Optimal Constant-Window Backoff Scheme for IEEE 802.11 DCF in finite Load Single-Hop Wireless Networks

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ABSTRACT

In this work, we propose and analyze a backoff enhancement for IEEE802.11 DCF that is quasi-optimal under all traffic loads. First, we give a new analysis of DCF scheme under finite load conditions in single hop configuration and we provide an accurate delay statistics model that consider the self-loop probability in every backoff state. Then we introduce the constant-window backoff scheme and we compare its performance to IEEE802.11 DCF with Binary exponential backoff. The quasi-optimality of the proposed scheme under all traffic loads is illustrated and numerical results show that it increases both the throughput and fairness of IEEE 802.11 DCF while remaining insensitive to traffic intensity.

Categories and Subject Descriptors

C.2.5 [**Computer-Communication Networks**]: Local and Wide-Area Networks—*Access schemes*

General Terms

Performance

Keywords

IEEE802.11 DCF, CSMA/CA, binary exponential backoff, short-term fairness, optimal constant-window backoff

1. INTRODUCTION AND RELATED WORKS

In the popular, and widely used IEEE802.11 standard for WLANs [1], the primary medium access control (MAC) technique is called distributed coordination function (DCF). DCF is a carrier sense multiple access with collision avoidance (CSMA/CA) scheme and slotted binary exponential backoff (BEB) rules. Since the introduction of the standard, many works have been interested in the analytical evaluation of its performance; most of them were based on the model of Bianchi, [2], and consider saturation throughput and delay analysis ([3, 4, 5] to cite few). In real networks, packets may be queued at node's buffer before being handled by the MAC protocol, and typical data traffics are bursty or streamed at low rates so that stations do note operate usually in saturated regime. Recent works have addressed the finite load performance of IEEE802.11 DCF with queueing at node's (queues with infinite capacity)[6, 7] or with simplifying assumptions [8]. The analysis of queueing model of MAC protocols is a challenging task, and generally does not permit to obtain closed-form expressions of quantities of interest. In [9], we use a two-stage technique to analyze a queuing model of DCF protocol. In order to acquire closed-form expression of system performance, a Markov chain model is first used to analyze the non-queueing operation of the system. The traffic load in this case is modeled as a probability of having a packet to transmit q, this probability is taken into account whenever the protocol is able to handle a new packet. In this way, q allows us to consider the fact that packet arrivals may occur anytime during the operation of the system. From the non-queueing model, we obtain the service-time statistics corresponding to a given q. In the second phase, we consider a queueing model of the system with a given arrival process $\lambda(t)$ and queue length K. Thus, the probability of having a packet to transmit q corresponds to the probability q_0 of having at least one packet in the queue. In order to link the two models, we use a recursive algorithm that updates the q value used in the Markov model to specify the service time statistics, to match the resulting q_0 from the queueing model. For lack of space, this part of work is not included in this paper.

It is well recognized that the key optimization issue of random access protocols is the design of an optimal retransmission scheme that keeps access rate to the multiple-access channel around its capacity. IEEE802.11 DCF uses a BEB retransmission scheme. The BEB scheme has the advantage of being simple and does not require cooperation among users or any information about the channel state. Its performances however are shown to be sub-optimal, in term of the achieved throughput as it needs several attempts to find approximately the best contention window, and also in term of short-term fairness as it favors the first successful user to compete again for the channel with small contention window against potentially others users with much higher contention window. Works in [10, 11] have derived specific

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fairness metric to illustrate this.

The enhancement of the DCF based BEB have been extensively addressed in the literature, the proposed schemes may be categorized into two classes:

1. Fully blind schemes: as in BEB, the change of the contention window's length is made upon collision or success but in a different manner than BEB (MILD [12], FCR [13], EIED [14] to cite few) in order to reach better the optimal backoff window and/or increase short-term fairness.
2. coherent schemes: here the optimization is made in order to dynamically adapt the contention window's length to meet directly some objective optimization condition. The objective condition is derived from an analytical model and its verification is made by measuring (estimating) some specific performance metrics from channel state, [15, 16, 17] to site few. Even if these schemes identify and try to reach an optimal operating point of the system, the way they update the backoff window is not optimal as in the blind schemes.

