Wireless Pers Commun (2014) 75:2243–2268
DOI 10.1007/s11277-013-1465-5

A Simple and Closed-Form Access Delay Model for Reliable IEEE 802.11-Based Wireless Industrial Networks

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Abstract With the ongoing popularity of the IEEE 802.11 standard, many analytical studies for the distributed coordination function (DCF) have been reported but due to lack of a comprehensive model, the research has been going on. In this paper, three probabilistic analytical access delay models have been proposed for the IEEE 802.11 DCF mechanism in saturated traffic and noisy industrial applications. The first and second one provide an accurate packet delay model by solving non-linear equations at low and high Signal to Noise Ratios (SNRs) respectively. The third one on the other hand offers an approximate and simple closed-form model which does not need solving any non-linear equation and therefore can easily be utilized in the distributed adaptive network quality of service provisioning algorithms for industrial nodes which usually have limited processing capabilities. Delay-reliability, delay-packet payload and delay-data rate tradeoffs has also been studied. Simulation results match the theoretical derivations in most SNRs, confirming the effectiveness of the proposed models.

Keywords IEEE 802.11 · Distributed coordination function (DCF) · Access delay · Wireless industrial network · Saturated traffic · Error-prone channel · Reliability

1 Introduction

Wireless communication has been an attractive option for most consumer devices and has also recently been used for industrial networks and factory automation systems due to the vast advantages: low cabling/installation and maintenance cost, easier installation and configuration, mobility, reduced risk of cable and control link disconnection, etc. The two main requirements of industrial networks are reliability and timeliness which contradicts with the shared, error-prone and non-deterministic behavior of the wireless medium. Changing

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current wireless technologies and standards towards industrial needs, and if not possible, developing new protocols is an advancing research field [1]. From timeliness perspective, industrial applications can be categorized into three types: non-real-time, soft-real-time and hard-real-time which the last one has very strict delay and reliability requirements. Up to now, most of the industrial networking companies have produced off the shelf wireless modules based on the two common wireless technologies; the low-rate IEEE 802.15.4 [2] for non-real-time applications and the high-speed IEEE 802.11 [3] for soft-real-time applications. To the authors' knowledge, no wireless technology has been developed to be capable of hard-real-time applications. Developing accurate models for the system performance metrics such as packet delay and reliability can help to improve these protocols for their new specific application, or to develop proper new ones. Distributed Coordination Function (DCF) is the basic Medium Access Control (MAC) mechanism of the IEEE 802.11, which plays an important role in the network delay and reliability and is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Binary Exponential Backoff (BEB) mechanisms. Performance evaluation of the DCF has been studied in several research papers through simulation, experiment or mathematical modeling. Most of the models are based on the simple 2-Dimentional Discrete-Time Markov Chain (2D-DTMC) introduced by Bianchi [4] and are accurate only for a specific network scenarios and parameters. They are mostly developed for the best-effort data networks, which have long packet payload (PL), are used in rather high Signal to Noise Ratio (SNR) conditions, and require high throughput and fairness as their main Quality of Service (QoS) parameters. Only a few references have studied the performance of the IEEE 802.11 standard in industrial applications, which have short packet lengths, are used in rather noisy environment, and packet delay and reliability are their most important QoS parameters [1]. In this paper a simple and closed-form packet delay analysis has been proposed for the near 100 %-reliable industrial wireless networks. Simulation results prove the accuracy of the model compared with the similar available models.

The contribution of this paper can be summarized as follows:

1. Two simple and intuitive analytical models have been proposed for the DCF average access delay which in contradict with other similar literature provides more accurate results.
2. A simple and closed-form approximate Markov analysis and packet delay formula has been proposed for the industrial scenarios. To the authors knowledge it is the first delay model that does not need to solve a non-linear equation and is suitable for distributed adaptive network Quality of Service (QoS) provisioning algorithms for industrial nodes which usually have limited processing capabilities.
3. Tradeoffs including delay-reliability, delay-packet payload and delay-data rate have also been thoroughly studied which helps to better understand and design wireless industrial networks.

This paper is organized as follows. In Sect. 2, we summarize the related work. Section 3 presents the proposed Markov model and delay analyses. In order to assess the accuracy of the proposed models in comparison with other models, the simulation results are presented in Sect. 4. Section 5 summarizes the work and provides future research opportunities.

2 Related Works

The performance of the IEEE 802.11 DCF scheme has been extensively studied in the literature using different methods and simplifying assumptions. Due to the lack of a comprehensive model, this performance analysis has been going on up to now [5–19]. Bianchi's

2D Markov Chain model [4] is the first and mostly used one (due to its simplicity) describing the binary exponential backoff mechanism of DCF. It provides a simple solution for estimating the network saturation throughput, assuming infinite retry-limit and error-free communication channel. Most of the models have extended the Bianchi's model to account for other parameters and situations, such as non-saturated traffic and finite buffer size [20], finite retransmission attempts [21–23], error-prone channel [23–26], channel capture [25], hidden terminal [27], and improving the accuracy of the model in predicting performance metrics by considering backoff freezing, etc. [28–31]. In most papers studying the DCF, the channel is assumed to be ideal, and the only reason for unsuccessful packet transmission, is the packet collision [4,17,20–22,29,31]. In some literature, a constant probability of bit-error has been considered [23,25,26]. From traffic point of view, most papers assume the saturation condition; each node always has a packet waiting to be transmitted [4,21–23,26,30,32]. This is a worst-case scenario which simplifies the network analysis and also results in an upper (lower) bound estimation about the normal/non-congested situation of the network delay (throughput). Some papers have extended these models to non-saturation traffic, in a limited and rather non-practical way in which the average incoming traffic rate of all nodes should be equal [20,29,31,33]. Due to the specific characteristics of industrial applications, current DCF models cannot be directly used. Reviewing the literature, shows the need for an accurate DCF model, which takes into account all of the industrial characteristics.

Using the IEEE 802.11 technology in industrial wireless networks has recently been studied by experimental measurement [34] and simulation [35–39] which shows satisfactory performance for soft-real-time applications. Tian and Tian [40] have analytically studied the DCF performance for periodic industrial traffic. Some papers have proposed modifications to the standard, to improve the performance for industrial applications: References [41,42] have modified the MAC layer to improve the timeliness in real-time applications. References [43] and [39] have respectively proposed a relaying scheme and a simple space-time block coding, to increase the link-reliability and thus decrease the packet delay. Kumarage et al. [44] have studied and improved the security issue of the industrial wireless networks.

On the other hand, network throughput, as the main QoS parameter of the data networks, has been the main target of most models. Bianchi's model [4] provides a simple estimation of the average throughput. Packet delay statistics, as one of the main parameters of real-time applications, have been studied in some literature which can be categorized into two types: Statistics-Based [17,21,22,30,40,45,46] and Probability Generating Function (PGF)-Based [20,23,31,32]. In the first type, transmission probability, collision probability, successful transmission probability, packet delay and throughput are calculated based on the network behavior and common statistics relationships. This method provides a simple, easy to understand and straight-forward way for the average packet delay calculation. Chatzimisios ([21] with ideal channel and [47] as the error-prone extension), and Raptits ([22] assuming ideal channel) have proposed the simplest and most-cited statistics-based models. The PGF-based methods on the other hand, build a PGF from the network description, and the delay statistics are derived from the first and higher order moments of this PGF using numerical inverse Z-transform. This method provides a rather comprehensive way for calculating average packet delay and its distribution in a very complicated numerical way, and to the authors' knowledge, to simplify the calculations, none of them have considered a proper error-prone channel in their analysis. To the authors' knowledge, no packet delay analysis has been performed that accounts for all industrial needs; high reliability, short packet payload and noisy channel. In this paper, we have developed a simple packet delay model considering all these characteristics. All of the DCF Markov analyses need to solve at least one non-linear equation. We have also proposed a simple closed-form formula for packet delay at low SNRs which only needs the probability of bit error as the input parameter, without the need for solving a non-linear equation. Simulation results confirm the superiority of the proposed models. Tradeoffs including delay-reliability, delay-payload and delay-rate have also been thoroughly studied.

