Analysis of Non-Saturation and Saturation Performance of IEEE 802.11 DCF in the Presence of Hidden Stations

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***Abstract*—In this paper, we propose an analytical model to evaluate the hidden station effect on both non-saturation and saturation performance of the IEEE 802.11 Distributed Coordination Function (DCF). DCF is a random channel-access scheme based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method and the binary slotted exponential backoff procedure to reduce the packet collision. Hidden stations cause most collisions because stations cannot sense each other's transmission and often send packets concurrently, resulting in significant degradation of the network performance. The proposed model generalizes the existing work on 802.11 DCF performance modeling for both non-saturation and saturation conditions, under the hidden-station effect. The performance of our model is evaluated by comparison with NS-2 simulations and found to agree with the analytic model.**

I. INTRODUCTION

IEEE 802.11 [1] is the most popular standard used in Wireless Local Area Networks (WLANs). The IEEE 802.11 Medium Access Control (MAC) defines two access methods: the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). The polling-based PCF uses a virtual carrier-sense mechanism aided by an access priority mechanism to control the channel access. This centralized MAC protocol is only usable on infrastructure network configurations because it needs a point coordinator to determine which station currently has the right to transmit. On the other hand, the contention-based DCF uses a random access scheme where each station has the right to initiate its transmission without infrastructure support. So, this scheme is useable not only in infrastructure network configurations but also in distributed and self-organized wireless networks. The support for various wireless networks has made the DCF very popular. However, it unavoidably suffers from the hidden station problem [2–7] because of multiple simultaneous transmissions on the same channel without any coordinator. In order to prevent the interference and confirm a successful transmission, DCF includes two access techniques: basic and Request-To-Send/ Clear-To-Send (RTS/CTS) access mechanisms. The basic access mechanism is a two-way handshaking method where the transmitter transmits a data frame and the receiver replies with an acknowledgement (ACK) frame to confirm a successful transmission. In addition to the basic access method, the RTS/CTS mechanism (four-way handshaking method) reserves the medium before transmitting a data frame by transmitting a RTS frame and replying a CTS frame. This RTS/CTS dialogue is designed to mitigate the interference from hidden stations.

The modeling of IEEE 802.11 has attracted a number of studies. Ref. [8] was the first to derive a model that incorporates the exponential backoff process inherent to 802.11 as a two dimensional Markov chain. This essentially results in a definition for the probability of transmission for a station in the network as being the sum of all probabilities of the station's backoff counter reaching zero given an arbitrary initial value. Ref. [9] follows the same Markov chain model and considers frame retry limits to avoid overestimating the throughput of 802.11 as in [8]. Ref. [10] modified this model to account for backoff slots being recounted as a result of a frozen timer when an ongoing transmission is detected. Ref. [13-15] modified this model to represent the non-saturation and saturation condition. Prior research has attempted to build an accurate model for 802.11 DCF. However, the hidden station effect on the backoff scheme has been largely ignored. The previous work considering hidden stations [2–7] does not include the backoff procedure; it only considers the hidden station effect in saturation condition, as in [16]. In this paper, we study the non-saturation and saturation performance of 802.11 DCF in the presence of hidden stations for both basic and RTS/CTS access methods and we deal with the backoff procedure as in [8-10, 15].

The rest of this paper is organized as follows. In section II, we introduce the vulnerable period to study the effectiveness of both basic and RTS/CTS access methods in the presence of hidden stations. In section III, we use a two-dimensional Markov chain model to calculate the packet transmission probability in the vulnerable period and the non-saturation and saturation throughput. In section IV, we validate the analytical model by comparing the numerical results with NS-2 simulation [11]. We also study the characteristics of both basic and RTS/CTS access methods in the presence of hidden stations for both non-saturation and saturation condition. Finally, conclusions are presented in section V.