Early in the work of Bianchi [2], the notion of optimal backoff window that optimizes the saturation network throughput has been introduced. Unfortunately, the calculation of this optimal window requires information about the network size N and the average duration of collisions $E[T_{col}]$. Even if N could be easily obtained in single-hop network, channel activity sensing is required to estimate $E[T_{col}]$ in case of heterogeneous networks, where users employ different physical rates and/or packet sizes. As DCF provides equal long-term access rate to different users, several studies have shown that it is unable to fairly and efficiently manage heterogeneous networks [7, 15, 18, 19]. As solution, time-based scheduling, that guarantee equal channel time access to different users, have been shown to increase both the throughput and fairness of the MAC protocol [19].

In order to achieve trivially time-based scheduling with DCF, it is sufficient to normalize the packet duration by normalizing the packet-size/physical-rate ratio, i.e., each physical rate is to be used with a corresponding packet size in order to get unique packet duration on the channel and hence, a priori, fair input to the system. In this case, we can implement the optimal-window backoff scheme of [2] without estimating $E[T_{col}]$.

In this work, we consider backoff-window optimization issue of finite load single-hop networks based on the idea in [2]. In order to avoid estimating collision durations, we suppose that packet durations are normalized. Obviously, the optimal backoff-window in this case will depend also on the traffic load. However, we will show that is sufficient to use the saturation's optimal window under all loads to achieve nearly the maximum achievable throughput.

The paper is organized as follows. In section 2 we introduce the analytical model, we derive the throughput and the delay statistics. In section 3 we introduce the optimal constant window backoff scheme. The performances of the two schemes are then deeply analyzed in section 4. Concluding remarks are provided in section 5.

2. BINARY EXPONENTIAL BACKOFF SCHEME

The analytical model we use is based on [2] but extends it to consider finite load performance. We consider a network of n nodes evolving in single hop configuration. Each

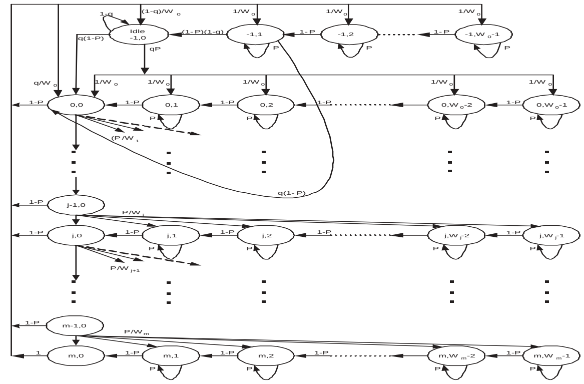

Figure 1: Markov chain model

node state is identified by its backoff window counter and backoff stage. The backoff counter and stage are modeled as a bidimensional discrete-time Markov process $(s(t), b(t))$ where $s(t)$ and $b(t)$ denote respectively the backoff stage and the backoff counter at time instant t. The unit-time of the Markov chain is an average of the three possible time slot durations that correspond to successful transmission, collision or idle, weighted by their probability of occurrence: $T_{avg} = p_{idle}\sigma + p_{suc}T_{suc} + p_{col}T_{col}$.

σ is the idle slot duration, T_{suc} and T_{col} are given in [2]. p_{idle}, p_{suc} and p_{col} will be derived in the following. The scheme defines a maximum number $m+1$ of retransmission trials after which the packet is dropped, and a maximum window size's order m'.

Let $\pi_{i,j}$ denotes the steady state probability of node to be in backoff stage i with backoff counter at j. $i \in \{0..m\}$, $j \in \{0..W_i - 1\}$ and W_i denotes contention window value at stage i. To avoid channel capture, each node must wait a random backoff time after each successful packet transmission. We add then the new states $(-1, j)$, $j \in \{0..W_0 - 1\}$ to model node's state during inter-packets transmission(Inter-transmission backoff (ITB) states). In order to consider the non-saturated regime we define q as the probability of having a packet to transmit (all nodes have the same q[1]), and to keep the analysis tractable we do not consider for the moment queueing at node's buffer (each node has at maximum one packet per time). In a queueing model, q corresponds to the probability of having at least one packet in the buffer.