3 Markov Chain Model and Packet Delay Analysis

In this section, after reviewing the DCF mechanism and our basic assumptions, the proposed DTMC model is fully analyzed. Then based on this model, the packet delay analysis is presented.

3.1 Distributed Coordination Function (DCF)

DCF is the basic and mandatory MAC protocol of the IEEE 802.11-based devices. It works as follows: if the medium has been idle for a Distributed Inter-Frame Space (DIFS) time, the sender terminal choses a random backoff interval between 0 and the Contention Window (CW) value. It counts down after each idle slot, freezes whenever the channel is sensed busy and continues the count down after the medium is sensed idle for a DIFS, after a successful transmission of other nodes, or for an Extended Inter-Frame Space (EIFS), after a collision/error of other nodes' packets. When the backoff counter reaches zero and the medium is still idle, the sender initiates the transmission. If the data is not successfully transmitted, the contention window is doubled until its maximum value $CW_{\max}$. The contention window is reset to $CW_{\min}$ after a data packet is transmitted successfully [notified by an Acknowledgement (ACK) packet received at the sender after a Short Inter-Frame Space (SIFS)], or after Retry-Limit (RL) unsuccessful attempts, when the data packet is discarded.

3.2 Assumptions

Here are some simplifying assumptions used in this paper, which are mostly common among the literature.

- All nodes always have a packet waiting to be transmitted (Saturation traffic condition, similar to [4,21–23,26,30,32,36–39]). It somehow represents the worst case scenario, from the system performance point of view.
- The collision probability of a packet transmitted by each station is constant and independent, regardless of the number of retransmissions already suffered (accurate for fairly large number of competing nodes [4]).
- Due to the industrial applications, the packet payload is assumed to be 32 Bytes (the typical value for monitoring/control applications [1,34,36–44,48–51]).
- The basic access mechanism of the DCF is used. Due to the small size of the packet payload in industrial applications, the four-way Request To Send/Clear To Send (RTS/CTS) mechanism is not practical [35,40]. RTS/CTS method improves the system performance when the data packets are large, as it reduces the length of the frames involved in the contention process, and thus the collision time.
- Due to rather low SNR's and small data payload in industrial environments, the lowest communication rate in IEEE 802.11 (R = 1 Mbps) has been chosen for simulation and

Table 1 IEEE 802.11 parameters

Parameter	Value
Data rate (DR)	1 Mbps (DBPSK)
Control rate (CR)	1 Mbps (DBPSK)
PHY header (PH)	24 Bytes
MAC header (MH)	28 Bytes
ACK size (ACK)	14 Bytes
Data packet payload (PL)	32 Bytes
Slot time (σ)	20 µs
SIFS	10 µs
DIFS	50 µs
EIFS	50 µs
CWmin (w)	31
CWmax (w_m)	1,023
Retry limit (RL)	Infinity (disabled)

comparison. In these conditions, higher data rates have no advantage and even result in higher packet delays [36,38,51]. This effect has also been briefly showed in this paper. The model can be extended to other PHY scenarios, by using the related modulation Bit Error Rate (BER) formula.

- Similar to most of the related works, the default $CW_{\min}$ and $CW_{\max}$ values of the standard has been considered [3] (see Table 1).
- All identical n nodes of the network are at the communication range of each other and the hidden-terminal case is not considered (similar to all other single-hop papers [17,20–23,25,26,28–35,40,46,47,52–54]). This configuration is common in industrial networks in which several sensors and actuators are located around an instrument in a cluster-way, and communicate with each other. The communication of the cluster with the central Access Point (AP) of the network is out of scope of this paper, because it is similar to a data network, rather than an industrial one; the data is aggregated and then submitted (in a larger packet); and also, this link is mostly for monitoring or reconfiguration purposes, so the short packet payload and real-time requirements do not hold.
- The wireless channel is assumed to be error-prone with Additive White Gaussian Noise (AWGN) (similar to other error-prone analyses [23–26]). The proposed model can be easily used with a more complicated channel model, by using its respective formula.
- Similar to several works [4,21–23,28–31,35], we only consider the service delay and the queue size is assumed to be infinite. Due to the independent nature of the service and queuing delay, the proposed model can easily be extended.
- To guarantee the near-100 % reliability of the network, RL is assumed to be infinity. Due to the quasi-static nature of the target network, thus no *permanenst* link breakage in normal working conditions, this reliability is feasible. On the other hand, as shown in Sect. 4, the typical number of retransmission attempts is well limited for typical SNRs. Of course at low SNRs, there is a severe trade-off between packet delay and packet reliability, and providing the 100 % reliability will cost rather high packet delays. By releasing the reliability requirements, lower delays can be expected [37]. This tradeoff has also been covered in this paper.

3.3 The Markov Chain Model

The probability that a station transmits in a randomly chosen slot-time (the channel access probability) equals [4]:

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1)+pW(1-(2p)^m)} \tag{1}$$

in which p is the probability of unsuccessful transmission due to packet/ACK error (p_e) or packet/ACK collision (p_c) and $W = CW_{\min}$. Assuming independence,

$$p = p_e + p_c - (p_e \cap p_c) = p_e + p_c - p_e p_c \tag{2}$$
$$p_e = p_{Data} + p_{ACK} - p_{Data} p_{ACK} \tag{3}$$
$$p_{Data} = 1 - (1-p_b)^{L_{Data}} \tag{4}$$
$$p_{ACK} = 1 - (1-p_b)^{L_{ACK}} \tag{5}$$
$$p_b = 0.5\exp(-SNR) \tag{6}$$
$$L_{Data} = PH + MH + PL \tag{7}$$
$$L_{ACK} = PH + ACK \tag{8}$$
$$p_c = 1 - (1-\tau)^{n-2} \tag{9}$$

p_b, p_{Data} and p_{ACK} are bit-error rate of DBPSK modulation, probability of data error, and probability of ACK error respectively. L_{Data} and L_{ACK} are the total data and ACK packet lengths respectively in which PH, MH and PL are PHY Header, MAC Header and packet PayLoad respectively. n is the number of competing nodes (node density). By solving the non-linear Eqs. (1) and (2) for each scenario, p and τ can be calculated.

3.4 Proposed Low-SNR Packet Delay Analysis

From a node point of view in its backoff count-down procedure, the probability of at least one transmission from other $n-1$ nodes in the considered time slot equals [22,23]:

$$P_{tr} = 1 - (1-\tau)^{n-1} \tag{10}$$

In a similar way, the probability that a transmission occurring on the channel is successful equals the probability of only one transmission from other $(n-1)$ nodes (which is the combination of 1 out of (n – 1), multiplied by the probability of transmission from one node, multiplied by the probability of no-transmission from the left (n – 2) nodes), multiplied by the probability of having an error-free transmission.

$$P_s = \binom{n-1}{1}\tau(1-\tau)^{n-2}(1-p_e) = (n-1)\tau(1-\tau)^{n-2}(1-p_e) \tag{11}$$

Average duration of a slot-time (the time interval between two consecutive data packet transmissions on the channel = the interval between two consecutive decrements of the backoff counter) is [4,21–23,29]:

$$E[Slot] = (1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_e \tag{12}$$

The average time the channel is sensed busy because of a successful transmission (the slot-time of a successful transmission) is [3,29]:

$$\mathrm{T_s} = \mathrm{T_{data}} + \mathrm{SIFS} + \mathrm{T_{ack}} + \mathrm{DIFS} \tag{13}$$

$$T_{Data} = \frac{L_{Data}}{R} \tag{14}$$

$$T_{ACK} = \frac{L_{ACK}}{R} \tag{15}$$

R is the channel bit rate (1 Mbps). For simplicity, similar to most related works [4,17,20–26,30–33,52,54], we assume that all nodes wait for the same time duration (DIFS) after a busy channel; either a successful transmission or a failure. In this way, the average time the channel is sensed busy by each station during an error is:

$$\mathrm{T_e} = \mathrm{T_{data}} + \mathrm{DIFS} \tag{16}$$

The parameters are defined in Table 1. By extending the method introduced in [22], the average packet delay at low SNRs, $E[D_{LS}]$, can be calculated as:

$$E[D_{LS}] = \sum_{i=0}^{\infty} E[D_i]p_i \tag{17}$$

In which p_i is the probability of successful transmission of the packet from the ith backoff stage, and $E[D_i]$ is the average delay of a successfully transmitted packet from the ith backoff stage.

