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# Contention Window Adjustment in IEEE 802.11-Based Industrial Wireless Networks

Mohsen Maadani, Seyed Ahmad Motamedi

***Abstract*****—**The use of wireless technology in industrial networks has gained vast attraction in recent years. In this paper, we have thoroughly analyzed the effect of contention window (CW) size on the performance of IEEE 802.11-based industrial wireless networks (IWN), from delay and reliability perspective. Results show that the default values of CWmin, CWmax, and retry limit (RL) are far from the optimum performance due to the industrial application characteristics, including short packet and noisy environment. In this paper, an adaptive CW algorithm (payload-dependent) has been proposed to minimize the average delay. Finally a simple, but effective CW and RL setting has been proposed for industrial applications which outperforms the minimum-average-delay solution from maximum delay and jitter perspective, at the cost of a little higher average delay. Simulation results show an improvement of up to 20%, 25%, and 30% in average delay, maximum delay and jitter respectively.

***Keywords*****—**Average Delay, Contention Window, Distributed Coordination Function (DCF), Jitter, Industrial Wireless Network (IWN), Maximum Delay, Reliability, Retry Limit.

## I. Introduction

DUE to the numerous advantages of wireless technology, its application in industrial networks has gained vast attraction [1]. Current wireless communication standards are mostly designed for data networks which have large packet payloads, work in low noise environments, and throughput is their main quality of service (QoS) metric. On the other hand, industrial networks use short payloads, work in rather noisy environment, and have delay and reliability as their main QoS parameters [2]. Therefore adopting current standards for use in industrial wireless networks (IWN) is an ongoing research field [1].

IEEE 802.11 is one of the most common wireless communication standards, which has distributed coordination function (DCF) as its mandatory medium access control (MAC) mechanism [3]. Its adjustable parameters are minimum contention window (CWmin), maximum contention window (CWmax), and retry limit (RL). Contention window (CW) adjustment for data networks based on the throughput as the QoS metric has been studied in the literature [4], [5], which proves its important effect on the network performance. To the authors' knowledge, no research has been done about CW adjustment in industrial wireless networks.

In this paper, we have thoroughly analyzed the effect of adjustable DCF parameters on the most important industrial QoS metrics: delay and reliability. Based on the analysis, an adaptive minimum-average-delay and a simplified solution have been proposed which improve the network performance significantly.

The paper is organized as follows: Section II reviews the related works. Section III provides the system model and assumptions. Section IV deals with analytical solution of the problem. Simulation results and the proposed schemes are provided in Section V. Section VI concludes the paper and suggests future works.

Dr. Mohsen Maadani is with the Department of Electrical Engineering, Shahr-e-Qods Branch, Islamic Azad University, Tehran, Iran (corresponding author; e-mail: maadani@qodsiau.ac.ir).

Dr. Seyed ahmad Motamedi is with the Department of Electrical Engineering, Amirkabir University of Technology.

## II. Related Works

The challenges of using wireless technology in industrial networks have been studied in literature [1], [2], [6]-[11]. References [2], [9]-[11] have provided Markov chain analytical models for IEEE 802.11-based industrial networks. An adaptive rate adaptation technique has been proposed in [12]. It is shown that increasing the data-rate improves the performance only at average-high signal to nose ratios (SNR) and to keep it simple, the lowest data-rate has the best performance. Tian et al. [13] have analyzed the DCF performance in periodic traffic. Islam et al. [14] review the security issue of IWNs. References [7], [8] have studied the use of multiple input multiple output (MIMO) technology in IWNs which shows improved performance, both in delay and reliability, at the expense of higher complexity.

CW adaptation/adjustment in data networks has been studied in some literature [4], [5], [15], [16]. Deng et al. [4] have shown that current CW and binary exponential backoff mechanism defined in the standard does not provide optimum throughput, and they have proposed a modified backoff mechanism, which increases the CW linearly after the CWmax/2 limit is reached. Simulation results prove its efficacy. Weng et al. [16] propose a CW selection based on the network scale, to optimize the throughput. Reference [15] has proposed a new backoff algorithm and dynamic CW control mechanism for the DCF which improves the network throughput. Hong et al. [5] have proposed a distributed congestion-based CW adaptation algorithm to for throughput optimization.

