proves that ZeroCollision algorithm guarantees the convergence of a single collision domain network to zero collision status.

Definition 1: Zero collision status
Given M active stations in a network with the common

contention window size CW, we say that the network achieves zero collision status if and only if there is no more collision in that network after a certain time k_0, where k_0 is a non-negative integer. In vector notation,

$$\sum_{i \neq j}^{M} \mathbf{S}_i^T[k]\mathbf{P}_i[k]\mathbf{S}_j^T[k]\mathbf{P}_j[k] = 0, \tag{8}$$

where $i, j \in \{1, 2, \cdots, M\}$ and $k \in \{k_0, \cdots\}$.

Definition 2: Convergence time
Convergence time of a zero collision status achieving network is the least possible k_0 which satisfies the definition 1.

Theorem 1: Convergence theorem
A network under ZeroCollision algorithm achieves zero collision status without regard to its initial access slot allocations for all the stations in the network if T_r is finite and the network size M is less than or equal to the contention window size CW.

Proof: Since M is less than or equal to CW, there are always CW-M *physically* vacant access slots. If neighbor vectors of colliding stations do not have vacant slots except their colliding access slot, the colliding stations should wait for less than or equal to T_r time to reflect physically vacant access slots. When the colliding stations have vacant slots including the colliding slot, according to the ZeroCollision algorithm, there is non-zero probability such that at least two of them independently chooses different vacant slots, which reduces the number of the colliding stations per access slot. This process repeats until any access slot is taken by at most only one station. If this status is reached, there is no more collision because at most one station will start its transmission in an access slot. Therefore the network achieves zero collision status. ■

IV. PROOF OF CONCEPTS AND EXPERIMENTAL RESULTS

A. Proof of Concepts

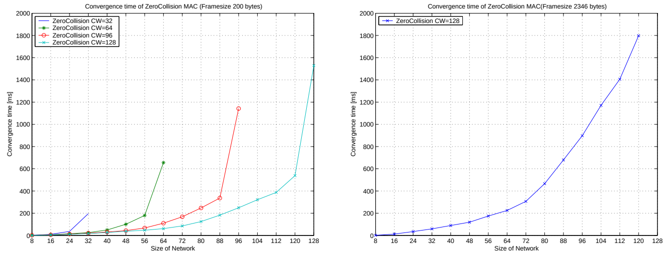
To verify the viability of the ZeroCollision algorithm, we implemented two visual MAC simulators dubbed as ZeroSim. As a baseline PHY/MAC protocol, we chose the popular IEEE 802.11 wireless protocols. The first simulator performs mostly scalar processing and emulates each station's behavior while the latter one performs mostly vector processing and emulates the whole network's behavior. ZeroSim is able to be operated on top of any type of IEEE 802.11 PHY parameters, precisely emulating IEEE 802.11 MAC protocol operations. There are mainly two random backoff algorithm modes available: *IEEE 802.11 CSMA/ZeroCollision* mode and *IEEE 802.11 CSMA/ExponentialBackoff* mode. Both modes can support any number of stations and any size of the contention window. The traffic model includes, but is not limited to, a saturated queue model with fixed/variable frame sizes. We performed more than 21,000 sets of simulations with various combinations of network and traffic parameters. Each parameter set is repeated 100 times to acquire significant statistics. The simulation platform was a dual CPU Xeon cluster computer consisting of 64 nodes. All empirical results showed that ZeroCollision algorithm successfully removes all the potential collisions in the network and is superior to the exponential backoff algorithm in virtually every appropriate performance metric. Detailed performance comparison and lessons from it are provided in the following section.