$$p_i = p^i(1-p) \tag{18}$$

$$E[D_i] = T_s + iT_c + Slot\sum_{j=0}^{i}\frac{W_j - 1}{2} \tag{19}$$

in which

$$\begin{array}{ll} W_j = 2^j W & 0 < \mathrm{j} \le \mathrm{m} \\ W_j = W_m = 2^m W & \mathrm{m} < \mathrm{j} \end{array} \tag{20}$$

By dividing the summation of (17) into $0 \le j \le m$ and $m < j$ regions, we have

$$\begin{aligned} E[D_{LS}] = &\left(\sum_{i=0}^{m} T_s + iT_c + Slot\sum_{j=0}^{i}\frac{W_j - 1}{2}\right)p^i(1-p) \\ &+ \left(\sum_{i=m+1}^{\infty} T_s + iT_c + Slot\left(\sum_{j=0}^{m-1}\frac{W_i - 1}{2} + \sum_{j=m}^{i}\frac{W_m - 1}{2}\right)\right)p^i(1-p) \end{aligned} \tag{21}$$

Due to the fact that most of the packet delay at low SNRs is due to the packet error (Fig. 7), we make the following approximation:

$$p \approx p_e \tag{22}$$

We will see at the next section that this approximation makes the packet delay more accurate. With some mathematical calculations, we have:

$$\begin{aligned} E[D_{LS}] &= T_s + T_e\frac{p_e}{1-p_e} + \frac{w-1}{2}Slot(\alpha+\beta+\gamma) \\ \alpha &= (1-p_e)\left(\frac{2(1-(2p_e)^{m+1}}{1-2p_e} - \frac{1-p_e^{m+1}}{1-p_e}\right) \\ \beta &= p_e(2p_e)^m(2^{m+1}-1) \\ \gamma &= p_e(2p_e)^m\left(\frac{(m+1)(1-p_e)+p_e}{1-p_e} - m\right) \end{aligned} \tag{23}$$

3.5 Proposed High-SNR Packet Delay Analysis

The proposed packet delay formula at Sect. 3.3, best works at low SNRs. In order to have a complete solution, in this section an accurate formula at high SNRs is presented. At high SNRs, the average packet delay can be estimated by multiplying the average number of slot-times required for a successful packet transmission (N_s) by the average slot-time duration.

$$E[D_{HS}] = E[N_s] \times E[Slot] \tag{24}$$

$E[N_s]$ can be calculated by summation of the average time each node elapses in each Markov stage:

$$E[N_s] = \sum_{i=0}^{\infty} d_i q_i \tag{25}$$

$E[d_i]$ is the average number of slot-times the node spends in the backoff stage i which due to the uniform distribution of the backoff counter value selection between 0 to W_i, will be equal to the middle of this range [Eq. (26)]. q_i is the probability of reaching to stage i which corresponds to$i$ transmission failures, and due to the independence of each failure to the previous ones, will be equal to probability of failure (p) to the power of i [Eq. (27)].

$$E[d_i] = \frac{w_i+1}{2} \tag{26}$$

$$q_i = p^i \tag{27}$$

Substituting (2), (26) and (27) in (25) results in:

$$\begin{aligned} E[N_s] &= \sum_{i=0}^{m-1}\frac{w_i+1}{2}p^i + \sum_{i=m}^{\infty}\frac{w_m+1}{2}p^i \\ &= \frac{w+1}{2}\left(\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p}\right) \end{aligned} \tag{28}$$

In the Eq. (28) the summation has been divided into two sub sections: $0 \le i < m-1$ (which with each increment, the contention window is doubled) and $m \le i$ (which contention window reaches to its maximum value, W_m). So the average packet delay at low SNRs equals:

$$E[D_{HS}] = \frac{w+1}{2}\left(\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p}\right)[(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_e] \tag{29}$$

3.6 Proposed Simplified Markov Chain Model

Comparing Fig. 7b, c, it can be noticed that at low SNRs, $p_e \gg p_c$, so, from the start of the calculations, we assume that $p \approx p_e$. This situation is valid for small packet sizes. So there is no need to solve a non-linear equation, and a closed form equation for the packet delay ($E[D_{APP}]$) can be written. By substituting (3) in (2), τ can be directly calculated and can be used in P_{tr} and P_s formulas. The closed-form approximate packet delay analysis is shown in Eq. (30).

$$
\begin{aligned}
E[D_{App}] &= T_s + T_e \frac{p_e}{1-p_e} + \frac{w-1}{2} \Big(\Big(1 - \Big(1 - \big(1-\tau'\big)^{n-1} \Big) \Big) \sigma \\
&\quad + \Big(1 - \big(1-\tau'\big)^{n-1} \Big) P'_s T_s + \Big(1 - \big(1-\tau'\big)^{n-1} \Big) \big(1 - P'_s\big) T_e \Big) (\alpha+\beta+\gamma) \\
\tau' &= \frac{2(1-2p_e)}{(1-2p_e)(w+1) + p_e w (1-(2p_e)^m)} \\
P'_s &= (n-1)\tau'(1-\tau')^{n-2} \qquad (30) \\
\alpha &= (1-p_e) \left(\frac{2(1-(2p_e)^{m+1}}{1-2p_e} - \frac{1-p_e^{m+1}}{1-p_e} \right) \\
\beta &= p_e (2p_e)^m (2^{m+1}-1) \\
\gamma &= p_e (2p_e)^m \left(\frac{(m+1)(1-p_e)+p_e}{1-p_e} - m \right)
\end{aligned}
$$

3.7 Delay-Reliability Tradeoff

The previous analyses were valid for $RL = \infty$ which causes very large delays at very low SNRs. On the other hand, by applying a limited RL, the delay can be reduced at the expense of packet loss (lower reliability). In this scenario, the probability of packet loss (P_{loss}), equals the probability of having $(RL+1)$ packet transmission failures:

$$P_{loss} = p^{RL+1} \qquad (31)$$

We can calculate the average packet delay by a similar manner with the condition that the packet is not dropped (with probability of $(1-p^{RL+1})$):

$$E[D_{Ave}] = \frac{(E[N'_S] - E[N_D])}{(1-p^{RL+1})} E[Slot] \qquad (32)$$

in which $E[N'_S]$ is the average number of slot-times for the limited RL,

$$E[N'_S] = \sum_{i=0}^{RL} E[d_i] q_i \qquad (33)$$

$E[d_i]$ and q_i are defined in (26) and (27), and RL is the Retry Limit. $E[N_D]$ is the average number of slot-times required to drop a packet:

$$E[N_D] = \sum_{i=0}^{RL} \frac{W_i+1}{2} p^{RL+1} = \frac{W+1}{2} (2^{RL}-1) p^{RL+1} \qquad (34)$$

It is worth noting that the Eq. (24) is the limit of the Eq. (32) when $RL = \infty$.

4 Model Validation

In this section, the proposed models have been compared with similar works and the simulation. The comparison is made at different SNRs and node densities for industrial networks. The results confirm the superiority of the proposed models.