To the authors' knowledge, no research has studied the CW adaptation for IWNs, targeting the delay and reliability as the QoS metric. In this paper we have analyzed the CW effect of the IWN's QoS parameters in various scenarios, including packet payload (PL), number of competing nodes (n), SNR, RL, etc. and two algorithms has been proposed which improve the network performance significantly.

TABLE I
IEEE 802.11 DCF Parameters

| Parameter | Value |
|---|---|
| Data Rate (DR) | 1 Mbps |
| Control Rate (CR) | 1 Mbps |
| PHY Header (PH) | 24 Bytes |
| MAC Header (MH) | 28 Bytes |
| ACK packet size (ACK) | 14 Bytes |
| Payload (PL) | 8-64 Bytes (default:32-Byte) |
| Slot Time | 20 µs |
| SIFS | 10 µs |
| DIFS | 50 µs |
| CWmin | Variable (default:31) |
| CWmax | Variable (default:1023) |
| Retry Limit (RL) | Variable/Infinite (default:6) |

## III. System Model and Assumptions

We have considered a typical industrial network architecture, which several nodes are located around an instrument in a cluster-way and communicate with each other [1], [11], [13], [14]. Simulation Parameters are listed in Table I [3]. We assume that the nodes use IEEE 802.11b-compliant transceiver and always have a packet for transmission (saturated traffic). The PL is small due to the industrial application [1], [11], [13], [14]. The communication channel is error-prone with the additive white Gaussian noise (AWGN) model. According to related works, the minimum data rate is used because higher data rates (corresponding to the high-rate modulations) have poor performance in noisy industrial environment [12].

## IV. Analytical Solution

The authors have proposed a simple Markov Model for IEEE 802.11 DCF mechanism in industrial applications assuming an infinite RL [10]. We have

$$Average\ Delay = \frac{CW_{\min}}{2}\left(\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p}\right)\times Slot \tag{1}$$

in which $m = \log_2\left(\frac{CW_{\max}}{CW_{\min}}\right)$ and $p$ is the packet error probability, which includes both channel error and packet collision. *Slot* is the slot-time (the interval between two consecutive decrements of the DCF backoff counter). Both $p$ and *Slot* depend on the probability that a station transmits in a randomly chosen slot-time ( $\tau$ ) which results in a non-linear equation.

$$\tau = \sum_{i=0}^{m} b_{i,0} \approx \frac{b_{0,0}}{1-p} = \frac{2(1-2p)(1-P_{tr})}{(1-2p)CW_{\min} + p(CW_{\min}-1)(1-(2p)^m)} \tag{2}$$

In order to find the optimum CW settings which minimize the average delay, we need to solve an optimization problem which includes a non-linear equation system. The outputs of the problem are CWmin and $m$ (CWmax) which depend on some parameters including signal to noise ratio (SNR), packet payload (PL), number of competing nodes (n), etc. If we need to minimize the jitter and maximum delay as well, we should add those equations to the optimization problem, which the latter does not have a closed-form. This causes a huge amount of calculations needed for each parameter-set which makes it impractical. On the other hand, simulations can cover a large range of parameter sets, and can avoid the simplifying assumptions made in the analytical models, which results in more realistic solutions. That is why we have chosen this method to resolve the proper CW setting problem, which will be discussed in next section.

## V. Simulation Results and Proposed Scheme

In this section, at first we study the high-SNR performance of the protocol with different CW and RL settings by simulation. Then the low-SNR region will be covered in detail. Similar to our previous works, the authors-written MATLAB code has been utilized as the simulator.