TABLE I
EXPERIMENTAL CONFIGURATION

Parameter	**Notation**	**ZeroCollision**	**Exp. backoff**
PHY protocol		IEEE 802.11b/DSSS Long Preamble	
Data TX rate	R_{TX}	11 Mbps	
Slot time	T_{SLOT}	20 μsec	
SIFS	T_{SIFS}	10 μsec	
DIFS	T_{DIFS}	50 μsec	
Contention Window	CW	Fixed 128 (if not specified)	Dynamic 32-1024
Network size	M	4 - 128	
Traffic model		Saturated queue	
Frame size	x	200 or 2346 bytes	
ACK size	L_{ACK}	14 bytes	
PHY Preamble	L_{Pre}	18 bytes	
PHY PLCP	L_{PLCP}	6 bytes	
PHY TX rate	R_{PHY}	1 Mbps	
Recycle Timer	T_r	5	0

B. Convergence time

During the pre-convergence period, there are collisions. Up to the reasonably large network size of 128 stations with fixed frame size 200 bytes, the convergence time is below 1600 msec, which is almost immediate after power up. Once the convergence is achieved there is no more collisions. If the 10 percent access slot margin is allowed given CW, the convergence time is even lower than 600 msec. After the convergence time, the network is completely collision free. Considering that one second is relatively very small compared to the typical quasi-static interval, which may last for many seconds, this empirical convergence time result is encouraging because the network is expected to have its maximal performance during the remaining period. The fixed 2346 bytes case shows, although its convergence time is larger than for the fixed 200 bytes frame case, convergence is still very fast.

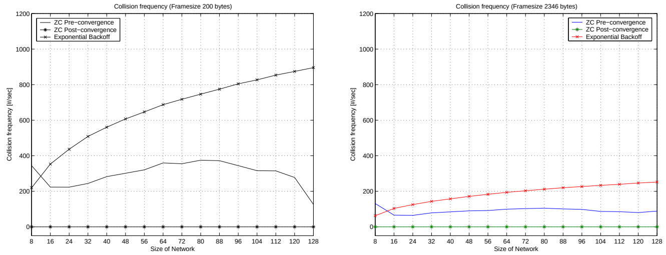


(a) Framesize 200 bytes (b) Framesize 2346 bytes

Fig. 3. Convergence time

C. Collision Frequency

The advantage of the ZeroCollision algorithm is more pronounced in Fig. 4 that shows the collision frequency. The collision frequency is defined as the number of collisions per unit time. The collision frequency of the exponential backoff algorithm increases as the logarithm of the network size. Meanwhile, after the convergence under ZeroCollision, the collision frequency becomes exactly zero. The pre-convergence case is also shown between exponential backoff and post-convergence. This figure hints that the network performance of ZeroCollision pre-convergence duration is somewhat between exponential backoff algorithm and ZeroCollision post-convergence. The pre-convergence performance, nonetheless, does not have much meaning since the duration is too short to affect the overall network performance. Therefore, we omit the pre-convergence performance for the rest of the analysis.

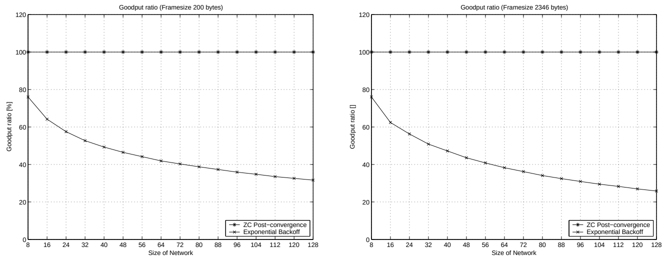


(a) Framesize 200 bytes (b) Framesize 2346 bytes

Fig. 4. Collision frequency

D. Goodput Ratio

The goodput ratio is defined as the ratio of successfully transmitted bytes and transmitted bytes. As expected, while the goodput ratio of exponential backoff decreases as the network size increases, ZeroCollision remains at 100 percent(see Fig. 5), which is the theoretical limit. This result in fact was apparent from Fig. 4. One notable point is that the framesize does not affect the goodput ratio much because under the perfect channel sensing and no fading environment, the sole factor to affect the goodput ratio is the collision event that is independent of the frame size.