The authors have been developing a MATLAB [55]—based simulation code (m-file) in recent years, to simulate the IEEE 802.11 protocol, in various physical layer (PHY) and network conditions. This simulator has been used in some of the authors' previous works, especially to evaluate different Multiple-Input Multiple-Output (MIMO) schemes and multipath-fading at the PHY [36–39]. Similar to some other literature [4,21–24,29] these simulators are built mostly due to the ease of use and also lack of other simulators to properly simulate real communication channel, including the multipath fading and MIMO channels. The latest version of this simulator has the ability to sweep various simulation scenarios, including SNR, node density, packet payload, retransmission limit, the number of traffic categories, number of iterations and other parameters. The average, maximum, standard deviation and probability density function of various parameters including each traffic category's packet delay, packet collision, number of packet retransmissions, packet loss, and packet error due to channel error can be easily captured. It also accounts for the packet failure due to the ACK error, which most of similar papers have ignored. Simulation results confirm the effect of this error on the packet delay, and it should definitely be accounted. The authors have simplified this simulator to be used for the DCF and Single Input Single Output (SISO) scheme in this paper. The number of iterations has automatically been chosen so that in each simulation scenario, each node successfully sends at least 40 packets. This number has been achieved experimentally, to cope with the transient variations in the produced curves and local minimums. This has resulted in about several hundred thousand iterations in dense networks and noisy environment. The IEEE 802.11 parameters have been specified in Table 1.

As mentioned before, the typical wireless industrial network has cluster architecture; different sensors and actuators are located near each other around a single instrument, and this architecture repeats factory-wide. The typical number of nodes and packet payload in industrial networks are 16-nodes and 32-bytes respectively [1,38–42,44,48,49,51,56]. Therefore different node numbers of 8 (low-density), 16 (average) and 32 (high-density) and packet payloads of 8–64 bytes have been assumed in the simulation. The RL is assumed infinity to ensure the 100 % reliability of the network. As the simulation results show, the actual required number of retransmissions is well limited. Delay-reliability of using limited RL has also been studied.

4.1 Average Packet Delay

In this section, we study the average delay, delay probability density function (PDF), and delay-payload tradeoff.

4.1.1 Average Packet Delay

Figures 1 and 2 compare at low and high SNR's respectively, the infinite RL extension of Chatzimisios model [21,24] which assumes error-free ACK and control packets, infinite RL and error-prone extension of the Raptis et al. [22], Felemban and Ekici [30], and Wang et al. [45] models, the proposed approximate closed-form model (Prop.App.), the proposed

Fig. 1 DCF average packet delay at low SNRs. **a** n = 8, **b** n = 16, **c** n = 32

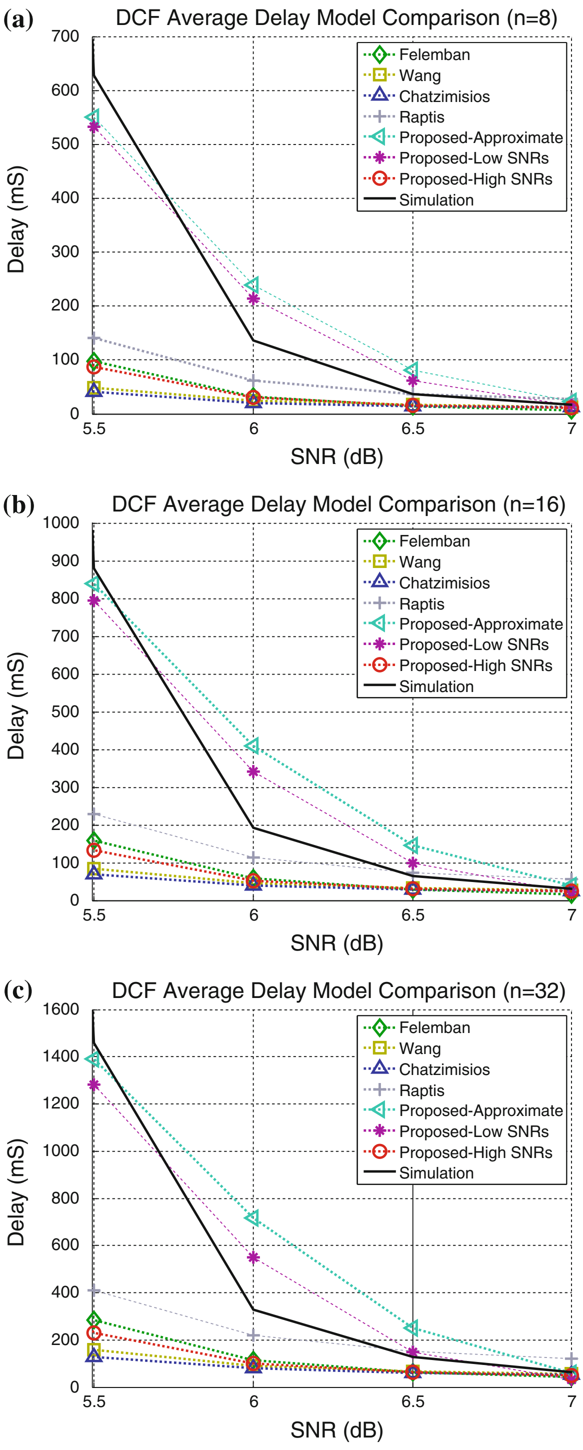
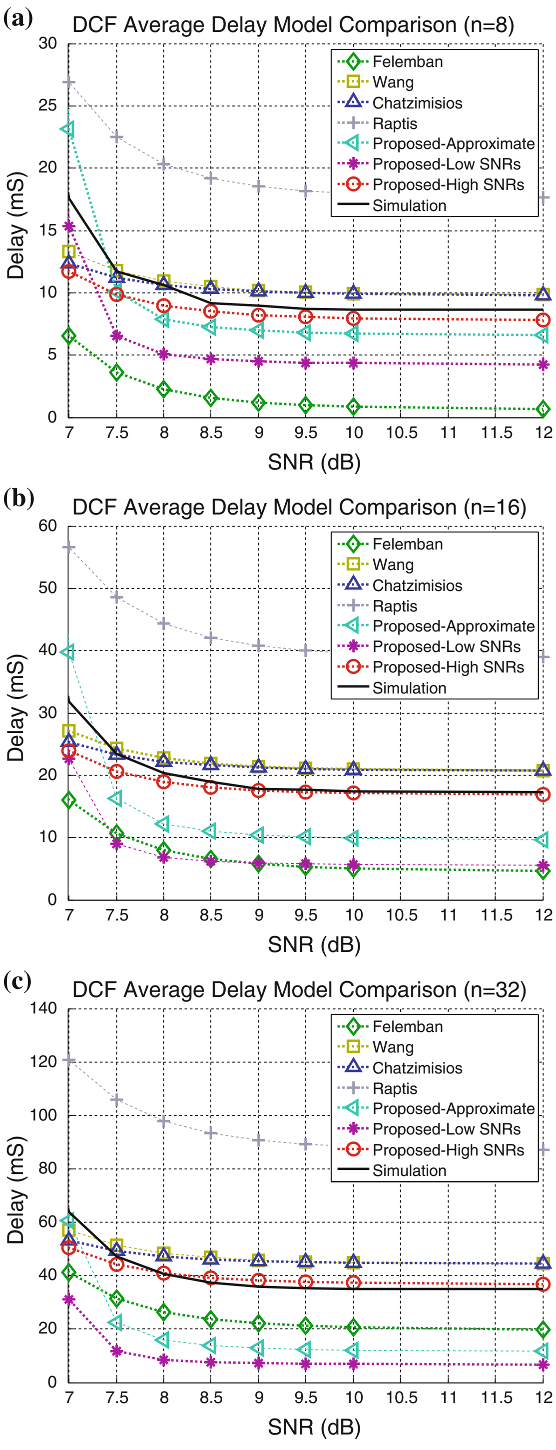


Fig. 2 DCF average packet delay at high SNRs. **a** n = 8, **b** n = 16, **c** n = 32



model for low-SNRs (Prop.Low), the proposed model for high-SNRs (Prop.High), and the simulation results (SIM). To have a fair comparison, the same simple DCF model [4] is used for the models. As can be seen, none of the models is capable of accurate modeling the packet delay at low SNRs, while the two proposed low-SNR and proposed approximate models provide an acceptable estimate. On the other hand, most of the models have an acceptable result at high SNRs among which the proposed high-SNR has the closest match. The proposed approximate model shows a good tradeoff between simplicity and accuracy; it results in predictions close to the Prop.Low at low SNRs, while provides a good approximate at high SNRs, especially for low node-densities. The proposed model for low SNRs shows best prediction, especially at very low SNRs and high node densities. On the other hand, Prop.High which is proposed for high SNRs, shows the best match to the simulation results, while under-estimating the packet delay at low-SNRs. This shows that more challenge is required to provide a comprehensive model that works at both low and high SNRs. To the authors' knowledge, no accurate delay analysis has been proposed at low SNRs.