Fig. 1 illustrates the Markov chain model used for the no-queueing model. The normalizing equation and the resulting steady state probability of being in state $(0,0)$ are given in Eqs. (1,2). The probability of transmission in a given slot is then

$$\tau = \sum_{i=0}^{m} \pi_{i,0} = \frac{1-p^{m+1}}{1-p}\pi_{0,0} \qquad (3)$$

Then the probabilities of busy, idle, success and collision are given respectively as $p = 1-(1-\tau)^{n-1}$, $p_{idle} = (1-\tau)^n$, $p_{suc} = n\tau(1-\tau)^{n-1}$, and $p_{col} = 1 - p_{idle} - p_{suc}$.

And the throughput is defined as

$$Thrp = \frac{p_{suc}L]}{T_{avg}} = \frac{p_{suc}L}{p_{idle}\sigma + p_{suc}T_{suc} + p_{col}T_{col}} \qquad (4)$$

Where L is the data packet duration.

2.1 Delay Statistics

[1]extension to heterogeneous case is straightforward [8]

$$\pi_{0,0}\left[\sum_{i=0}^{m}p^i+\sum_{i=0}^{m}\sum_{j=1}^{W_i-1}\frac{(W_i-j)p^i}{W_i(1-p)}+\sum_{j=1}^{W_0-1}\frac{(W_0-j)p(1-q)}{W_0(1-p)}+\frac{1-q}{q}\right]=1 \quad (1)$$

$$\pi_{0,0}=\begin{cases}\left[\frac{W_0(1-p)[1-(2p)^{m'+1}]+(1-2p)^2[1-p^{m+1}]+2^{m'}W_0(1-2p)[p^{m'+1}-p^{m+1}]}{2(1-p)^2(1-2p)}+(1-q)\left[\frac{p(W_0-1)}{2(1-p)}+\frac{1}{q}\right]\right]^{-1} & m\geq m'\\ \left[\frac{W_0(1-p)[1-(2p)^{m+1}]+(1-2p)^2[1-p^{m+1}]}{2(1-p)^2(1-p)}+(1-q)\left[\frac{p(W_0-1)}{2(1-p)}+\frac{1}{q}\right]\right]^{-1} & m\leq m'\\ \left[\frac{(W_0+1-2p)[1-p^{m+1}]}{2(1-p)^2}+(1-q)\left[\frac{p(W_0-1)}{2(1-p)}+\frac{1}{q}\right]\right]^{-1} & m'=0 \quad \text{(constant window)}\end{cases} \quad (2)$$

We define packet success delay as the time duration a packet lasts in the system since its being handled by the MAC layer until the reception of acknowledgement of its successful reception.

A successful transmission may occur at one of the several backoff stages. The *average* time that a packet spends in the first backoff stage before its first transmission depends on whether the packet comes directly from the idle state or from ITB states. Conditioned on being in the first transmission stage $(0,0)$, this time is

$$D_0 = [1-(1-q)(1-p)]\frac{W_0-1}{2}D_B \quad (5)$$

D_B denotes the average time that nodes spent in every backoff state. Many analyses of 802.11 delay take D_B equal to T_{avg} and ignore the self-loop probability p on every backoff state. In fact, D_B is geometrically distributed with parameter p and variates depending on the states of the $(n-1)$ remaining nodes

$$D_B=\sum_{k=0}^{\infty}p^k(1-p)(kT_B+\sigma)=\frac{pT_B+(1-p)\sigma}{1-p} \quad (6)$$

Where T_B denotes the average slot duration seen by a node in backoff state when the channel is busy. Conditioned on channel busy probability p, T_B is

$$T_B=\frac{(n-1)\tau(1-\tau)^{n-2}[T_{suc}-T_{col]}+[1-(1-\tau)^{n-1}]T_{col}}{p} \quad (7)$$

Similarly, for the other backoff stages, the *average* time that a packet spends in the stage i before its transmission

$$D_i=D_{i-1}+\frac{W_i-1}{2}D_B+T_{col} \qquad i\in\{1\dots m\} \quad (8)$$

D_{i-1} represents the time that the packet spends in the system until it's $(i-1)$th. transmission, $Tcol$ the fact that the last transmission was not successful, and $\frac{W_i-1}{2}D_B$ the average backoff time at the current backoff stage. Conditioned on starting transmission at the state $(0,0)$, transmission success probability at the $i.th$ stage is

$$p_i^{suc}=\frac{\pi_{i,0}(1-p)}{\pi_{0,0}}=p^i(1-p) \qquad i\in\{0\dots m\} \quad (9)$$

The delay of a successful transmission can then be seen as a geometric random variable taking values in the set $\{D_i^{suc}=D_i+T_{suc},\ i=0\dots m\}$.