### A. High SNR Performance

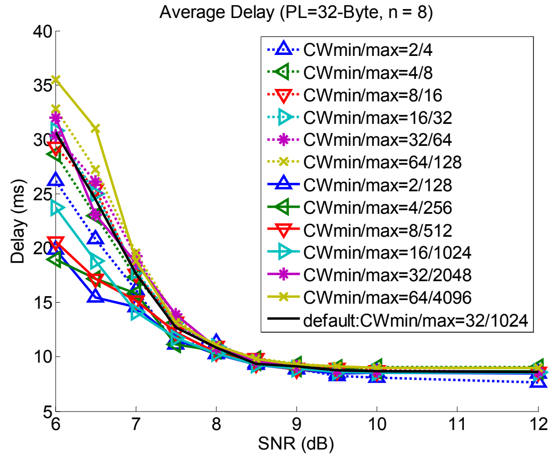
Simulation results show that due to the low probability of packet error, limited number of competing nodes and short packet payloads, CWmin values from 16 to 64 provide similar delay performance. Therefore only a few retransmissions is needed, and the CWmax value does not play an important role in high-SNR delay performance. According to next subsections results, we suggest a CWmin/max=32/64 setting. The default value of RL (RL=6) is enough at high SNRs, due to low packet collisions/errors occurred in industrial scenario.

### B. Low SNRs Performance of the Default Setting

Figs. 1 and 2 depict the average delay and reliability performance of the default settings (CWmin/max=32/1024, RL=6), and various low and high CWmin/max combinations for the same RL. As can be noticed, the delay is well limited at low SNRs, but at the cost of large packet loss ratio (PLR) of over 50% for SNR=6 and below. CWmin=2 provides the lowest delay, but it in a large PLR at low SNRs, and PLR=10% high SNRs, which makes it impractical. On the other hand, PLR performance for other CW settings is similar (not acceptable), while some settings provide lower average delay. It can be concluded that the default DCF parameters are not suitable for the noisy industrial environment.

### C. Proposed Schemes for the Infinite RL Scenario

Here, to satisfy the reliability metric of the industrial networks, we have set the RL value to infinite. In other words, the packet is retransmitted as much as needed to reach the destination. This is not a practical setting, because an unsuccessful packet transmission (for example due to a faulty receiver) can pause the transmitter node from sending packet to any other destination. However, the results can be used as a rule of thumb, and can be useful in focusing on the CW effect. As illustrated in next subsection, a well limited value of RL (40) can well satisfy both reliability and stability of the network performance at typical low SNR values.

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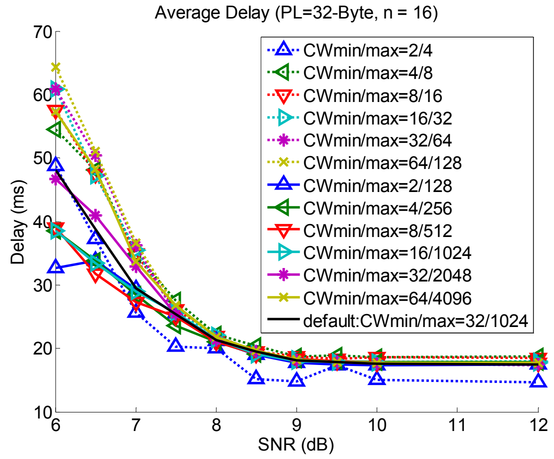


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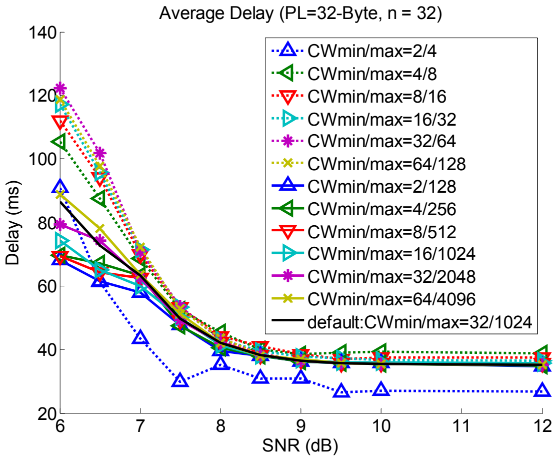
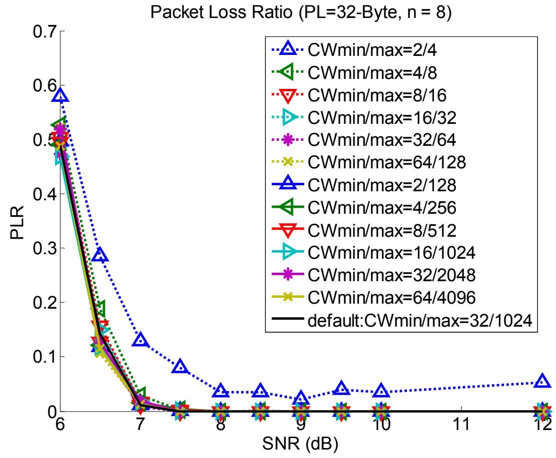