4.1.2 Packet Delay Probability Density Function (PDF)

Figures 3 and 4 show the packet delay PDF at low and high SNRs respectively for different node densities. At low SNRs it is on the order of a few seconds, while it reduces to a few milliseconds for high SNRs. This shows that using IEEE 802.11 for real-time applications is not practical at very noisy situations, but it works well in average to high SNRs. It is also worth noting that the delay PDF has a Gamma distribution.

4.1.3 Delay-Packet Payload Tradeoff

Figures 5 and 6 study the effect of packet-payload on the average delay at low and high SNRs respectively. Interestingly, the packet delay has a linear relationship with the packet payload. At high SNRs (Fig. 6), the proposed analysis is the best match, but at low SNRs (Fig. 5) none of the models provide an accurate result. The proposed models are a good approximate. The reason for the inaccuracies at low SNRs relies on the simple DCF model used. It is more described in the next subsection.

4.2 DCF Markov Chain Analysis

Figure 7 compares the probability of channel access (τ), collision (p_c), packet error (p_e), and total error (p) between the Chatzimisios's and Wang's model (Cha..) which don't accounts for the probability of ACK error, proposed approximate model (App..), the accurate model (Acc..), and the simulation, which reveals the most important reason of inaccuracies of the packet delay models: due to the simplified Markov model used, the DCF probabilities are not estimated correctly and overestimate the simulation. Interestingly, the Fig. 7c shows a close match between the proposed approximate model and the simulation which is the reason for the acceptable accuracy. Figure 7c confirms the key assumption of the proposed approximate and low-SNR models; estimation of $P_f \approx P_e$. In the approximate model, only probability of collision depends on the number of competing nodes (n), so only one curve is plotted in other three subfigures (a), (c) and (d).