Alternatively, the *average* delay of packet drop is simply $E[D_{drop}]=D_m+T_{col}$, with drop probability $p_{drop}=p^{m+1}$.

3. OPTIMAL CONSTANT-WINDOW BACKOFF SCHEME

The optimal backoff window can be seen as the transmission probability τ_{op}, below which the channel utilization is reduced due to high probability of idle slots and above which reduction is due to high collision probability. The function of the optimization is then to adapt the backoff window's length to achieve this τ_{op}. Obviously, under finite load conditions, the backoff window must be optimized with respect to traffic intensity (q). However, it is also obvious that the $\{\tau_{op}\}$ will not be achieved for small arrival rate ($q\leq q_t$, q_t is some threshold on arrival rate) even with the minimal backoff window($W_0=1$, minimum backoff delay). For this reason, we propose in this work to use the optimal backoff window's length W_{op}^s (the largest one) of the saturated regime $(q=1)$ for all arrival rates. The intuition behind this choice is that below q_t the system is lightly loaded so that the probability of going into backoff is very small and thus the effect of using a large W is minimal. Above q_t, the loss incurred by using a backoff window $W_0=W_{op}^s\geq W_{op}$ is due to the fact that idle slot probability is higher than the optimal one, but in this case, the packet collision probability is lower that the optimal one, since in CSMA system the idle slot duration is small compared to the collision duration, the loss in the achieved throughput is small.

When we differentiate the throughput (Eq. 4) with respect to τ, we find that it is maximal for transmission probability τ_{op} verifying[2]

$$\tau_{op} = \frac{\alpha-(1-\tau_{op})^n}{\alpha n} \quad \text{where} \quad \alpha=\frac{T_{col}}{T_{col}-\sigma} \quad (10)$$

From Eq.(2) we have for the constant backoff case $(m'=0)$ in saturation conditions $(q=1)$

$$\tau = \frac{2(1-p)}{(W_0+1-2p)}=\frac{2(1-\tau)^{n-1}}{[W_0-1+2(1-\tau)^{n-1}]} \quad (11)$$

The saturation optimal fixed backoff window is then

$$W_{op}^s=1+\frac{2(1-\tau_{op})^n}{\tau_{op}^s} \quad (12)$$

We look now under which condition on q the τ_{op} could not be achieved even with the minimal allowed value of the backoff window $W_0=1$ (no backoff[3]). From Eq.2, we have for $W_0=1$ that $\tau=\frac{q(1-p)}{qp+1-p}$. With a little algebra we find that the situation of $\tau\leq\tau_{op}$ is possible for

$$q \leq q_t=\frac{\tau_{op}(1-p_{op})}{1-p_{op}-\tau_{op}p_{op}} \quad (13)$$

$$\text{Where} \quad p_{op} = 1-(1-\tau_{op})^{n-1} \quad (14)$$

In Fig 2, we plot the Optimal transmission probabilities and the corresponding optimal backoff windows Vs arrival rates. We can see that for arrival probabilities $q\leq q_t$ the achieved transmission rates are below the optimal ones even with backoff window equal to 1. We say then that the system is in lightly loaded regime. Above q_t, τ_{op} is achieved by increasing the backoff window's size. We observe also

[2]The uniqueness of τ_{op} can be simply verified [2]

[3]We take $W_0=1$ only for analytical purpose, in real system the lowest value of W_0 we may take is 2

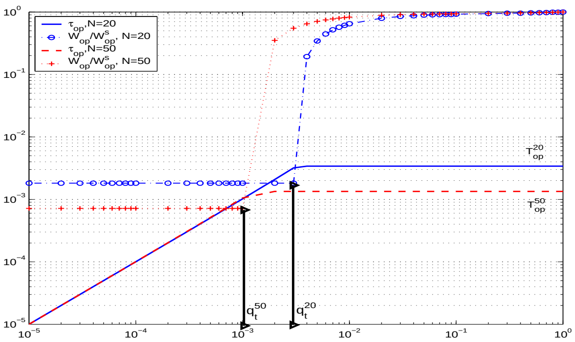

Figure 2: Optimal transmission probabilities and the corresponding optimal backoff window(normalized to the saturation optimal window) vs. arrival rates