(a) Framesize 200 bytes (b) Framesize 2346 bytes

Fig. 5. Goodput ratio

E. Network Throughput

Network throughput is defined as the ratio of successfully transmitted bytes per unit time and max data transmission rate. The theoretical limit of IEEE 802.11b can be arithmetically calculated and turns out to be about 78.6 percent which corresponds to 8.65 Mbps under extremely ideal traffic model and backoff event; there are only two stations in the network. One is the only traffic source and the other does the reception only with acknowledgment. The source station always happens to pick zero backoff. Then the theoretical limit of the network throughput can be calculated as follows:

$$f(x) = \frac{\alpha}{\beta + \gamma + \delta} \times 100 \tag{9a}$$

$$\alpha = x / R_{TX} \tag{9b}$$

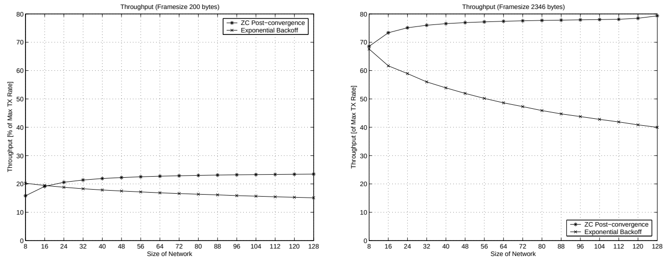
$$\beta = (L_{Pre} + L_{PLCP}) \times 8 / R_{PHY} \tag{9c}$$

$$\gamma = (x + L_{ACK}) \times 8 / R_{TX} \tag{9d}$$

$$\delta = T_{SIFS} + T_{DIFS} \tag{9e}$$

where x is the length of MAC Protocol Data Unit(MPDU). $f(\cdot)$ is maximized at $max(x)$, which is 2346 bytes in IEEE 802.11. At $x = 2346$ bytes, $f(x) = 78.6$ percent.

We should mention that this theoretical limit of the network throughput cannot be achieved in practice under CSMA/ExponentialBackoff protocol because of the non-zero probability of collisions where there is more than one source and the randomness of backoff delay. In fact they are negatively correlated. Surprisingly however, the theoretical limit of the network throughput is achieved under CSMA/ZeroCollision protocol as shown in Fig. 6(b). Noteworthy observations are listed up as follows:



(a) Framesize 200 bytes (b) Framesize 2346 bytes

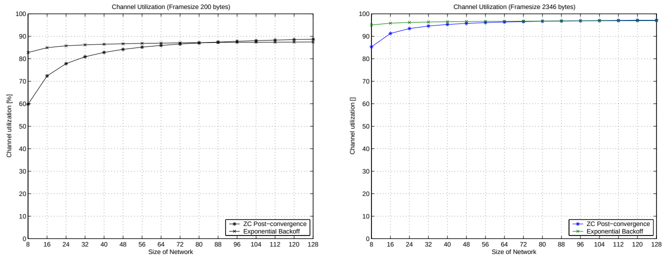
Fig. 6. Network throughput

- Under ZeroCollision the network throughput increases as the network size increases.
- Under exponential backoff the network throughput decreases as the network size increases (see Fig. 6(a)). The per-user throughput becomes worse.
- The throughput gap becomes larger when the frame size increases
- There is a performance crossing at small network size regime. It occurs when the network capacity is operationally set large (e.g., 128) while the true network size is very small (e.g., 8). If the network operator knows the capacity requirement of a given network (such as home or office network) and sets the capacity appropriately, higher performance under ZeroCollision is always guaranteed.
- The strictly higher performance of ZeroCollision is also achieved when stations are allowed to have multiple

access slots adaptively instead of a fixed single access slot. The design of this adaptiveness is surely feasible but not covered in this research.