Fig. 3 Low-SNR delay distribution. **a** n = 8, **b** n = 16, **c** n = 32

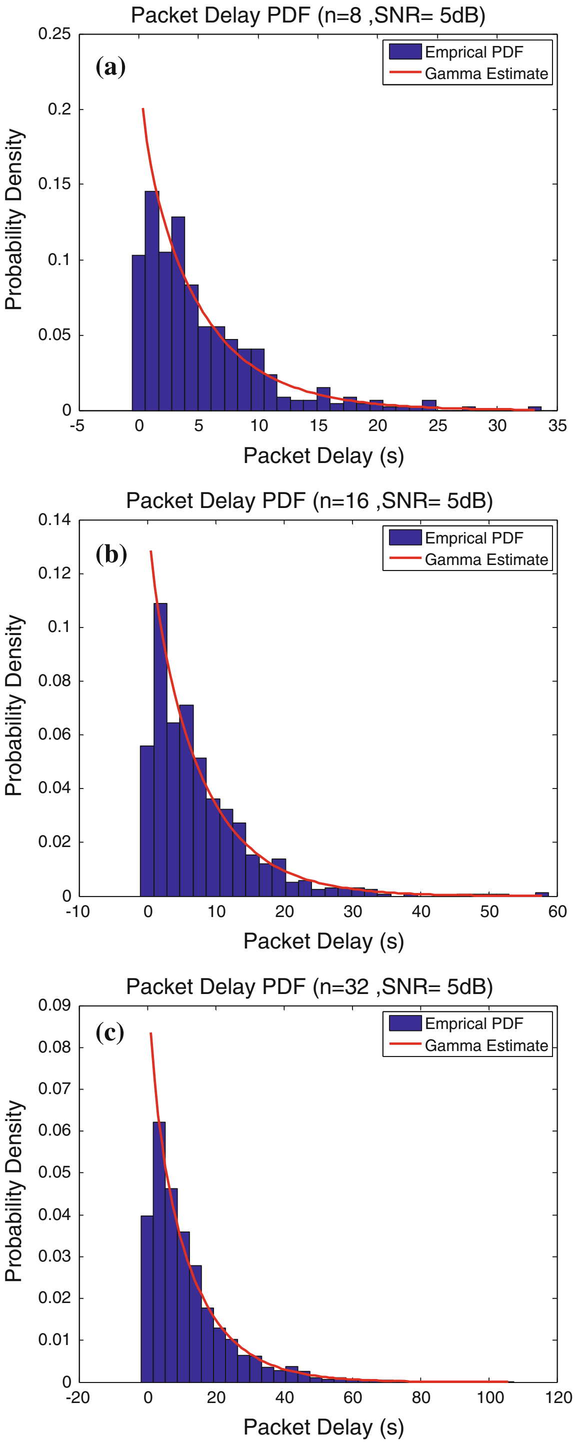


Fig. 4 High-SNR delay distribution. **a** n = 8, **b** n = 16, **c** n = 32

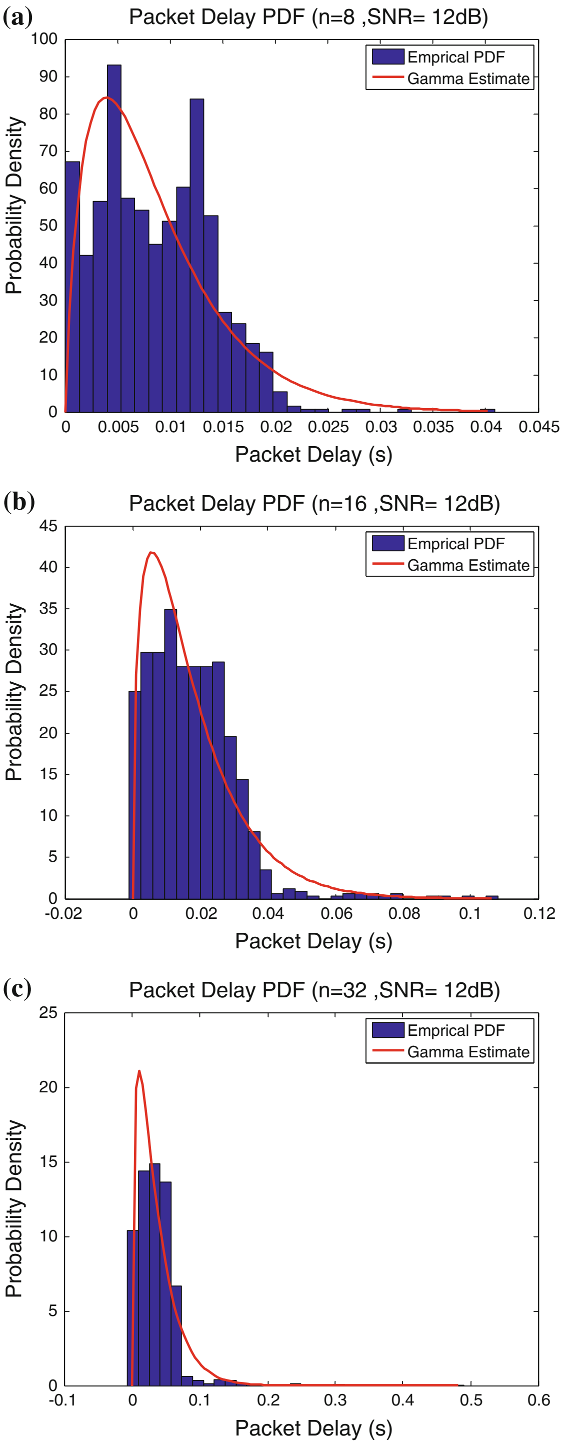


Fig. 5 Low-SNR delay-payload tradeoff. **a** n = 8, **b** n = 16, **c** n = 32

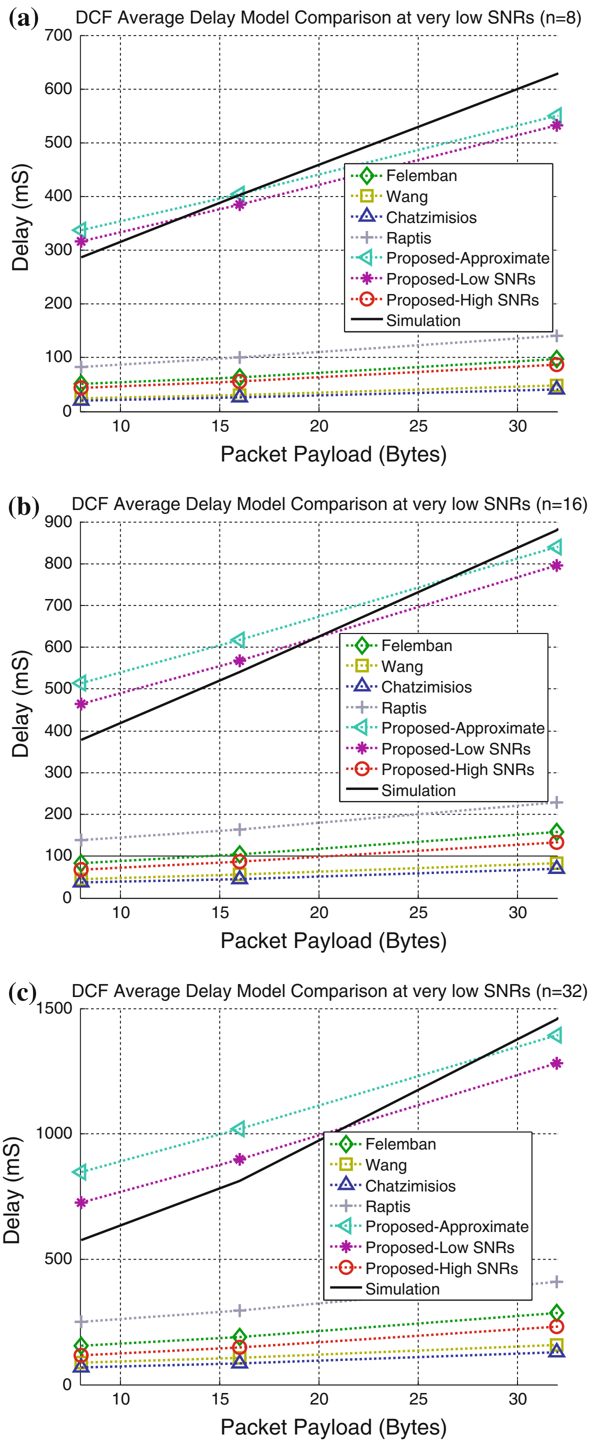
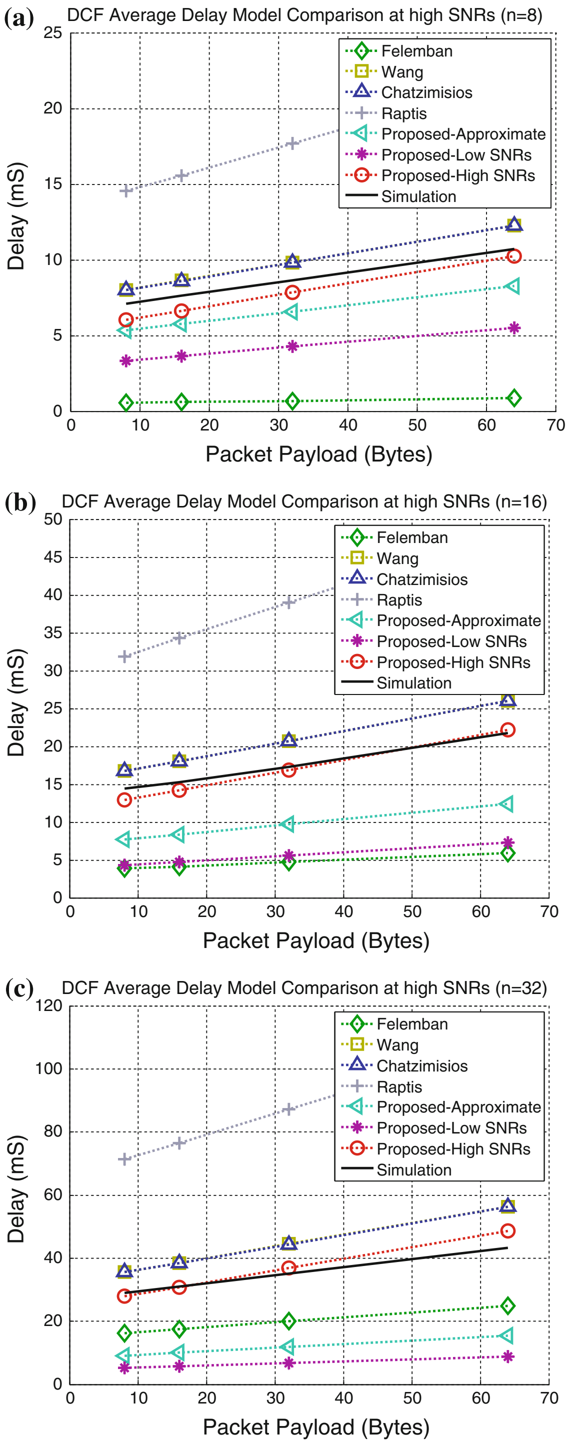


Fig. 6 High-SNR delay-payload tradeoff. **a** n = 8, **b** n = 16, **c** n = 32



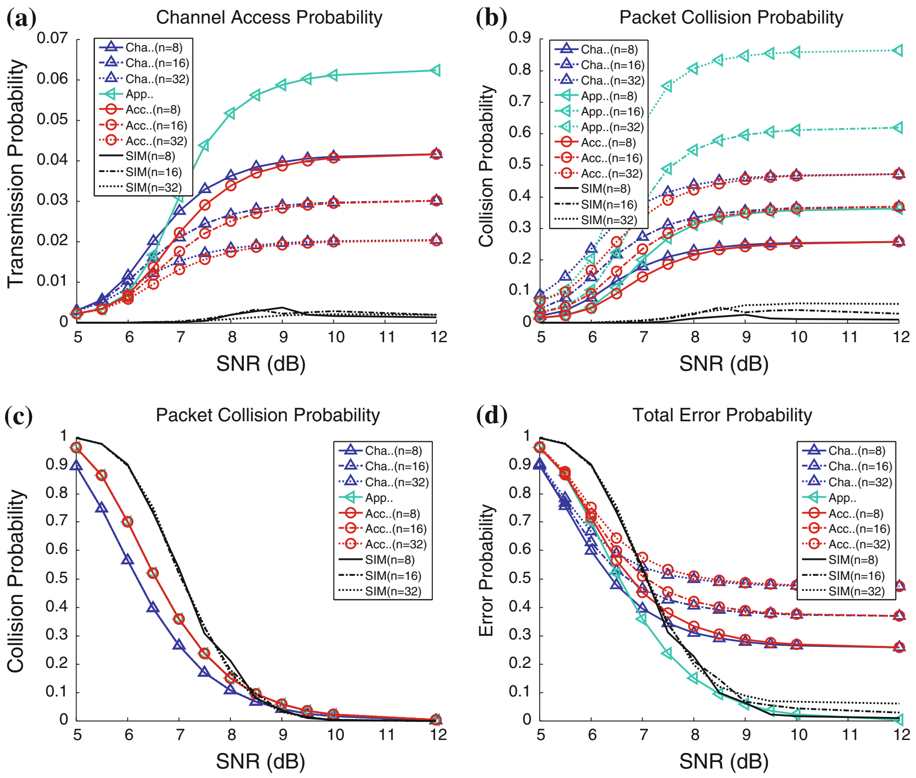


Fig. 7 Probability of **a** channel access, **b** packet collision, **c** packet error, and **d** total error