II. THE HIDDEN STATION EFFECT ON 802.11 DCF

The DCF is the fundamental access method of the IEEE 802.11. It is based on the CSMA/CA and a backoff procedure to reduce the collision probability between multiple stations accessing the channel. The CSMA/CA mechanism defines two channel states: idle and busy. If a station senses no transmission on the channel, it considers the channel state as idle; otherwise it considers the channel state as busy. When a station tries to access the channel, it enters the backoff procedure that randomly chooses a backoff time in a range $(0, CW_0 - 1)$ with a uniform probability. The CW_0 is known as the minimum contention window size. During the backoff procedure, if the station senses channel as idle, its timer decrements one backoff slot. If the

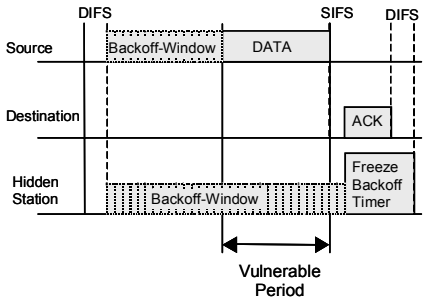

Fig. 1.The vulnerable period for the hidden stations: Basic access method

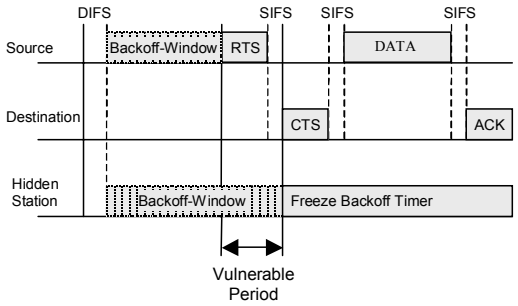

Fig. 2.The vulnerable period for the hidden stations: RTS/CTS access method

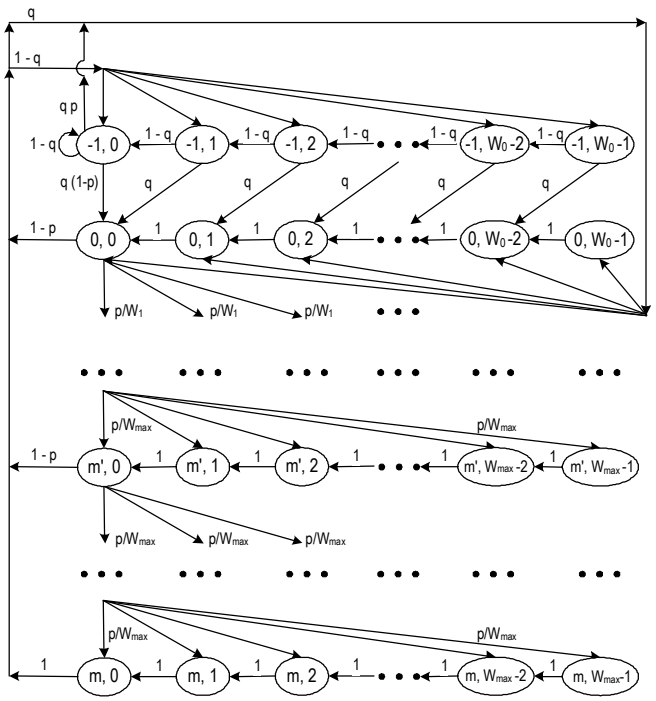

Fig. 3. Markov chain model for backoff procedure

channel is sensed as busy, the timer is frozen. After the channel becomes idle again, the timer resumes from the frozen slot and counts down the remaining backoff slots. After the timer finishes the countdown, the station accesses the channel again. If the transmission fails, the station repeats the backoff procedure and doubles the contention window size. After every failed transmission, the exponential backoff mechanism doubles the contention window size up to a predefined maximum range.

However, if some stations are hidden to each other so they cannot sense each other's transmission, they may mistakenly determine the channel as idle and transmit concurrently. The period from the end of the previous transmission until an ongoing transmission is detected is called the *vulnerable period*.

A. Hidden Station Effect on the Basic Access Method

The basic access method is shown in Fig. 1. Any station that can sense the transmission from the source, called *covered station*, will determine the channel as busy and defer its own transmissions for the duration of the Network Allocation Vector (NAV). The only possible packet collision between the source and a covered station happens if they finish their backoff countdown simultaneously. The vulnerable period for covered stations is one backoff slot long. On the other hand, the hidden stations do not sense the transmission from the source until they receive an ACK, so they sense the channel as idle until sensing the ACK. If any one of these hidden stations completes its backoff procedure before sensing the ACK, it will send another data frame to the destination, which will collide with the data frame from the existing source. The vulnerable period for hidden stations equals the length of a data frame.