F. Channel Utilization

Channel utilization is defined as the ratio of busy period and the sum of busy and idle periods. For the small network size (at a fixed network capacity $CW = 128$), the channel utilization of CSMA/ExponentialBackoff is higher than that of CSMA/ZeroCollision. For the large network size, the channel utilization of CSMA/ZeroCollsion is higher. At the same network throughput, the higher channel utilization implies higher throughput. That's not quite the case here. Roughly speaking, ZeroCollision has higher network throughput and lower (or similar) channel utilization over the almost entire network size regime. Hence, ZeroCollision has a higher efficiency and induces less inter-cell interference than exponential backoff.



(a) Framesize 200 bytes (b) Framesize 2346 bytes

Fig. 7. Channel utilization

G. Delay

Under the saturated queue traffic model, we define delay as the time difference between the end of the previous successful transmission and the end of the next successful transmission. Fig. 9 shows the empirical delay performance of two algorithms. Two noteworthy aspects of ZeroCollision algorithm are as follows: it has delay upper bounds at a given network size. This fact remarkably differentiates between ZeroCollision and exponential backoff. Besides, the empirical results suggest that the maximum delay under ZeroCollision is almost always lower than the average delay of exponential backoff. It achieves higher network throughput and lower delay at the same time. Under a saturated queue traffic model, the transmission delay of ZeroCollision becomes constant.

$$d(x) = T_{active} \times (M-1) + T_{SLOT} \times (\mathrm{CW}-M) \tag{10a}$$

$$T_{active} = 2 \times T_{PHY} + \frac{x + L_{ACK}}{R_{TX}/8} + T_{SIFS} + T_{DIFS} \tag{10b}$$

$$T_{PHY} = (L_{Pre} + L_{PLCP})/(R_{PHY}/8) \tag{10c}$$

H. Effect of Under-provisioning

Now we look into an under-provisioning situation where the network size M is larger than CW. Although this under-provisioning effect is not likely to happen in practice because the base station can perform the admission control by filtering out extra associations over CW or because stations can scan the channel in prior to their first time transmissions, it is worthy of observing under-provisioning effect to understand the ZeroCollision algorithm better.

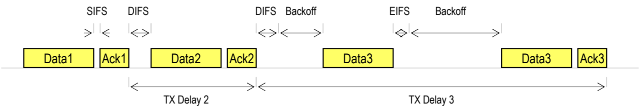
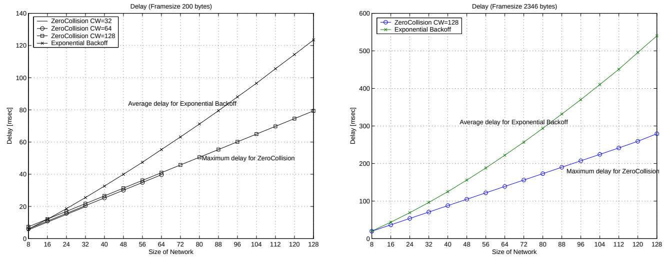


Fig. 8. Definition of delay under saturated queue traffic model



(a) Framesize 200 bytes (b) Framesize 2346 bytes

Fig. 9. Delay

- As a side, we can see the effect of optimally choosing CW for a given network. For a network of size under 32, the $CW = 32$ case has strictly higher throughput than the $CW = 128$ case.
- After exceeding the configured network capacity, the throughput of ZeroCollision starts to drop. This drop is precisely the effect of the under-provisioning. In fact, the extra stations cause overbooking over the same slots which lead to continual collisions for those slots. Therefore in under-provisioning situation, some users' transmission will be completely blacked out while others will not experience performance degradation at all. We call this a partial outage.
- However, the network throughput of ZeroCollision with under-provisioning is maintained higher than that of exponential backoff, until the network size is more than twice of CW. This is an interesting feature of ZeroCollision considering that it is designed to have hard capacity supporting maximally CW stations in a network. In other words, the performance of ZeroCollision network is superior to that of exponential backoff network up to double the predefined hard capacity. Considering that CW is usually chosen by the network operator who can estimate the nominal network size, 100 percent margin is regarded more than sufficient.