4.3 Effect of Higher Data-Rates

As mentioned before, higher data-rates are suitable for high SNR scenarios, not for noisy industrial applications. In this section, we study the effect of increasing the data-rate. As described at the standard [3], the physical layer header (PH) and control packets (such as ACK) are always transmitted at the basic 1 Mbps control-rate, R_c, using the DBPSK modulation, and the MAC header (MH) and packet payload (PL) are transmitted at data-rate, R_d. To show the destructive effect of using higher data rates on the packet delay, we consider the data-rate of 2 Mbps using DQPSK modulation with the BER probability shown in Eq. (35).

$$p_{b2} = Q_1(a,b) - \frac{1}{2} I_0(ab) \exp\left(-\frac{1}{2}(a^2+b^2)\right),$$

$$a = \sqrt{SNR\left(1-\sqrt{\frac{1}{2}}\right)} \quad \text{and} \quad b = \sqrt{SNR\left(1+\sqrt{\frac{1}{2}}\right)} \tag{35}$$

The Eqs. (4), (14) and (15) change as follows:

$$p_{Data} = 1-(1-p_{b2})^{MH+PL}(1-p_b)^{PH} \tag{36}$$

$$T_{Data} = \frac{PH}{R_c} + \frac{MH+PL}{R_d} \tag{37}$$

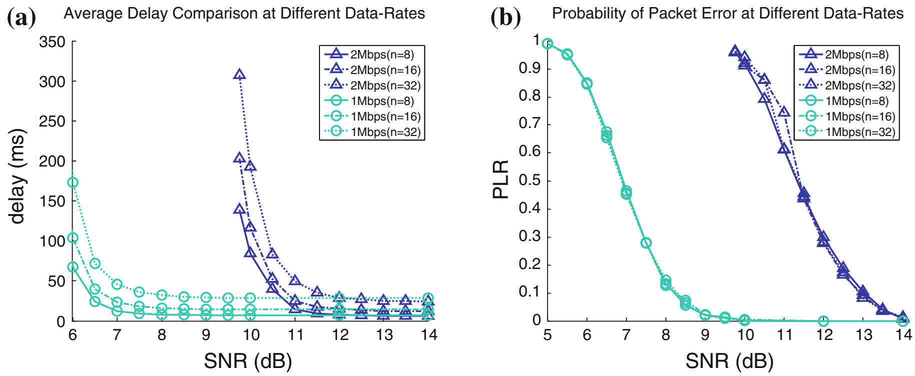


Fig. 8 **a** Average packet delay **b** packet error comparison between data-rate of 1 and 2 Mbps

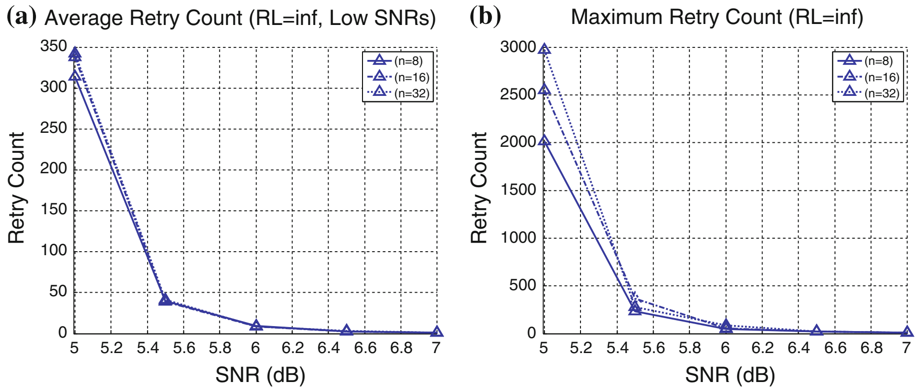


Fig. 9 The number of retransmission needed for the reliability of 100 % **a** average, **b** maximum

$$T_{ACK} = \frac{L_{ACK}}{R_c} \tag{38}$$

Figure 8 compares the average packet delay and the Packet Loss Ratio (PLR) of the two data-rates. As can be seen in Fig. 8a, the higher data-rate outperforms at very high SNRs (above 12 dB) which are rarely seen in noisy industrial applications. On the other hand, due to the short packet payloads used in industrial applications, this outperformance is minor; a large portion of the packets are still transmitted using the basic low data-rate. This confirms the wise choice of using the lowest data-rate for industrial applications. In data-networks which usually have very large payloads and are used at high SNRs, higher data rates result in significant lower packet delays.

4.4 Delay-Reliability Tradeoff

In previous sections, the RL was assumed to be infinite. In other words, the packet is retransmitted until it reaches the destination correctly. This results in a highly reliable scenario, at the expense of very high packet delays at very low SNRs. On the other hand, the delay can be decreased by releasing the RL to be limited. In this section we study the tradeoff between the delay and reliability for the limited RL scenario.

Fig. 10 Average packet delay for RL = 7 and **a** n = 8, **b** n = 16, and **c** n = 32 nodes

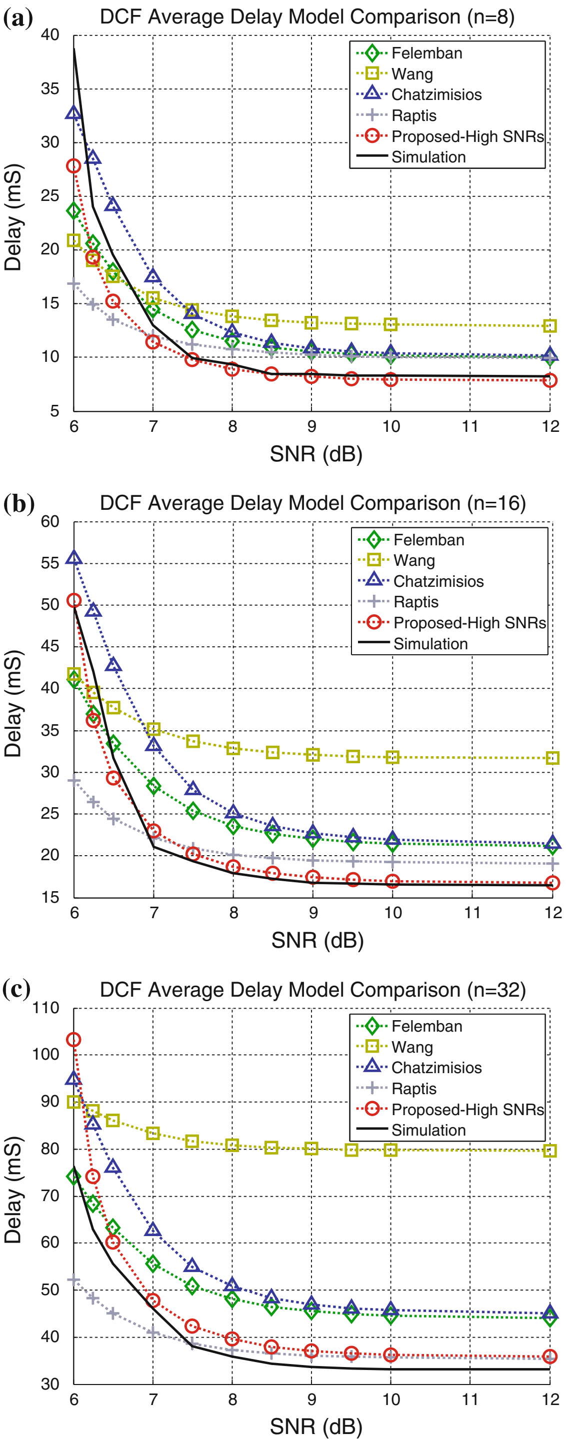
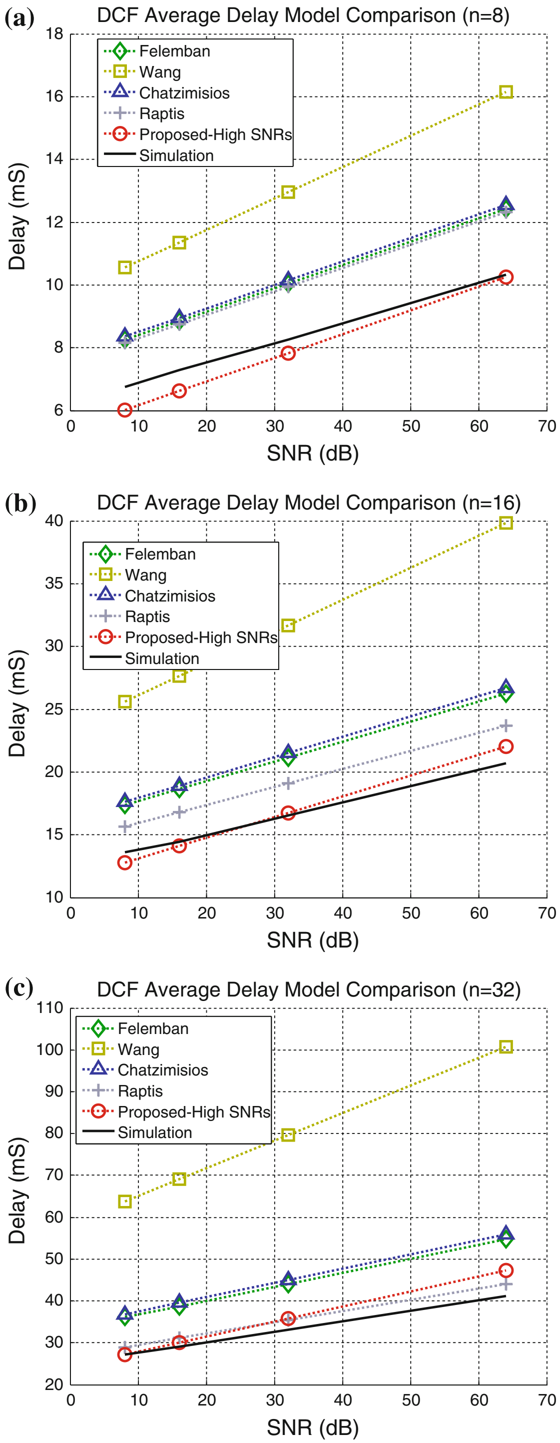


