Performance analysis of IEEE 802.11 ad hoc networks in the presence of hidden terminals

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Abstract
The paper discusses analytical models for the estimation of channel utilization and media access delay for IEEE 802.11 ad hoc networks in finite load conditions in the presence of hidden terminals. The simulation results show that the analytical estimated channel utilization and media access delay metrics are fairly calculated.

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1. Introduction
The IEEE 802.11 standard [1] gains an ongoing and continuous public acceptance in the deployment of ad hoc networks. It offers important benefits, such as low deployment cost, high data rates, mobility support, IP-based communication, integration with 3G and beyond 3G systems, etc. However, some drawbacks also arise, mainly due to the wireless nature of the standard, such as the increased transmission errors at the physical layer, the performance impairment at the MAC layer due to packet collisions, the routing overheads, the power constraints, the security vulnerabilities, etc.

The paper deals with the performance impairment at the MAC layer and specifically it concentrates on the channel utilization and the delay analysis of IEEE 802.11 ad hoc networks in finite load conditions under the hidden terminal problem. The fact that the paper assumes finite load conditions instead of saturation ones as most of the other relevant works do, constitutes one of the key contributions of this work. The other contribution concerns the fact that most of the other relevant papers focus only on throughput/utilization analysis, while this work also derives media access delay results.

Generally speaking, the performance analysis of IEEE 802.11 networks is an area of important research interest in the international literature. Some works assume clear channel conditions [2–4], while some others take also into consideration the hidden terminal problem [5–7]. More specifically for the latter mentioned works [5] provides a worst-case analysis of the collision probability, while [6,7] analyze the hidden terminal problem using the BER and SNR metrics, respectively.

The rest of the paper is organized as follows. Section 2 gives a brief description of the IEEE...
802.11 MAC layer and presents the hidden terminal problem. Section 3 discusses the proposed analytical utilization and delay models and Section 4 validates the accuracy of the analytical estimated metrics through appropriate simulation scenarios. Finally, concluding remarks are given in Section 5.

2. Brief description of the IEEE 802.11 MAC layer

The basic IEEE 802.11 standard [1] defines two mechanisms for accessing the medium: the mandatory Distributed Coordination Function (DCF) and the optional Point Coordination Function (PCF). DCF uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol to transmit data in a simple and robust way without transmission delay guarantees. PCF is located over DCF and its access protocol is a centralized polling-based one that can guarantee transmission delay bounds.

According to DCF, a node can initiate a transmission only if it senses the medium as being idle for a time interval greater than a Distributed InterFrame Space (DIFS). If a collision occurs, the transmission is deferred and a backoff process starts. Unlike wired networks (with Carrier Sense Multiple Access with Collision Detection support), in a wireless environment, collision detection is not possible. Hence, an acknowledgement (ACK) frame is used to notify the sending node that the transmitted data has been successfully received. The transmission of an ACK is initiated at a time interval equal to Short InterFrame Space (SIFS) that follows the reception of the sending data (see Fig. 1(a)).

The above transmission mechanism does not protect the wireless nodes from the hidden terminal problem. This problem arises, for example, when for three stations, namely A, B and C, A is able to communicate with B and C, but C is not within the range of B (see Fig. 2). In this case, C is hidden for B. This means that, when B transmits a frame to A, C may sense the medium as being idle. If C also transmits a frame towards A, then a collision will occur at A.

In order to alleviate the hidden terminal problem, the IEEE 802.11 standard includes a virtual carrier sense mechanism, which is based on the exchange of two short control frames: a Request To Send frame (RTS), which is sent by a potential transmitter to the receiver and a Clear To Send frame (CTS), which is sent back from the receiver in response to RTS. The RTS and CTS frames include a duration field that specifies for a station the time interval necessary to completely transmit its data and the related ACK. Other stations can hear either the sender or the receiver and refrain from transmitting until the data transmission is complete (see Fig. 1(b)).

The RTS/CTS mechanism adds a considerable overhead in the medium, especially for the transmission of small data packets. In this context, the use of RTS/CTS is controlled through the RTS Threshold attribute, where only packets with size greater than the value of the RTS Threshold are transmitted with the RTS/CTS mechanism.

3. The proposed analytical utilization and delay models

This section presents our analytical channel utilization and media access delay models for IEEE 802.11 ad hoc networks under finite load conditions.
taking also into consideration the hidden terminal problem. The channel utilization is the percentage of time in which useful information is transmitted in the wireless medium. The media access delay is the time from the beginning of a packet transmission from a node till its successful reception from the next node. The ‘beginning of a packet transmission’ refers to the moment that the transmitter picks the packet in order to transmit it. According to this definition, and assuming a large packet inter arrival time compared to the time slot (thus a packet does not wait for a DIFS interval in the first transmission attempt), the media access delay of a packet transmitted from a node is equal to the duration needed for the packet to be successfully transmitted plus the time taken for all its unsuccessful transmissions, which is equal to the expected duration of each unsuccessful transmission (backoff time plus the duration of a collision) times the number of unsuccessful transmissions. In order to derive the channel utilization and media access delay metrics, we firstly assume clear channel conditions, i.e., no hidden terminals, and afterwards, we extend our analysis to include also the hidden terminal problem.