V. VoIP Application

For a promising application, we analyze the VoIP capacity and compare it with the literature. First we have the VoIP traffic model as follows: each VoIP source generates VoIP data from G.711 codec with 64 Kbps information data rate. The latency budget between a subscriber station and a base station is 40msec. Considering the constant transmission delay

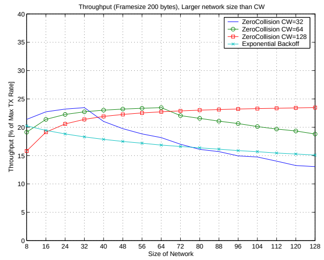


Fig. 10. Throughput of ZeroCollision algorithm in under-provisioning case

of ZeroCollision, we seek the maximum VoIP capacity within the given latency budget. This allows us to use 320 bytes of information data per 40 msec per user, which turns to be $x = 394$ bytes per MAC frame. Given CW, we can find the maximum value of M using (10) such that

$$d(394) < 40 \text{ msec} \tag{11}$$

Fig. 11 is the solution graph of (11). The non-linearity is from the capacity limit of the network and the integer round off. We find out CW does not have big impact on VoIP capacity once CW is larger than 60. So given $CW = 64$, 40 ms latency, and IEEE 802.11b/DSSS/LongPreamble PHY, we can compare the transmission delay of VoIP traffic between under exponential backoff and under ZeroCollision. Assuming a VoIP packet generation is uniformly distributed between two successive transmissions, the analysis shows that the VoIP capacity under ZeroCollision is roughly 400 percent higher than that under exponential backoff. Fig. 12 shows this result. Note transmission delay of exponential backoff is random while that of ZeroCollision is deterministic. Similar analysis and comparison can be done on top of IEEE/802.11a PHY, leading to the same conclusion with different numerical results.

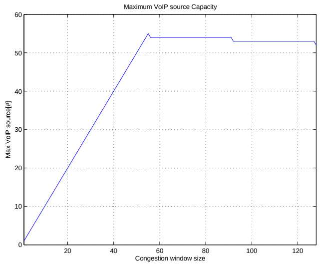
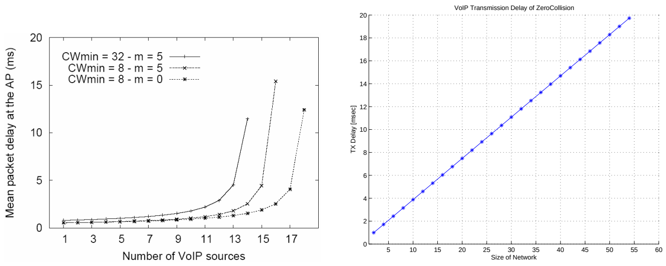


Fig. 11. VoIP capacity of ZeroCollision



(a) Exponential backoff [3]

(b) ZeroCollision

Fig. 12. VoIP transmission delay

Two more lessons need to be mentioned at this point. The analysis above is VoIP source based but not VoIP session based, where a session usually consists of two independent VoIP traffic sources. In the infrastructure mode network, a subscriber station is paired with a base station to form a VoIP session. This implies that when there are $M/2$ upstreams from $M/2$ subscriber stations, the base station should support $M/2$ VoIP downstreams as well. In fact in the generic IEEE 802.11 MAC, this is practically not possible because the MAC protocol does not support asymmetric channel allocation. However in ZeroCollision, the base station can allocate multiple access slots in its **S** vector to support M VoIP capacity without further degradation. This argument can be applied to the elastic traffic model as well.

VI. DISCUSSION

A. *Comparison*

While ZeroCollision enjoys a guaranteed orthogonal access slot allocation as in TDMA, it does not suffer from under-utilization. Even under the momentary absence of traffic, it achieves almost maximal utilization. This is because the idle slot time T_{SLOT} is relatively much smaller than the single frame transmission + acknowledgement time T_{active}. Also as in CSMA/ExponentialBackoff, ZeroCollision does not require any central coordinator and is highly adaptive to the network size. In short, ZeroCollision carries advantages of TDMA and CSMA/ExponentialBackoff.