B. *Hidden Station Effect on the RTS/CTS Access Method*

The RTS/CTS access method is shown in Fig. 2. As in the basic access method, the vulnerable period for the covered stations is also one backoff slot long. The hidden stations will set their NAV after receiving the CTS frame from the destination, so the vulnerable period for the hidden stations equals the length of the RTS frame plus a SIFS period. Unlike the basic access method, the vulnerable period for hidden stations in RTS/CTS access method is a fixed length period and is not related to the length of the data frame from the source.

III. THE NETWORK THROUGHPUT MODEL

The key contribution of this paper is the combined analytical evaluation of both non-saturated and saturated throughput in the presence of hidden stations. In the analysis, we assume the following conditions: (a) ideal channel condition, i.e., no capture effect; (b) constant and independent collision probability of a packet transmitted by each station, regardless of the number of collisions already suffered; and (c) fixed number of stations.

From the two-dimensional Markov chain model in [8], [9] and [15] we have the stationary probability τ_1 that a station will transmit a packet in a randomly chosen time slot. Additionally, we derive the stationary probability τ_2 that a station will transmit in its vulnerable period as defined above. When the vulnerable period equals one backoff slot, τ_2 equals τ_1. So, τ_1 can be considered as a special case of τ_2.

A. Markov Chain Model of Station Transmissions

Consider the number of contending stations as fixed, defined as n. Let $b(t)$ be the stochastic process representing the backoff timer for a given slot. As in [8], the key approximation in this model is that the probability p of a transmitted packet colliding with another packet is independent of the station's backoff stage $s(t)$. So, the two-dimensional process $\{s(t), b(t)\}$ can be modeled

$$b_{0,0}=\left\{\frac{1}{2}\cdot\left(\frac{1-p^{m+1}}{1-p}\right)+\frac{W_0}{2}\cdot\left(\frac{1-(2p)^{m+1}}{1-(2p)}\right)+\left(p\cdot\frac{W_0-1}{2}+\frac{1}{qW_0}\right)\cdot\left(\frac{(1-q)-(1-q)^{W_0+1}}{q}\right)\right\}^{-1} \tag{4}$$

$$\tau_2=\sum_{i=0}^{m}\sum_{k=0}^{V}b_{i,k}=$$

$$=\left\{1+(V+1)(\frac{p-p^{m+1}}{1-p})-\frac{V(V+1)}{2W_0}\cdot\left(\frac{(\frac{p}{2})-(\frac{p}{2})^{m+1}}{1-(\frac{p}{2})}\right)-\frac{V(1-q)}{qW_0}+\frac{1}{W_0}\left(\frac{(1-q)^{W_0-V+1}-(1-q)^{W_0+1}}{q^2}\right)+\frac{V(2W_0-V-1)}{2W_0}\left(1+p\left(\frac{(1-q)-(1-q)^{W_0+1}}{q}\right)\right)\right\}\cdot b_{0,0} \quad ,V\le W_0$$

$$=\left\{\frac{W_0+1}{2}+\frac{1}{2}\left(\frac{p-p^X}{1-p}\right)+(V+1)\left(\frac{p^X-p^{m+1}}{1-p}\right)-\frac{V(V+1)}{2W_0}\cdot\left(\frac{(\frac{p}{2})^X-(\frac{p}{2})^{m+1}}{1-(\frac{p}{2})}\right)+\frac{W_0}{2}\left(\frac{(2p)-(2p)^X}{1-(2P)}\right)-\frac{(1-q)}{q}+\left(p\frac{W_0+1}{2}+\frac{1}{qW_0}\right)\left(\frac{(1-q)-(1-q)^{W_0+1}}{q}\right)\right\}\cdot b_{0,0} \tag{6}$$

$$W_0<V\le W_m,\quad 0\le X\le m$$

$$=\qquad 1 \qquad V>W_m$$

as a discrete-time Markov chain, shown in Fig. 3.