3.1. Utilization analysis

Fig. 2 depicts a conventional IEEE 802.11 ad hoc network where the nodes’ transmission range is $r$ and the wireless channel data rate is $R$. Let now consider the node A of Fig. 2. The small circle includes the nodes that are inside the coverage area of node A. The big circle contains also the hidden nodes for node A, which are the nodes at the ring between the big and the small circles.

We are going firstly to derive the channel utilization in respect to the aggregate traffic produced in the small circle. Let us assume that the aggregate offered traffic load in the wireless channel is generally distributed with a mean value of $g$ packets per second and that the payload size of packets transmitted in the wireless medium is also generally distributed with a mean value of $P$ bits. Let us also assume that the network operates under finite load conditions, so, the offered traffic consists not only of new packets but also of previously collided packets. If we isolate this cell from the network, ignoring the hidden terminals and supposing that all nodes are in line of sight with each other, the utilization of the cell, as defined in [8] is

$$ U_{\text{LOS}} = \frac{S}{B + I}. $$

where $S$ is the average transmission time of the packet payload in the wireless medium, $B$ is the average busy period of the medium, and $I$ is on average the idle period of the medium.

Let us define as $\tau$ the duration of an IEEE 802.11 time slot (i.e., $20\mu$s for 802.11b). Let assume that 802.11 is a pure slotted system where all stations are synchronized to the channel time and sense the channel with the predefined slot time. As also happens in [2], assume also that the propagation delay is ignored. If $p$ is the probability that no packet arrives in a time slot, then $(1 - p)$ is the probability that at least one packet arrives in a time slot. Packet arrivals in a time slot can be modelled as Bernoulli trials with probability of success $(1 - p)$, which is the probability that at least one packet arrives in a time slot. Accordingly, the number of consecutive idle slots (i.e., the number of consecutive slots until a packet arrival occurs) follows the Geometric distribution $(1 - p)p^{n-1}$, where $n$ is the number of consecutive idle slots. Hence, the expected duration of an idle period for the slotted system is the expected duration before the first arrival occurs. This is given as

$$ I = \tau \sum_{n=1}^{\infty} np_n = \tau \sum_{n=1}^{\infty} n(1 - p)p^{n-1} = \frac{\tau}{1 - p}. $$

For the busy period, consider the probability that a packet is successfully transmitted. This is the conditional probability that a single arrival occurs in a time slot, given that at least one arrival occurs. Let us define $p_1$ as the probability that a single arrival occurs in a time slot. Since the probability that at least one arrival occurs is $(1 - p)$, the probability that a packet is successfully transmitted is given as

$$ p_s = \frac{p_1}{1 - p}. $$

Subsequently, let define $t_b$ as the average number of slots for which at least one packet arrives, referred as busy slots, given as

$$ t_b = \sum_{n=1}^{\infty} np(1 - p)^{n-1} = \frac{1}{p}. $$

Note that there are $t_b p_s$ slots where a successful transmission occurs with the remaining $t_b(1 - p_s)$ slots indicating that a collision is occurring. Given as the time needed for a successful transmission...
and $T_c$ as the time a collision takes, the expected duration of a busy period is

$$ B = T_s t_b p_s + T_c t_b (1 - p_s) = \frac{T_c + p_s (T_s - T_c)}{p}, \quad (5) $$

where and $T_c$ are given in [2].

Lastly, for a packet of $P$ bits transmitted over a wireless channel supporting a data rate of $R$ bits/s, the transmission time of the packet payload is $T_p = P/R$, and the average time for which payload information is transmitted in the channel is given by

$$ S = T_p t_b p_s = \frac{P p_t}{R p (1 - p)}. \quad (6) $$

Using Eqs. (2), (5) and (6) in Eq. (1), an expression for the channel utilization for clear channel conditions can be derived.

Let now consider the hidden terminal problem. We are going to derive the channel utilization related to a random node, e.g., node A of Fig. 2.

Consider that node A belongs to a group where all nodes can hear each other. Under the hidden terminal problem, the success of a transmission of node A depends on two additional conditions:

- “Node A does not transmit during any transmission of a node outside its coverage area.” Let the probability of this condition be $e_21$.
- “No node outside the coverage area of node A yet within the collision domain of node A transmits during a transmission of node A.” Let the probability of this condition be $e_22$.