B. *Sensitivity*

Since ZeroCollision takes idles slots as sufficient statistics for access, imperfect carrier-sensing due to defective hardware or random fading process of the wireless channel may cause drift of time pointer. One simple but effective counteraction to this is to make periodic beaconing access slot among CW slots be fixed; the base station uses the same access slot for beacon frames and does not change it such that subscriber stations can have a good reference slot. This feature also enables the support for power-saving mode stations.

C. *Asymmetric channel access*

As discussed in section V, a base station may have multiple access slots to maximize the overall network performance.

D. *Asynchronous operations*

Although we assumed simultaneous power-ups of stations for simulation and illustration purpose, the ZeroCollision algorithm is not limited by synchronization. In fact, it is fully distributed such that each station may maintain different time pointer and therefore different Access Vectors. For example, station i's slot number 5 may correspond to station j's slot number 14.

E. Effect of new association

By allowing one period of scanning before the first transmission, a newly associating subscriber station can cause no collision at all. In other words, the convergence times provided in Fig. 3, in fact, are upper bounds.

F. Effect of implicit disassociation

Some stations leave the network without any explicit notification. The access slots used by them are recycled after the inactivity of Tr periods.

G. Easy implementation

ZeroCollision is compatible with any kind of CSMA based PHY standards. What is required is only to change the random backoff algorithm from exponential backoff to ZeroCollision.

VII. CONCLUDING REMARKS AND FUTURE RESEARCH DIRECTION

We proposed a new medium access control random backoff algorithm, dubbed ZeroCollision, which is compatible with, but not limited to CSMA protocols. The empirical results and the analysis for primary performance metrics such as throughput, goodput, delay, etc., show that ZeroCollision is highly superior to the prevalent exponential backoff algorithm. Although all the performance figures are based on IEEE 802.11 PHY families in this paper, since this algorithm is independent of PHY protocols and virtually the whole portion of the associated MAC protocols, its application can be easily extended to other well-known wireless or wired technologies. This algorithm independence also guarantees the ease of implementation and high backward compatibility.

In the saturated queue model with the largest frame size, ZeroCollision achieves roughly double throughput, half delay and zero collision simultaneously, compared to generic exponential backoff algorithms. To the authors' knowledge, this performance is the best among fully distributed medium access control algorithms known to the public. Moreover, we see the potential of ZeroCollision to outperform even centrally coordinated channel access algorithm (such as in PCF) since it does not require message exchanges, thereby no additional overhead between subscriber stations and the coordinator. The currently ongoing probabilistic analysis supports this idea. These superiorities are achieved through three principles: the relaxation of the infinite soft capacity constraint, the learning process, and the notion of sufficient statistics for channel access decision.

In this paper, our network configuration model was limited to a single collision domain infrastructure mode network. Apparently, the extension of ZeroCollision to multiple collision domain ad hoc networks will be interesting and expected to be fruitful. Also, this random access algorithm brings about a variant version of hidden/exposed node problem in multiple collision domains. The performance analysis for elastic traffic model should not be missed as well. The combination of saturated queue and elastic traffic models could incur interesting and more practical results.

REFERENCES

[1] IEEE Standard for WirelessLAN Medium Access Control and Physical Layer Specification, IEEE Std 802.11-1999 (R2003), Nov. 1999.

[2] IEEE Standard for WirelessLAN Medium Access Control and Physical Layer Specification, IEEE Std 802.11a-1999 (R2003), Nov. 1999.

[3] N. Hedge, A. Proutiere, and J. Roberts, "Evaluating the voice capacity of 802.11 WLAN under distributed control," *Proc. LANMAN,* 2005.