Fig. 11 Delay-payload tradeoff for RL = 7, **a** n = 8, **b** n = 16, and **c** n = 32 nodes



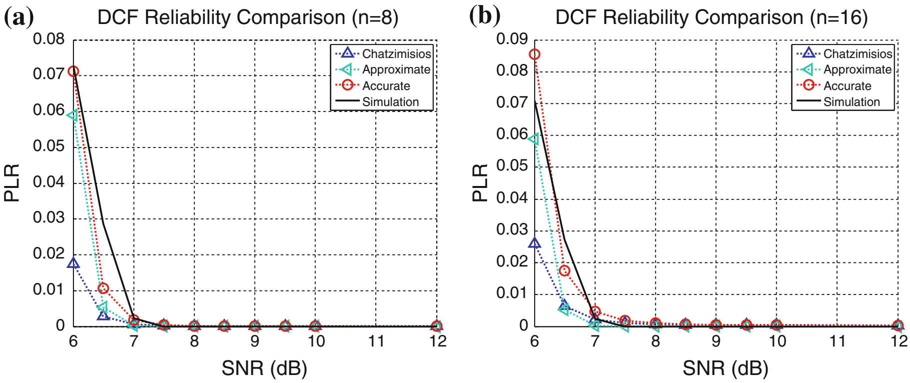


Fig. 12 Packet loss probability for RL = 7 and **a** n = 8, **b** n = 16 nodes

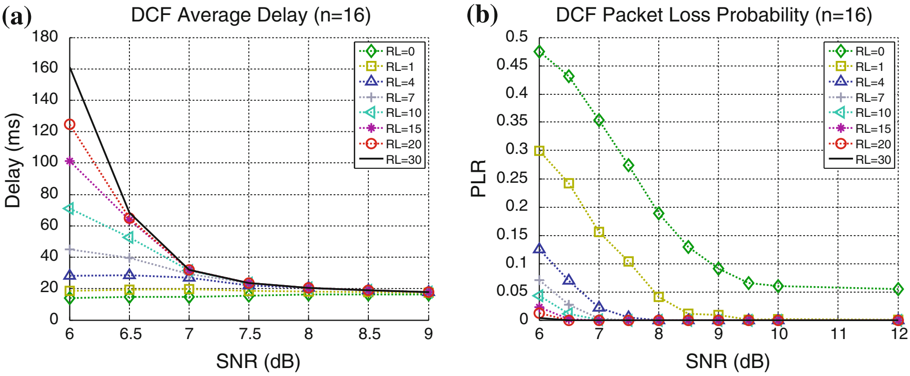


Fig. 13 Delay-PLR tradeoff for different RL values for n = 16 **a** delay, **b** PLR

4.4.1 Average Number of Retransmissions for a Reliable Network

Figure 9 shows the average and maximum number of retransmissions required to have the reliability of near-100 % ($RL = \infty$). The average is close to zero at high SNRs, due to the low error probability. The maximum, on the other hand, is 1, 2 and 3 for the node densities 8, 16 and 32 respectively (not shown here). Interestingly, the node density has negligible effect on the number of retransmissions. At low SNR's due to the high probability of packet error, the number of retransmissions increases exponentially, which is far beyond the typical value of the RL (7). This reveals the need for the limited RL in some scenarios which will be studied in next subsections.

4.4.2 Average Packet Delay

The effect of applying the typical RL value (7) [3] on the average packet delay is shown in Fig. 10. Comparing with Figs. 1 and 2 confirms the significant decrement of the packet delay at low SNRs, but there is no noticeable change at high SNRs, because the average number of retransmissions is close to zero at that region. Interestingly, the proposed high-SNR model shows a good approximate at low SNRs, especially in average node densities ($n = 16$) shown in Fig. 10b.

4.4.3 Delay-Packet Payload Tradeoff

Figure 11 shows the effect of packet payload on the packet delay for the $RL = 7$ scenario which has insignificant difference with the $RL = \infty$ scenario (shown in Fig. 6) for the proposed high-SNR and and also the Chatzimisos models. This is not the case for other models.

4.4.4 Delay-Reliability Tradeoff

Figure 12 shows the probability of packet loss at different SNRs and node densities for the $RL = 7$. Figure 13 compares the delay and PLR tradeoff for different RL values. By considering the required reliability as a given parameter, the proper RL can be chosen to have the minimum delay.

5 Conclusions and Future Works

In this paper, three analytical access delay models have been proposed for the IEEE 802.11 DCF mechanism in saturated traffic and noisy industrial applications. The first and second one provide an accurate model by solving non-linear equations at low and high SNRs respectively. The third one offers an approximate, simple and closed-form packet delay formula without the need to solve a non-linear equation which makes it a suitable candidate to be used in the distributed adaptive QoS provisioning algorithms for industrial nodes having limited processing capabilities. Simulation results match the theoretical derivations in most SNRs, confirming the effectiveness of the proposed models. AAt the end, different tradeoffs including delay-payload, delay-reliability and delay-data rate was thoroughly studied. The most important reason for inconsistencies relies on the simple DCF model used. Our ongoing and future work include, providing a more accurate DCF model, applying more realistic channel models such as multipath fading, developing a more detailed and accurate DCF delay model which would be applicable at all SNR regions, and performance analysis of IEEE 802.11 in Vehicular Ad-Hoc Networks (VANETs) [6,14,57].

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