(c)

Fig. 1 Average packet delay for default RL and typical payload of 32-Byte. (a) 8, (b) 16, and (c) 32 competing nodes

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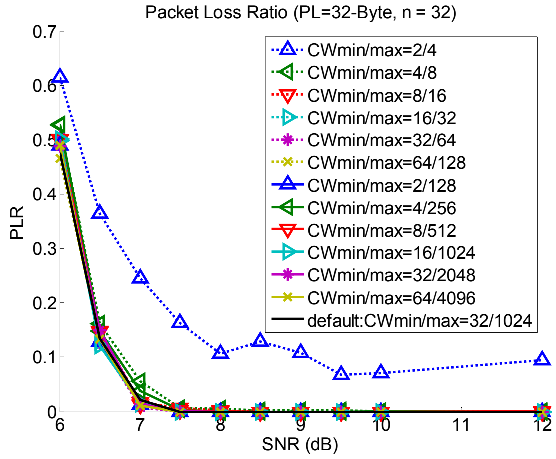


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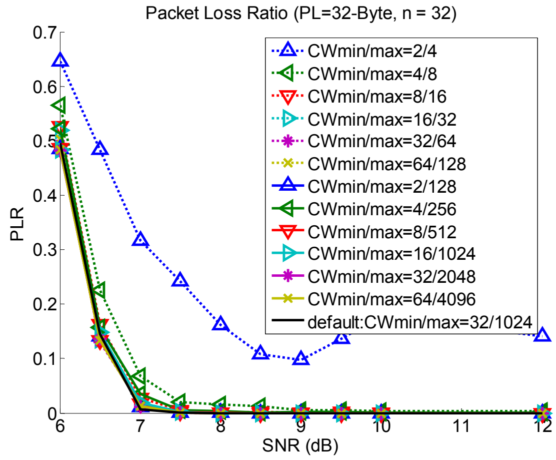



(c)

Fig. 2 Packet loss ratio for default RL and typical payload of 32-Byte: (a) 8, (b) 16, and (c) 32 competing nodes

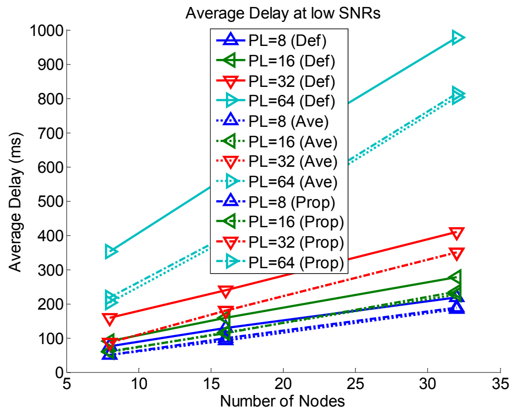
TABLE II
MINIMUM AVERAGE DELAY SETTINGS

| Payload (Byte) | CWmin | CWmax |
|---|---|---|
| 8 | 2 | 32 |
| 16 | 4 | 32 |
| 32 | 32 | 64 |
| 64 | 8 | 32 |