Based on the 802.11 standard [1], the contention window, also called backoff window, increases exponentially from minimum contention window, $CW_{\min}$, to maximum contention window, $CW_{\max}$. It can be represented by

$$W_i=\begin{cases}2^i W_0 & i\le m'\\ 2^{m'}W_0 & i>m'\end{cases} \tag{1}$$

where m is the maximum backoff stage and m' is the backoff stage at which the contention window size reaches the maximum value, CW_{max}, and remains at CW_{max} after this stage. $W_0 = (CW_{min}+1)$ and $W_m = (CW_{max}+1)$. We set $m = m' = 5$ in this paper.

The backoff states $(-1, k)$ for $k\in(0, W_0-1)$ in Fig. 3 represent the post-backoff stage. After a successful transmission, the station resets its CW value to W_0 and performs a random backoff procedure even if there are no pending packets in the queue. This post backoff ensures that there is at least one backoff interval between two consecutive transmissions of a station. We assume that each station can buffer one packet and q represents the probability that at least one packet waits for transmission during a slot time. If $q = 1$, then the station is in saturation condition and does not go to post-backoff stage. In this Markov chain, the transition probabilities are

$$P(-1,0\,|\,-1,0)=1-q \tag{2}$$

$$P(0,0\,|\,-1,0)=q(1-p)+\frac{qp}{W_0}$$

$$P(0,k\,|\,-1,k)=\frac{qp}{W_0} \qquad 1\le k\le W_0-1$$

$$P(-1,k-1\,|\,-1,k)=1-q \qquad 1\le k\le W_0-1$$

$$P(0,k-1\,|\,-1,k)=q \qquad 1\le k\le W_0-1$$

$$P(-1,k\,|\,i,0)=\frac{(1-q)(1-p)}{W_0} \qquad 0\le k\le W_0-1,\quad 0\le i\le m-1$$

$$P(-1,k\,|\,m,0)=\frac{1-q}{W_0} \qquad 0\le k\le W_0-1$$

$$P(0,k\,|\,i,0)=\frac{q(1-p)}{W_0} \qquad 0\le k\le W_0-1,\quad 0\le i\le m-1$$

$$P(0,k\,|\,m,0)=\frac{q}{W_0} \qquad 0\le k\le W_0-1$$

$$P(i+1,k\,|\,i,0)=\frac{p}{W_{i+1}} \qquad 0\le k\le W_{i+1}-1,\quad 0\le i\le m-1$$

$$P(i,k-1\,|\,i,k)=1 \qquad 1\le k\le W_i-1,\quad 0\le i\le m$$

Let $b_{i,k}=\lim_{t\to\infty}P\{s(t)=i,\ b(t)=k\}$, $i\in(0,m)$, $k\in(0,W_i-1)$ be the stationary distribution of the Markov chain. By using the normalization condition for a stationary distribution, we have

$$1=\sum_{k=0}^{W_0-1}b_{-1,k}+\sum_{i=0}^{m}\sum_{k=0}^{W_i-1}b_{i,k} \tag{3}$$

Based on the chain regularities, we can obtain $b_{0,0}$ in (4), and the stationary probability τ_1 (that a station transmits a packet in a randomly chosen time slot), can be represented as:

$$\tau_1=\sum_{i=0}^{m}b_{i,0}=\frac{1-p^{m+1}}{1-p}b_{0,0} \tag{5}$$

The stationary probability τ_2 (that a station transmits a packet in a vulnerable period), can be represented as Eq. (6) where V is the vulnerable period length in the units of backoff slots. X is the minimum backoff stage at which the backoff window size is greater than V. For example, if $W_1 < V \le W_2$, then use $X = 2$ in Eq. (6). As already noted, τ_1 is a special case of τ_2 because τ_1 can be considered as the vulnerable period with the duration of one slot time. Using $V = 0$ and $X = 0$ in first case of Eq. (6) can verify this.

In the stationary state, the collision probability p is the probability that at least one covered station transmits in the same

backoff slot as the source, or at least one hidden station transmits in the vulnerable period. Thus p can be expressed as:

$$p = 1 - (1-\tau_1)^{n_C - 1}(1-\tau_2)^{n_H} \quad (7)$$

where n_C is number of the covered stations that includes the transmitting station itself, and n_H is the number of the hidden stations. The total number of contending stations, n, equals $n = n_C + n_H$. We solve the nonlinear Eqs. (4)–(7) by numerical method to obtain τ_1 and τ_2.