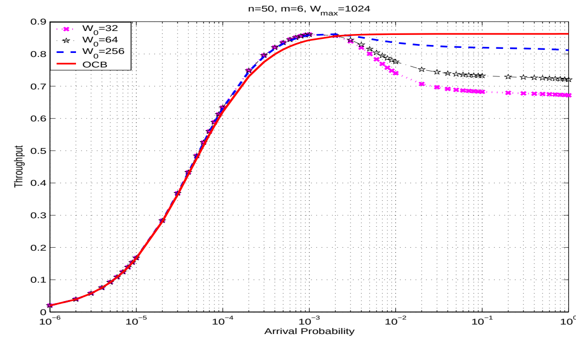

Figure 3: Throughput

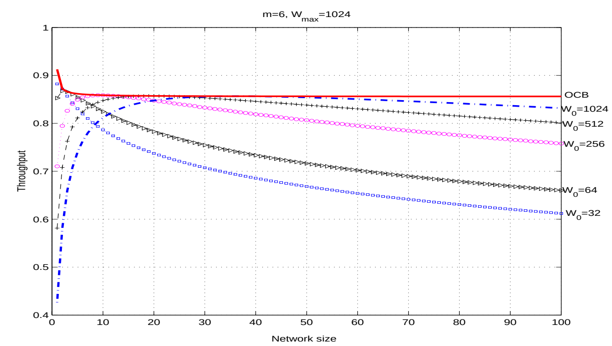

Figure 4: Throughput Vs. Network size

that the optimal backoff window increases, in a first phase, exponentially and then, in a second phase, slowly converges to the saturation optimal window. During the first phase of increase we say that the system is in transition regime while during the second phase it is in saturation regime.

4. NUMERICAL RESULTS

In this section, we compare the performance of the IEEE 802.11 DCF based BEB with the proposed optimal constant backoff(OCB) scheme. Table 1 summarizes the parameters used for our numerical results.

Fig. 3 shows the achieved throughput Vs. packet arrival probability for network of size $n = 50$. The optimal window for OCB scheme in this case is 1392 slots. We consider multiple BEB cases with different initial backoff window $W_0 = 16, 64, 256$. We see then that during the lightly loaded regime ($q \leq 10^{-3.5}$ in this case), both OCB and BEB (independently from W_0) perform similarly and increase their channel utilization with increasing q. During this pahse, almost all packets are transmitted directly at their arrivals without any backoff delay.

During the transition regime ($10^{-3.5} \leq q \leq 10^{-2.8}$), we observe that the BEB throughput is slightly higher than the OCB one. During this phase, the probability of busy slot at packet arrival increases for the two schemes. They start then to execute occasionally their backoff mechanisms. As the BEB scheme begins with a relatively small value of W_0, its busy slot probability is bigger than for OCB (the users are not delayed for a long time), so it enters more frequently into backoff states, but as the system is still lightly loaded, it succeeds its transmission without excessive backoff delay (the panel of backoff windows (from W_0 to W_{max}) is sufficient to statistically multiplex efficiently all access demands). The OCB scheme operates differently; as its backoff window is bigger (1392), its busy slot probability is smaller than for BEB (high idle probability), so it enters less frequently the backoff state. But in the same time, as the system is lightly loaded, even if the system delays far enough the unlucky users who find the system busy at their packet arrival, the channel is not used frequently during this time which explains the small loss in channel utilization.

Finally in the saturation regime ($q \geq 10^{-3.5}$), and depending on W_0, the throughput achieved by BEB scheme decreases and then saturates, while the OCB throughput saturates at a higher value. The degradation of throughput of BEB can be seen as a failure of the scheme to adapt its window to access demands (high collision probability). The OCB scheme is more efficient during this phase, as its backoff window is tailored for saturated regime. Even if it continues to delay unlucky user for a longer time than BEB, the channel utilization get higher as the load increases. In fact, OCB fixes the optimal window in order to keep transmission probability in an optimal level. At this optimal level, loss due to idle slots is equal to loss due to collision. Below this optimal level, idle slot probability increases while success and collision probabilities decrease. Above the optimal transmission level, success increases but also collisions. In carrier sense multiple access scheme, idle slot duration is shorter than collision duration, the scheme tries then to equalize the duration of idle and collision events which explains the large value of the optimal contention window's size.