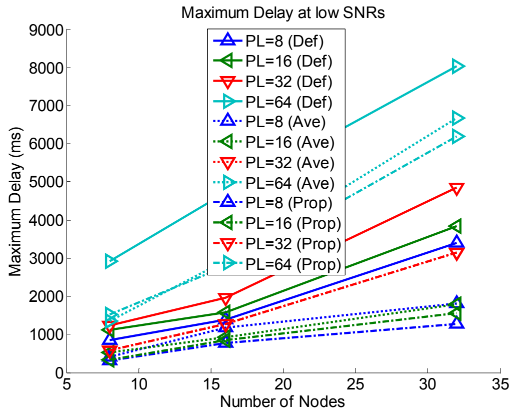
We have performed an extensive greedy simulation for different combinations of the CWmin/max parameters, with the target of finding the required setting for the minimum average delay. At first we tried to find the suitable setting for fixed number of nodes and variable packet payload, but a single setting was not acquired. Then we changed the fixed parameter to the payload, and hopefully a single setting was reached for different number of competing nodes which resulted in our adaptive CW setting scheme. Interestingly, this scenario is more practical, because the packet length is usually a constant value in typical industrial applications. Reviewing the simulation results, we reached to a single CWmin/max=32/64 setting which results in a close-to-minimum delay performance at all payloads, which leads to our simple solution. Fig. 3 (a) shows the performance comparison between the default setting (Def), payload-dependent adaptive CW setting aiming to minimize the average delay (Ave), and the proposed simple solution (Prop). Due to the importance of other delay metrics, namely maximum delay and jitter, the corresponding parameters are depicted in Figs. 3 (b) and (c) respectively. The minimum-average-delay settings are shown in Table II, and as mentioned before, the proposed simple setting is CWmin/max=32/64. As can be noticed, default CWmin/max delay metric values (solid lines) are much higher than proposed solutions. For example, at PL=64-Byte, our proposed schemes result in an improvement of 20%, 25% and 30% in the average delay, maximum delay, and jitter respectively. It is worth noting that the improvement decreases for shorter packets. Comparing the dotted curves (Ave), and dash-dot ones (Prop) in Fig. 3 (a), we notice they have close performance, but the maximum delay and jitter of the minimum-average setting is higher than the simple one (Figs. 3 (b) and (c)). In other words, by using the proposed simple setting, we will have both better jitter and maximum delay performance and a much simpler protocol (single CWmin/max value in contrast with an adaptive one) at the cost of a little higher average delay.

*D.Proposed Setting for the Limited RL Scenario*

In this section, we have released the RL value to be finite with the target of finding the proper RL setting. As mentioned before, infinite RL is not a practical choice and makes the network unstable. Revisiting the Fig. 2, we see that CWmin=2 has the worse PLR. Finding the suitable RL for it will ensure that it satisfies the required reliability in other CW values. Figs. 4 and 5 show the average delay and PLR respectively for PL=32-Byte, CWmin=2 and various CWmax values. It can be seen that with RL=40, the PLR relies below 0.1 for various CWmax ranges, which is acceptable for most monitoring applications. On the other hand, CWmax of 128 can provide a fair tradeoff between delay and reliability. In other words, CWmin/max=2/128, with RL=40 results in PLR=0.01 which is acceptable for most industrial applications.




(a)

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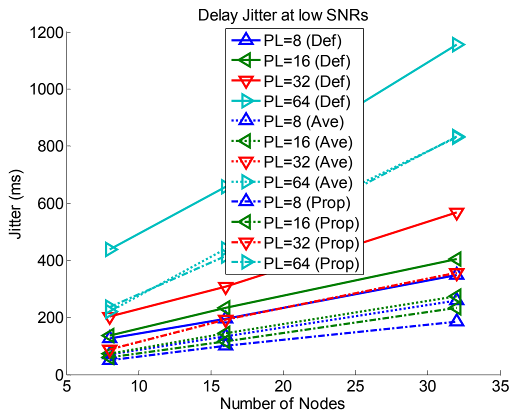


(c)

Fig. 3 Delay performance comparison between default, and proposed optimum CWmin/CWmax setting, (a) average, (b) maximum, and (c) jitter

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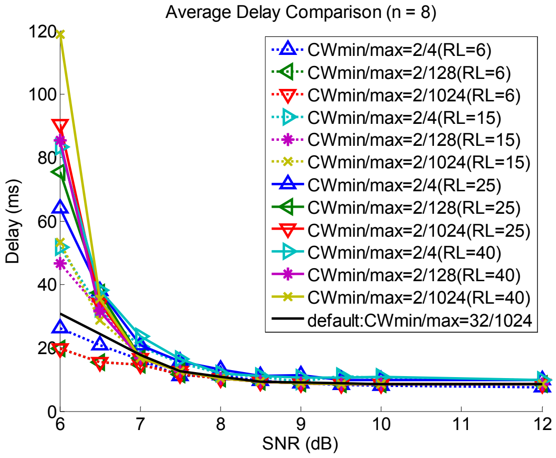