$e_21$ is equal to the probability that node A transmits during the idle period. This is simply $\frac{1}{B + s}$.

$e_22$ is equal to the probability that no packet arrives during the transmission time $T_s$ or, in other words, no packet arrives for $T_s/\tau$ slots. This is equal to $p^{T_s/\tau}$.

Let $N$ be the existing groups of nodes that can affect the transmission of node A. Combining the above two conditions for all existing groups except the group of node A we have

$$ e_2 = e_1 \cdot e_2 = \frac{I}{B + I^s} p^{T_s/\tau}, \quad (7) $$

where $I$, $B$, $p$, $T_s$, $\tau$ are the same as in the analysis with no hidden terminals consideration.

The channel utilization $U$ related to a random node is now

$$ U = U_{LOS} \cdot e_2. \quad (8) $$

For our analysis, where we assume that the nodes are uniformly distributed across the network area, $N$ is the quotient of nodes that are in line of sight with a specific node to the nodes that can affect the transmission of this node [9]. If $\rho$ is the nodes’ density and $r$ is the transmission range of each node, then $N = \rho \pi (2r)^2 / \pi r^2 = 4$, where $U_{LOS}$ is the channel utilization for clear channel conditions given above by Eq. (1). Combining all the above

$$ U = \frac{S}{(B + I)^4} p^{3T_s/\tau}. \quad (9) $$

3.2. Delay analysis

For the media access delay estimation, consider again a node (e.g., node A of Fig. 2) and a cell that includes all nodes in the coverage area of the considered node. Let $G$ be the normalized traffic of a cell with respect to the packet transmission time, given as $G = g \cdot P/R$. Moreover, the mean number of retransmissions before a packet is sent is $G/U$ [8].

Excluding the last, successful transmission, the actual mean number of retransmissions is $m = (G/U) - 1$. Considering a large packet inter arrival time compared to the time slot, we can assume that the packet does not wait for a DIFS interval in the first transmission attempt. The expected media access delay of a packet transmitted from a node is equal to the duration $T_s$ needed for the packet to be successfully transmitted plus the time taken for all its unsuccessful transmissions. The second is equal to the expected duration of each unsuccessful transmission (backoff time plus the duration $T_c$ of a collision) times the number of unsuccessful transmissions, $m$. Accordingly, the media access delay is given as

$$ d_m = T_s + m(T_c + T_F), \quad (10) $$

where $T_F$ is the expected number of backoff slots in a retransmission and $T_F$ is the time where the backoff counter freezes because of transmissions that are in progress. Considering that the backoff slots in each attempt are uniformly distributed between 1 and the contention window, then

$$ T_F = \frac{1}{m} \sum_{j=0}^{m-1} \frac{1}{2} W_2^j = \frac{1}{2m} W_2^{m-1}, \quad (11) $$

where $W$ is the minimum contention window.

For the time $T_F$ that the backoff counter freezes because of another transmission, consider that the
probability that the backoff counter expires is simply $1/X$. Under the finite load conditions of our case, the transmitter of a node can be thought as a G/G/1 queue with utilization factor, where $d_m$ is the media access delay and $g_N$ is the node traffic. The probability that a node transmits is equal to the probability that the backoff counter expires, given that it has a packet in the transmitter. This is $u/X$. Hence, if $M$ is the number of nodes in a cell, in $X$ slots where the backoff counter decreases, there will occur $M \cdot (U/X) \cdot X = M \cdot g_N \cdot d_m = g \cdot d_m$ additional transmissions. From all these transmissions, there are $g \cdot d_m [(m/(m + 1))]$ retransmissions and $g \cdot d_m [1/(m + 1)]$ successful transmissions. In this way, all these transmissions add an additional backoff time of

$$F = g \cdot d_m [T_s/(m + 1) + mT_c(m + 1)].$$

(12)

Eventually, the media access delay can be derived by substituting $F$ into Eq. (10), giving

$$d_m = \frac{m(T_s + \tau X) + T_s}{1 - gm(T_s + mT_c)/(m + 1)}.$$  

(13)

4. Models' validation

In order to validate the accuracy of the analytic approximation of the channel utilization and media access delay metrics derived in the previous section, several simulation scenarios were considered in the Pythagor simulation platform [10], an open C++ simulation tool for IEEE 802.11 a/b/g networks.