To illustrate better the superiority of OCB aver BEB, we plot in fig. 4 the achieved throughput of the two schemes in saturation vs. network size. We observe that OCB performs better than BEB at all network size. We observe also that BEB operates differently depending on its initial backoff window value. We can see that every value of W_0 has only a limited interval of network sizes where it performs optimally which shows the inability of BEB to adapt efficiently the backoff window to the access demands. Fig. 5 depicts the normalized achieved delay (to packet transmission time T_{suc}) Vs. packet arrival probability. We observe a logical behavior with respect to the throughput, i.e., no excess delay in the non-backoff regime, delay of OCB slightly greater than BEB in the transition regime and lower in saturation regime. Moreover, we can see that OCB packet's mean delay at saturation approximates $50 * T_{suc}$, which is the delay of a pure TDMA scheme with 50 users in saturation.

δ	σ	$SIFS$	$DIFS$	$EIFS$	H	$E[P]$	RTS/CTS	ACK
$1\mu s$	$20\mu s$	$10\mu s$	$50\mu s$	$364\mu s$	416	8184	352	304

Table 1: Parameter set used for numerical results

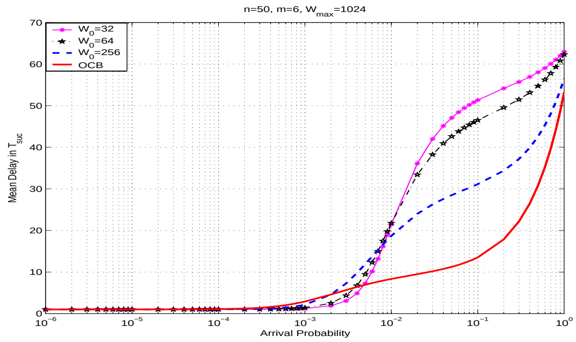

Figure 5: Normalized delay

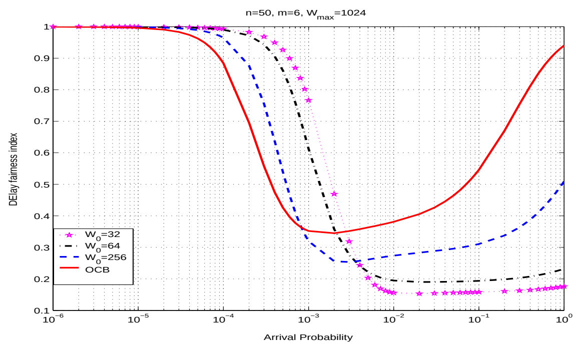

Figure 6: Jain fairness Index

To illustrate the BEB unfairness, we use the Jain's fairness index relative to the delay. The Jain's fairness can be related to the delay statistics as follow

$$Jain's\ index = \frac{1}{1 + \frac{var(D)}{E[D]^2}} \tag{15}$$

Fig. 6 pictures the Jain index for the same setting as previously. We can see that OCB is less fair than BEB during the transition phase but much more fair in saturation regime. We observe also that during the transition phase, the system can not guarantee equal service time even with the exact window OCB scheme. As the system is not really loaded, neither unloaded, packets got service depending on the system's state at their arrival time: lucky users got immediate service while others are delayed. During the saturation regime, OCB becomes fairer as all packet get access from backoff states while BEB remain unfair due to its intrinsic unfairness.

5. CONCLUSION

In this work, we analyzed the performances of IEEE 802.11 DCF protocol in finite load conditions, and we introduced an accurate statistical model of the system delay. Then, we proposed an optimal constant window backoff scheme that brings the system to operate at maximum throughput. Since in CSMA mechanism the duration of idle slots is small compared to that of collisions, we propose to use the optimal window's length obtained at saturated regime under all traffic loads independently from the exact system load. We have shown then the effectiveness of this choice, and we have compared OCB performances to the BEB ones. The optimal window's size in saturation condition requires just information about the network size. This information is easier to obtain in single hop networks, and its coherence time is larger compared to other parameters (backlog state, active nodes, or any other information measured from the channel state).

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