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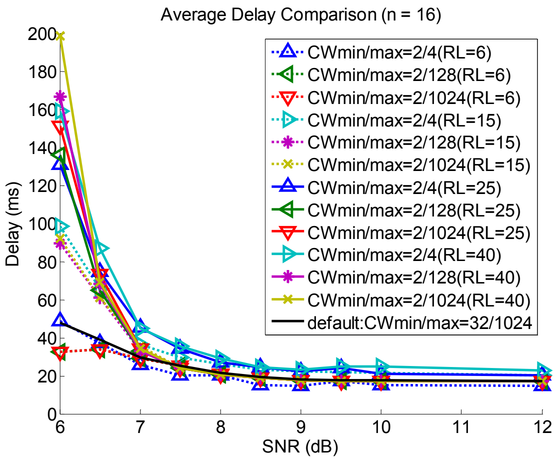


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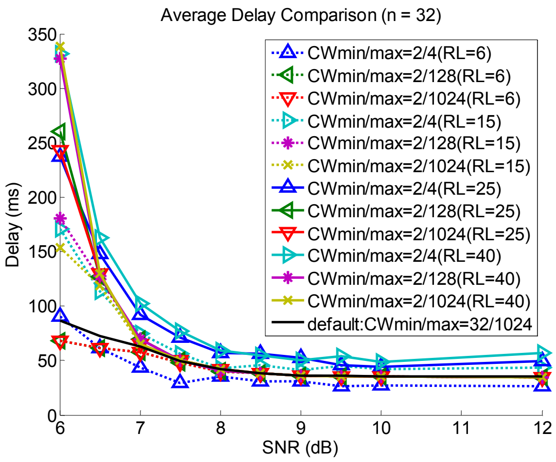
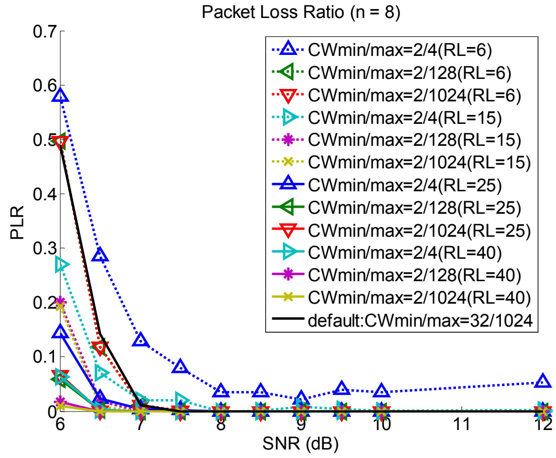
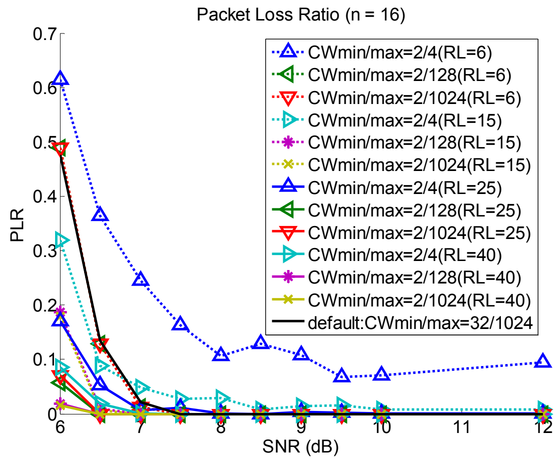



(c)

Fig. 4 Average delay comparison for limited RL and typical payload of 32-Byte: (a) 8, (b) 16, and (c) 32 competing nodes




(a)