The estimated models stand for any input traffic model, as long as the parameters $g$, $p$, $p_1$ and $P$ are given in a closed form. For our validation tests, although the input traffic depends on many characteristics specific to each network, the Poisson distribution with a mean value of $g$ packets/s was adopted to efficiently characterize the aggregated generated traffic inside a cell. Consequently, $p$ and $p_1$ can be easily derived as follows:

$$p = \frac{(gT)^0}{0!} e^{-gT} = e^{-gT},$$

(14)

$$p_1 = \frac{(gT)^1}{1!} e^{-gT} = gT e^{-gT}.$$  

In addition, an exponential distribution with a mean value of $P$ bits was chosen for the packet payload size. The exponential distribution has been proven adequate to describe the packet size distribution in IEEE 802.11 networks (e.g., [2]). In order to take into account the MSDU (Maximum Service Data Unit) size, a truncated exponential distribution for the payload size has also been considered. The results were almost similar to those arisen when assuming pure exponential distribution. Table 2 summarizes the results of the validation process.

Tables 2 and 3 summarize the results of the comparison between the analytical metrics and the Pythagor output. In all cases the results show that the models are fairly accurate. The main reason for the fact that the simulation results have always slightly higher numerical values than the analytical results is the assumption that 802.11 is a pure slotted system where all stations are synchronized to

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<th>Table 1 Simulation parameters</th>
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<tr>
<td>Parameter</td>
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<td>Time slot duration ($\tau$)</td>
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<td>SIFS</td>
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<td>DIFS</td>
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<td>Minimum contention window ($W$)</td>
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<td>MAC header</td>
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<td>ACK</td>
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<td>Channel data rate ($R$)</td>
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<td>RTS threshold</td>
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<td>Packet payload ($P$)</td>
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<th>Table 2 Model validation for the channel utilization metric</th>
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<td>Channel traffic (g) Kb/s (1 packet = 8P bits)</td>
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<th>Table 3 Model validation for the media access delay metric</th>
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<td>Channel traffic (g) Kb/s (1 packet = 8P bits)</td>
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the channel time and sense the channel with the pre-defined slot time.

Employing now the analytical expressions for the channel utilization and media access delay metrics (see Eqs. (9) and (13) respectively), Figs. 3 and 4 depict these metrics versus the channel traffic for channel data rates of 2 Mb/s, 5.5 Mb/s and 11 Mb/s. Two different scenarios are considered: one for RTS Threshold equal to 128 bytes (dashed curves) and one for RTS Threshold always on (dotted curves) meaning that all packets are transmitted using the RTS/CTS mechanism. Together with the analytical results, the simulation results obtained by Pythagor are also depicted.

Concerning both scenarios, as is shown in Fig. 3, the maximum channel utilization and the channel traffic value for which this maximum is obtained as well as the range of channel traffic values for which the channel utilization remains high depend on the channel data rate. Note that as the channel data rate increases, the utilization curve becomes smoother having lower maxima at larger channel traffic value with a larger set of channel traffic values for which the channel utilization remains relatively high. For example, for the channel data rate of 2 Mb/s, the maximum channel utilization is 18%, while for 11 Mb/s, it falls to 13%. Furthermore, for the channel data rate of 2 Mb/s, the range of channel traffic values for which the channel utilization is above 4% is from 50 Kb/s to 1 Mb/s, while for 11 Mb/s, this range becomes larger from 100 Kb/s to 4 Mb/s.

The same behaviour for media access delay is shown in Fig. 4 for both scenarios where both the minimum media access delay and the range of channel traffic values for which the media access delay remains low depend on the channel data rate. As in Fig. 3, note that as the channel data rate increases, the media access delay curve becomes smoother having lower media access delay minimum and a larger set of channel traffic values for which the media access delay remains relatively low. After a specific channel traffic value depending on the channel data rate, the media access delay increases rapidly as a consequence of the fact that the number \( m = (G/U) - 1 \) of retransmission attempts increases a rate more than quadratic.

In the case where the RTS/CTS mechanism is always enabled, the peak channel utilization is better than the case where the RTS threshold is 128 bytes. Specifically, it is 3% higher for data rate 2 Mb/s, 10% higher for 5.5 Mb/s, and 17% for 11 Mb/s. In clear channel conditions, the utilization in the second simulation case would be less than in the first case. However, due to the existence of hidden terminals, the system performance seems to be

![Fig. 3. Channel utilization.](image-url)
better if the RTS/CTS mechanism is always used. The media access delay is less in the case where the RTS/CTS mechanism is always used. As now, the probability of collisions is smaller, the number of retransmission attempts is also smaller, and thus this results in smaller media access delay.

5. Conclusions

The paper presents analytical models for the estimation of channel utilization and media access delay for IEEE 802.11 ad hoc networks in finite load conditions under the hidden terminal problem. In order to validate the accuracy of the analytic approximations of the channel utilization and media access delay, several simulation scenarios were evaluated with the Pythagor simulation platform. In all cases the results of the comparison between the analytical channel utilization and media access delay metrics estimate and the Pythagor outputs show that the models are fairly accurate.

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References

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