B. Throughput Analysis

Let P_{tr} be the probability that there is at least one transmission in the considered slot time.

$$P_{tr} = 1 - (1-\tau_1)^n \quad (8)$$

The probability of a successful transmission, P_s, is the probability that exactly one station transmits on the channel, conditioned on that at least one station transmits. This probability can also be considered as that one of n backlogged stations transmits and none of its covered station transmits in the same time slot and none of the hidden station transmits in the vulnerable period.

$$P_S = \frac{n\tau_1(1-\tau_1)^{n_C-1}(1-\tau_2)^{n_H}}{P_{tr}} \quad (9)$$

The normalized system throughput S can be represented as

$$S = \frac{P_S P_{tr} E[P]}{(1-P_{tr})\sigma + P_S P_{tr} T_S + (1-P_S)P_{tr} T_C} \quad (10)$$

where the $E[P]$ is the average packet length and σ is the duration of an empty backoff slot. The T_S and T_C are the average times the channel is sensed busy because of a successful transmission or a collision, respectively. They are different in the basic and RTS/CTS access methods:

$$\begin{aligned} T_S^{bas} &= H + E[P] + \delta + SIFS + ACK + \delta + DIFS \\ T_C^{bas} &= H + E[P] + \delta + ACK\_Timeout \end{aligned} \quad (11)$$

where $H = PHY\_Header + MAC\_Header$. The δ is the propagation delay. The $ACK\_Timeout = SIFS + ACK + DIFS$. For RTS/CTS access method, the T_S and T_C can be expressed as:

$$\begin{aligned} T_S^{rts} &= RTS + \delta + SIFS + CTS + \delta + SIFS \\ &\quad + H + E[P] + \delta + SIFS + ACK + \delta + DIFS \\ T_C^{rts} &= RTS + \delta + CTS\_Timeout \end{aligned} \quad (12)$$

where $CTS\_Timeout = SIFS + CTS + (2\times\sigma)$.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

We compare the results of our analytical model with an ns-2 simulation [11]. All the parameters used in the analytical model and the ns-2 simulation are summarized in Table I.

In order to focus on the hidden station effect and reduce the capture effect on the throughput, we use a ring topology in our analytical model and ns-2 simulation. This topology is composed of one access point located in the center of a ring and 16 stations uniformly distributed on the ring. The capture effect can be ignored because of equal distance from the access point to all stations. The transmission range and carrier sensing ranges are set at 597 meters. In this study, we vary the ring diameter, defined as d, to obtain different number of hidden stations in the 16-station network: (a) d = 540 meters—each station can sense all the packets from the other 15 stations, so there is no hidden stations and there are 16 covered stations; (b) d = 600 meters—only 1 station is hidden and the other 15 are covered; (c) d = 630 meters—3 hidden stations and 13 covered stations; (d) d = 680 meters—5 hidden stations and 11 covered ones.

Table I. System parameters

Transmission Rate	1 Mbps
Packet Payload	250 Bytes
MAC header	224 bits
PHY header	192 bits
RTS	160 bits + PHY header
CTS	112 bits + PHY header
ACK	112 bits + PHY header
DIFS	50 μs
SIFS	10 μs
Slot Time (σ)	20 μs
Propagation Delay (δ)	1μs
CW_{min}	31
CW_{max}	1023

B. Model Validation and Performance Analysis

First, we compare the results of our analytical model with the ns-2 results for different offered load in both basic and RTS/CTS access methods, as shown in Figs. 4 and 5. The analytical throughput (curves) is very close to the simulation results (symbols) in both the basic and RTS/CTS cases.

As shown in Fig. 4 and 5, the throughput can be divided into three conditions: non-saturation, transition and saturation. In the non-saturation condition, as the offered load increases, the throughput increases linearly before reaching its maximum value. However, the success probability decreases obviously, especially in the cases of 3 and 5 hidden stations (Fig. 6 and 7). In this condition, the offered load is fairly low so the average interval between two consecutive transmissions of a station is very long. Almost all the packets can be transmitted successfully within the retransmission limit without delaying the next packet. The throughput still can increase linearly with the offered load in presence of hidden stations. In the transition condition, the throughput decreases from its maximum value to a steady state one. This transition phenomenon in basic access case is more obvious than that in RTS/CTS access method. As the number of hidden station increases, the amplitude of this transition overshoot also increases. It values are about 10%, 160%, 680% and 1700% in the case of no hidden station, 1, 3 and 5 hidden stations, respectively. On the other hand, as the number of hidden station increases, the transition overshoot occurs at a lower offered load. It is at 80% of the offered load in the no-hidden-station case and falls to 30% of the offered load in the 5-hidden-stations case. In the saturation condition, the throughput and success probability keep a steady-state value even as the offered load still increases. Comparing the saturated

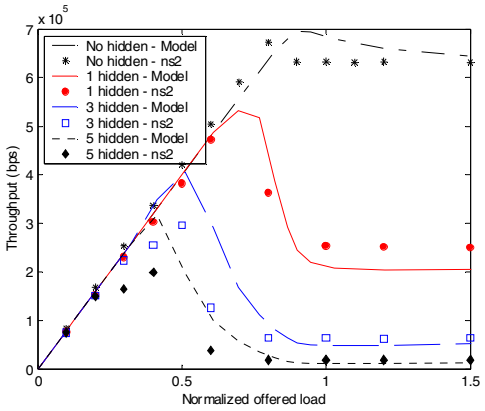

Fig. 4. Throughput versus offered load: Basic access method

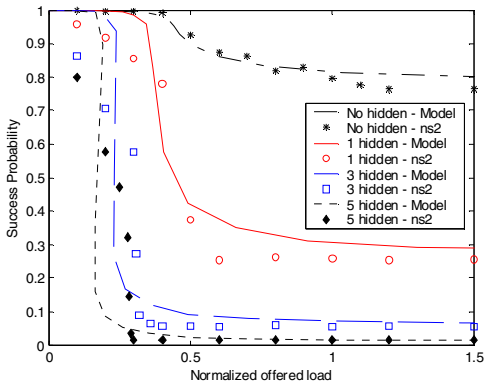

Fig. 6. Success rate versus offered load: Basic access method

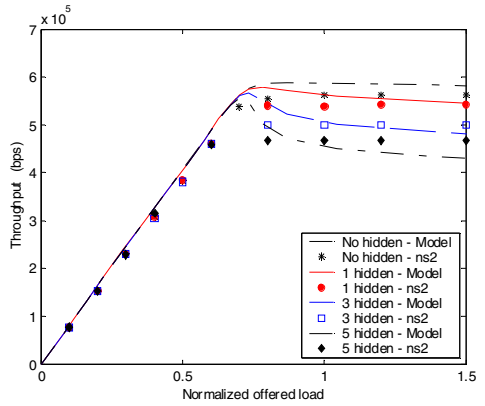

Fig. 5. Throughput versus offered load: RTS/CTS access method

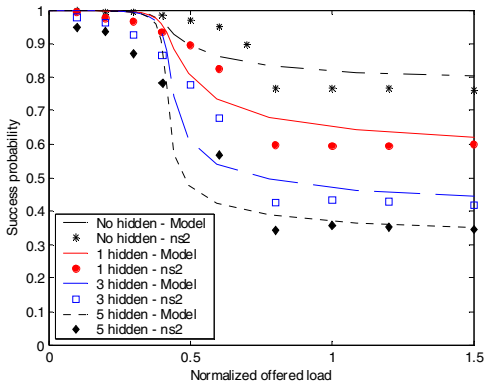

Fig. 7. Success rate versus offered load: RTS/CTS access method

throughput of the basic and RTS/CTS access methods in Figs. 4 and 5, we can see that the basic access method is much more sensitive to the hidden station effect. The network saturated throughput decreases 50% because of just one hidden station and loses about 80% and 90% of throughput in the presence of 3 and 5 hidden stations, respectively. On the other hand, RTS/CTS access method is more robust to the hidden-station effect. It only loses about 10%, 20% and 30% of throughput in the presence of 1, 3 and 5 hidden stations, respectively.

V. CONCLUSION

In this paper, we derived a combined analytical model to compute both the non-saturation and saturation throughput of the IEEE 802.11 DCF in the presence of hidden stations for both the basic and RTS/CTS access methods. The proposed model is in good agreement with NS-2 simulations and, thus, can be used to accurately estimate the network throughput. The previous work [8,15] can be considered as a special case of our model, with zero hidden stations.

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