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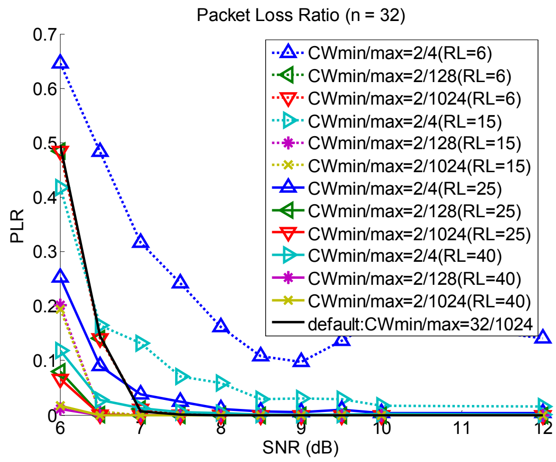


(c)

Fig. 5 Packet loss ratio comparison limited RL and typical payload of 32-Byte: (a) 8, (b) 16, and (c) 32 competing nodes

## VI. Conclusion

IWNs have earned vast attention in recent years due to their numerous advantages. On the other hand, wireless technologies are mostly designed for data networks which have different characteristics and QoS metrics than industrial ones. Performance analysis and proper parameter-tuning are the main research challenges of IWNs. Most of the current literature is focused on the data networks throughput optimization, while IWNs have delay and reliability as main QoS parameters.

In this paper, we have thoroughly analyzed the effect of CW and RL parameters of the IEEE 802.11 DCF in industrial applications, which shows the sub-optimum performance with default values. Based on extensive greedy simulations for various CWmin/max and RL combinations, an adaptive CW algorithm has been proposed which significantly improves the average delay performance. Also a simplified setting CWmin/max=32/64 with RL=40 has been proposed which outperforms the default and minimum-average settings both in maximum delay and jitter metric, at the cost of a little higher average delay.

Future work includes analytical modeling of the proposed algorithm and providing a similar algorithm for the enhanced distributed channel access (EDCA) MAC mechanism.

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**M. Maadani** (M'10) received two BSc. degrees in biomedical engineering and electronic engineering from Amirkabir University of Technology (AUT), Tehran, Iran and his MSc. degree in electronic engineering from Sharif University of Technology (SUT), Tehran, Iran in 2003 and 2006 respectively. He received his Ph.D. degree in electronic engineering from AUT in 2014. He was a senior technical engineer in communication and R&D department of "Iran Control and Communication Systems Supply" (ICS) Company, Tehran, Iran from Jan 2006 to Sep 2007 and works as a senior technical engineer in the national project "Developing the Strategic Plan Document of Iran Smart Electricity Grid" from Sep 2013 to present. Dr. Maadani has been a faculty member at Department of Electrical Engineering, Shah-e-Qods Branch, Islamic Azad University (IAU), Tehran, Iran since 2007. His recent research activities are mainly focused on the Physical and Medium Access Control (MAC) layers of wireless networks, including Wireless Industrial Networks (WIN), Wireless Sensor Networks (WSN), Wireless Local Area Networks (WLAN), Wireless Personal Area Networks (WPAN), Multiple Input Multiple Output (MIMO) Communication Systems, Cross-Layer Design, and adaptive Quality of Service (QoS) provisioning schemes. He has published several scientific papers and has acted as a reviewer in several international journals and conferences. Dr. Maadani is a member of IEEE, EAI and IACSIT.

**S. A. Motamedi** received the BSc degree in electronic engineering from Amirkabir University of Technology (AUT), Tehran, Iran, in 1979. He received the MSc degree in computer hardware in 1981 and PhD degree in information systems (computer hardware) in 1984, both from University of Pierre & Marie Curie (Paris VI), France. Currently he is a Full Professor at the Electrical Engineering Department of Amirkabir University of Technology (AUT) and has been a faculty member of this institute since 1984. His research interests include Parallel Processing, Image Processing, Microprocessor Systems, Wireless Industrial Networks, Wireless Sensor Networks, Automation and Biomedical Engineering. Prof. Motamedi was the president of Iranian Research Organization for Science and Technology (IROST) from 1986 to 2001. He is the head of High-Speed Processing Research Center, AUT, Tehran, Iran. He has been the author of several books and has published a lot of scientific papers in international conferences and journals. Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran.