Wireless Personal Communications (2020) 114:1763–1783
https://doi.org/10.1007/s11277-020-07447-3

Performance Evaluation of the Networks with Wi-Fi based TDMA Coexisting with CSMA/CA

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Published online: 8 May 2020

Abstract

The wireless technology is widely used in industries with timing stringent tasks. However, it lacks of the consideration of the co-channel interference when designing and estimating the performance of the media access strategies. Thus, it is hard to guarantee the real-time and reliable packet transmissions. In this study, we first propose a Wi-Fi based TDMA access scheme to provide the stringent timing and reliability guarantees under the coexistence with the CSMA/CA scheme. Then, we theoretically analyze the delay of the Wi-Fi TDMA scheme and the throughput of the CSMA/CA scheme considering mutual interferences. The effectiveness of the proposed Wi-Fi TDMA scheme is demonstrated by numerous simulation results since the results show that the retransmission times and the average access delay of the TDMA station are small when varying the CSMA/CA packet length, TDMA packet length, TDMA slot length and TDMA duty cycle. The simulation results also show that the analysis TDMA delays are almost the same with the simulation ones which indicate the accuracy of our theoretical analysis models. Additionally, numerous simulations have been done to show the impact of the Wi-Fi TDMA scheme on the typical CSMA/CA scheme by varying the TDMA frame length and the TDMA duty cycle under centralized and distributed slot assignment strategies.

Keywords Wi-Fi TDMA · CSMA/CA · Real-time · Reliability · Coexistence

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1 Introduction

As the development of the wireless technology, it has been widely used in industry applications, such as industry process control, intelligent robotics, and IoTs (Internet of Things). These applications have stringent timing and reliability requirements [1–4]. Many researches have been done to improve the real-time and reliable transmissions of wireless industry networks, such as the multi-path routing [4] and scheduling policies [5, 6]. However, the non-deterministic end-to-end delay and high packet loss rates caused by the co-channel interferences are still the critical challenges in the current wireless industry networks, especially in the public scenarios where multiple networks overlap with each other.

The typical wireless industry standards are WirelessHart [1], ISA100.11a [7] and WIA-PA [8]. They transmit packets at low power levels which perform poorly in scenarios with high interferences. The Wi-Fi technology has been introduced into wireless industries due to its economics, flexibility of deployment and high transmit rates [3, 5, 9]. It also has better performances than the low-power standards in scenarios with high interferences. Some corporations have developed Wi-Fi based access points for wireless industry applications, such as the SIMENS SCALANCE W/WLC, AWK from MOXA, and Wi-Fi AP from Advantech.

However, the Wi-Fi devices adopt the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) scheme which will result in non-deterministic delay. Thus, it is not suitable for industry control system. It is well recognized that the TDMA (Time Division Multiple Access) scheme is more suitable for the wireless industry [1, 5]. Some researchers have investigated the scheduling policies of TDMA schemes, or Wi-Fi based packet access schemes [5, 10–14]. However, most of them have ignored the coexistence of heterogeneous access schemes which interfere with each other. It also lacks of the consideration of the impact of the TDMA based scheme on the typical Wi-Fi networks.

Considering that, we focus on studying the Wi-Fi based media access schemes with high real-time and reliable packet transmission ability in scenarios with heterogeneous access schemes. Our contributions include,

- *We introduce a simple Wi-Fi based TDMA scheme* This scheme considers the co-channel interference from heterogeneous media access schemes in the same coverage area, and it combines the advantages of the Wi-Fi standard and the TDMA scheme. Hence, it can provide the real-time and reliable transmissions in coexistence scenarios.
- *We analyze the delay of the proposed Wi-Fi TDMA scheme under the interference of the CSMA/CA stations* Most of the previous performance analysis of the TDMA have not considered the interference from heterogeneous stations. The proposed delay analysis model considers the co-channel interferences from heterogeneous media access schemes. Hence, the analysis model is practical and can be used to predict the performance of the proposed Wi-Fi TDMA scheme.
- *We analyze the throughput of the CSMA/CA scheme under the interference of the Wi-Fi TDMA scheme* The analysis model of the CSMA/CA throughput considers the interference of the Wi-Fi TDMA scheme. This model is important for both the typical CSMA/CA scheme and the Wi-Fi TDMA scheme since it could be used to evaluate the coexistence performance of the Wi-Fi TDMA scheme.

The paper is structured as follows. In Sect. 2, we survey the related work. In Sect. 3, we introduce the network model and the problem of coexistence networks. The Wi-Fi TDMA scheme is given in Sect. 4. The theoretical analysis models are introduced in Sect. 5. Simulation results are given in Sect. 6. At last, we conclude this paper in Sect. 7.

2 Related Work

The main challenge in designing efficient media access schemes with good coexistence performance is to coordinate the co-channel interferences. In [15], the coexistence of multiple WirelessHart networks has been studied. This study, however, is only for homogeneous coexisting networks. Some researchers have studied the media access schemes in scenarios where the devices with IEEE 802.15.4 standard coexist with the Wi-Fi devices [16]. The IEEE 802.15.4 standard working on low power level is easily interfered by the Wi-Fi devices which work on high power level [17]. In [18], the authors have proposed the guide busy tone (GBT) scheme to guarantee the reliable Zigbee (working on IEEE 802.15.4 standard) communication under Wi-Fi interferences. The authors in [19] have proposed a new superframe structure for IEEE 802.15.4e standard to mitigate the interferences from Wi-Fi and ZigBee. The authors in [20] have proposed the OLA (Overlap Avoidance) scheme for scenarios with WLAN coexisting with WPAN (adopting IEEE 802.15.4 standards) in cooperate and independent working methods. In [21], the authors have proposed the Cooperative Busy Tone (CBT) strategy to guarantee the coexistence of the Zigbee and Wi-Fi standards. They have analyzed the network performance when the TDMA and CSMA/CA schemes are adopted by the Zigbee. The authors in [22] have adopted the adaptive coding to improve the throughput of the Zigbee network under the interference of Wi-Fi networks. In [23], the authors have proposed to adopt the IFS duration to reduce the conflict between the IEEE 802.11b/g/n standards and the IEEE 802.15.4 standards. They have also analyzed the packet losses of the IEEE 802.15.4 standard. The PA-MAC scheme has been proposed for WBAN (Wireless Body Area Network) in scenarios with interferences of other WBANs and Wi-Fi networks [24]. Recent researches have proposed the LTE-U (LTE in Unlicensed spectrum) technology to mitigate the traffic burden of the licensed frequency. For scenarios with LTE-U coexisting with Wi-Fi networks, most of the researches have focused on improving the network throughput on the shared frequency [25–29].

Although the above researches have studied the coexistence of different media access schemes, most of them focus on the network throughput other than the real-time and reliability of the packet transmissions.

Some researchers have studied the coexistence of the TDMA scheme with the Wi-Fi scheme. The authors in [21] have analyzed the throughput of the TDMA scheme (with IEEE 802.15.4 standard) when it coexists with Wi-Fi standard. In [30], the authors have analyzed the performance of the ISA100.11a standards (adopting TDMA scheme) under the interference of the IEEE 802.11b standards. The authors in [5, 31] have proposed the RT-WiFi scheme considering the coexistence of the Wi-Fi networks. However, they have not estimated the delay of the RT-WiFi and the throughput of the typical Wi-Fi networks.

The most famous performance analysis model of the CSMA/CA scheme is based on the Markov model [32]. Some researchers have extended the Markov based model to the IEEE 802.11ac standards [33, 34]. The authors in [35] have analyzed the distributed slot assignment strategy by adopting the Markov chain model and queueing theory. In [36], the authors have analyzed the performance of a TDMA scheme with multiple channels. In [37], the M/G/1 queueing model has been adopted to analyze the performance of the

TDMA based MAC scheme. The authors in [38] have estimated the performance of the TDMA scheme in WirelessHart standard. However, these analysis models could not be adopted directly into this study since they have not considered the coexistence of the TDMA scheme and the CSMA/CA scheme.

3 Network Model

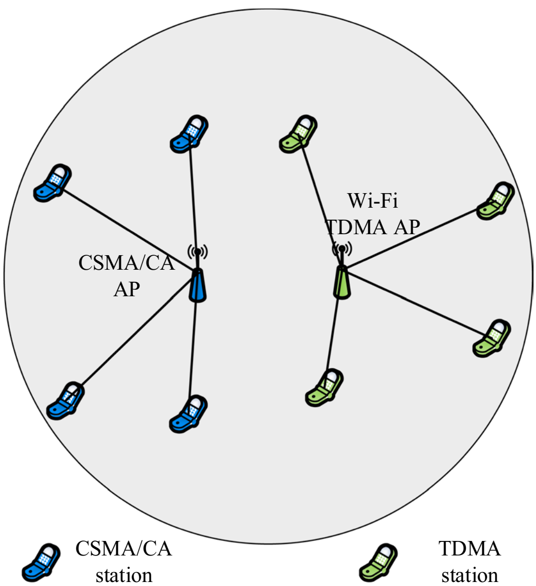
We consider a scenario with stations working on different media access schemes which are the CSMA/CA scheme and the Wi-Fi TDMA scheme. These stations are in the same coverage area, as shown in Fig. 1.

Since all the stations share the same unlicensed frequency, collisions will happen if they transmit packets simultaneously. Under this situation, it is hard to provide the real-time and reliability guarantees for the Wi-Fi TDMA station, and the throughput of the CSMA/CA stations will be degraded. Hence, it is important to design an efficient Wi-Fi TDMA access scheme to coexist with the typical CSMA/CA stations.

In this study, we consider a network with one Wi-Fi TDMA AP and one CSMA/CA AP. The two APs share the same coverage area and multiple stations are randomly located in the area. We introduce an efficient Wi-Fi TDMA scheme to guarantee the real-time and reliable transmissions of the Wi-Fi TDMA stations while considering the throughput of the CSMA/CA stations.

Moreover, theoretically analyzing the performance of the proposed Wi-Fi TDMA scheme is important for both the CSMA/CA stations and the Wi-Fi TDMA stations. Hence, we theoretically analyze the delay and throughput performances of the Wi-Fi TDMA stations and the CSMA/CA stations, respectively.

Fig. 1 Network model



4 Real-Time Wi-Fi TDMA Scheme

To provide deterministic delay of stations with real-time and reliability requirements, we introduce and implement the Wi-Fi TDMA scheme. The Wi-Fi TDMA scheme is working on the IEEE 802.11 stack. The basic idea of the Wi-Fi TDMA scheme is to cancel the carrier sensing function and retransmit a packet when it fails due to collisions. In the proposed real-time Wi-Fi TDMA scheme, we set the retransmission timer $T_{timeout}$ to be SIFS (Short Inter-Frame Space) plus the transmission time of an ACK message. The main steps of the scheme are:

Step 1 The Wi-Fi TDMA station sends a packet in the assigned slot without carrier sensing, and waits for the ACK message
Step 2 If the station receives the ACK message before $T_{timeout}$, the transmission is successful;
Step 3 If the station doesn't receive the ACK message when it is timeout, it retransmits the packet immediately.
Step 4 Repeat Step 3 until the packet is successfully transmitted.

The TDMA station sends a message without carrier sensing is to force the CSMA/CA stations to stop transmitting messages and transfer into the random collision avoidance stage. The station adopting the real-time Wi-Fi TDMA scheme has a higher priority when contending for the shared channel since we have that $T_{timeout} < DIFS$. Thus, the scheme is a preemptive TDMA scheme which could provide real-time and reliable guarantees by retransmission and ACK messages.

The relationship between the Wi-Fi TDMA scheme and the CSMA/CA scheme is illustrated in Fig. 2. The CSMA/CA station detects the collision only after it finishes the transmission of an on-going packet. After the detection of a collision, it will enter the collision avoidance stage. Thus, the retransmission times of a TDMA station is most related to the packet length of the CSMA/CA station.

The Wi-Fi TDMA station can adapt its transmit rate according to the channel quality. The transmit rate could be obtained by reading the value in the corresponding register. We assume that the Wi-Fi TDMA station and CSMA/CA station send packets with the same rate.

Considering that the propagation delay is very short compared to the processing delay, we ignore it when calculating the end-to-end delay. Let T_{tdma}, T_{csma} and T_{ack} denote the transmission delays of a TDMA frame, a CSMA/CA frame and an ACK message, respectively. The transmission delay equals to the time of processing the head of a packet and the payload. Thus, according to the IEEE 802.11 standard, we have that,

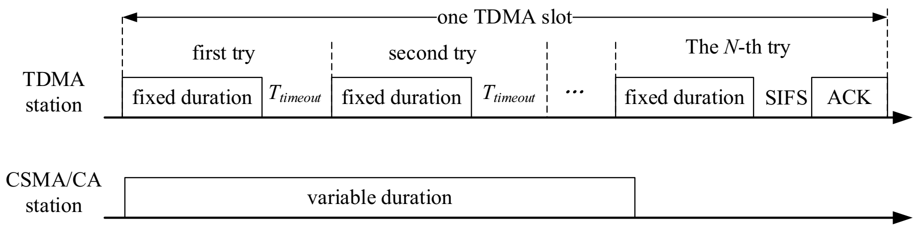


Fig. 2 Preemptive TDMA scheme

$$\begin{cases} T_t = T_{tdma} + SIFS + T_{ack} \\ T_s = T_{csma} + SIFS + T_{ack} + DIFS \\ T_c = T_{csma} + DIFS \end{cases} \tag{1}$$

where T_t and T_s are delays of successfully transmitting a TDMA frame and a CSMA/CA frame, respectively. T_c is the delay when a CSMA/CA packets fails to transmit a packet.

Therefore, the following conditions should be satisfied to guarantee the successful transmission of a TDMA packet,

$$(N-1) \cdot T_t \geq T_c - DIFS \tag{2}$$

$$N_{\max} = \left\lceil \frac{\max\{T_c\} - DIFS}{T_t} \right\rceil + 1 \tag{3}$$

where N is the retransmission times of a Wi-Fi TDMA station and N_{max} is the maximum retransmission times of a Wi-Fi TDMA station.

5 Analysis Model of the Wi-Fi TDMA Scheme

5.1 The impact of the Wi-Fi TDMA station to the CSMA/CA station

The Wi-Fi TDMA station periodically preempts the channel and sends packets, while the CSMA/CA station can only contend for channel and send packets when the Wi-Fi TDMA station frees the channel. We divide the continuous time into the TDMA slot and the CSMA/CA slot. If the transmission cycle of a TDMA station is denoted by T_p, we can illustrate the time frame in Fig. 3.

The Wi-Fi TDMA media access scheme can be viewed as a periodic interference to the CSMA/CA scheme. Considering of the unpredictable retransmission of the TDMA access scheme, the interference to the CSMA/CA scheme is unpredictable.

If and only if a CSMA/CA station does not conflict with another CSMA/CA station and it suffers no interference from a Wi-Fi TDMA station, the CSMA/CA station can transmit a packet successfully. We study a scenario with n independent CSMA/CA stations, the backward state is m, the minimum contention window size is $CW_{\min}$ and $W_{min} = CW_{min} + 1$. If P_t is the probability a CSMA/CA station be interfered by the Wi-Fi TDMA stations, we can obtain the probability p a CSMA/CA station conflicts with the other stations and the sending probability τ of a CSMA/CA station according to [28],

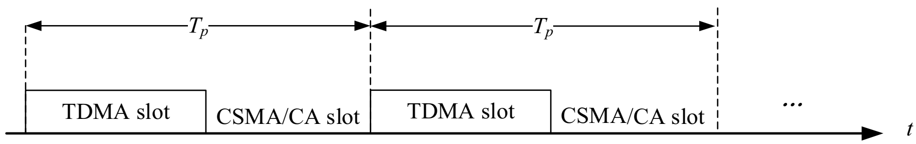


Fig. 3 An example of the TDMA period and CSMA/CA period

$$\tau = \frac{2(1-2p)}{(1-2p)(W_{\min}+1)+pW_{\min}(1-(2p)^m)} \tag{4}$$

$$p = 1-(1-\tau)^{n-1}\cdot(1-P_t) \tag{5}$$

It is hard to obtain the closed-form expression of p and τ according to expressions (4) and (5).

In the following, we analyze the interference a CSMA/CA station suffered from the Wi-Fi TDMA station in a T_p period. As shown in Fig. 4, a CSMA/CA station will be interfered if and only if it sends packets at the beginning or the end of the T_p period.

Recall Eq. (1), at the beginning of a T_p period, the maximum interference duration of a CSMA/CA frame is $T_c - DIFS$. At the end of a T_p period, the maximum interference duration of a CSMA/CA frame is $T_s - DIFS$ since we need to consider the interference of the ACK message. Let t be a variable denoting the interference duration. Assume that the interference probability is uniform distribution, then the average interference time of a CSMA/CA station in a T_p period is,

$$\int_0^{T_c-DIFS}\frac{1}{T_c-DIFS}tdt+\int_0^{T_s-DIFS}\frac{1}{T_s-DIFS}tdt=\frac{1}{2}(T_c+T_s-2DIFS) \tag{6}$$

When a TDMA station is sending a packet, the CSMA/CA station will transfer into the froze state since it senses a busy state of the channel. Thus, the time duration T_t' is not available to the CSMA/CA station. We have that $T_t < T_t' < 2T_t$. Let assume that the probability of T_t' obeys to the uniform distribution, then we have that,

$$\begin{aligned} E(T_t') &= \int_0^{T_t}\frac{1}{T_t}tdt+T_t \\ &= \frac{3}{2}T_t \end{aligned} \tag{7}$$

The available transmission time of a CSMA/CA station within a T_p period is T_p minus $E(T_t')$. Let the probability of a CSMA/CA station interfered by a Wi-Fi TDMA station be the fraction of the interference duration to the available time of the CSMA/CA station. Thus, we have that,

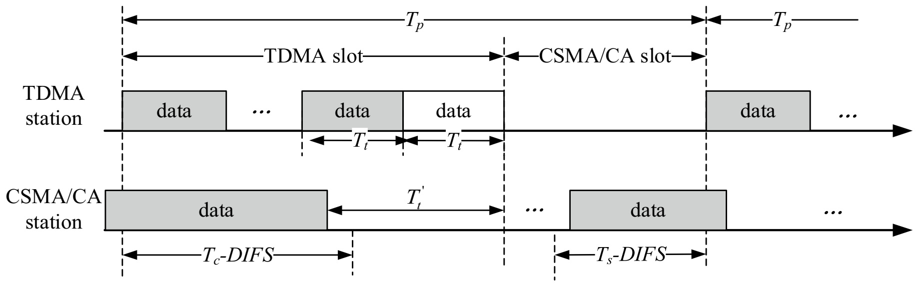


Fig. 4 The interference a CSMA/CA frame suffered from the Wi-Fi TDMA station

$$P_t = \frac{T_s + T_c - 2DIFS}{2T_p - 3T_t} \tag{8}$$

By solving Eqs. (4), (5) and (8), we can obtain all the unknow variables.

In the scenarios where the proposed preemptive Wi-Fi TDMA scheme coexists with the CSMA/CA scheme, the Wi-Fi TDMA station will periodically interfere with the CSMA/CA station. We extend the estimation equation of the throughput of the CSMA/CA scheme in [28] by adding the inference from the Wi-Fi TDMA station. Combing the analysis in Sect. 5, we could estimate the normalized throughput of the CSMA/CA station under the interference of the Wi-Fi TDMA station by the following equation,

$$S = \frac{P_{suc}P_{tr}T_{csma}}{\left(1 - P_{tr}\right)\sigma + P_{suc}P_{tr}T_s + \left(1 - P_{suc}\right)P_{tr}T_c + P_{tr}P_tT_t} \tag{9}$$

The numerator in Eq. (9) is the net payload of a CSMA/CA station, the denominator equals to T_p.

5.2 Delay of the Wi-Fi TDMA Station

From Fig. 2, we can see that the retransmission times of a TDMA frame within a TDMA slot is related to the remaining length of a CSMA/CA frame, which is denoted by T_{csma}^{rema}. If T_{csma}^{rema} is in the range of $(0, T_t]$, it needs to retransmit only once; if it is in the range of $(T_t, 2T_t]$, it needs to retransmit twice, and so on. Let divide T_{csma}^{rema} into multiple segments of T_t and label the retransmission times in each segment. The relationship between T_{csma}^{rema} and the retransmission times is illustrated in Fig. 5, where k_{max} is the maximum retransmission times. Note that: (1) the k_{max}-*th* duration could be no greater than T_t, which equals to $T_{csma} - (k_{\max} - 1)T_t$; (2) at the duration of a SIFS duration and T_{ack} duration, the conflict with a TDMA frame could also happen when $SIFS + T_{ack} < T_t$, and it will trigger a retransmission.

From the previous assumption, it has an equal chance of conflicting in the time domain. From Eq. (1), we have that the time for completely transmitting a CSMA/CA frame is $T_s - DIFS$. Thus, the probabilities of retransmission times could be represented by the ratio of T_{csma}^{rema} to $T_s - DIFS$. Furthermore, we can estimate the expected retransmission times by the following equation,

$$E(k) = \sum_{i=1}^{k_{\max}-1} i\frac{T_t}{T_s - DIFS} + k_{\max}\frac{T_{csma} - (k_{\max} - 1)T_t}{T_c - DIFS} + \frac{SIFS + T_{ack}}{T_s - DIFS} \tag{10}$$

During the transmission of a Wi-Fi TDMA frame, it only needs to transmit once if there are no conflicts with the CSMA/CA frame. If conflicts happen, the station will retransmit

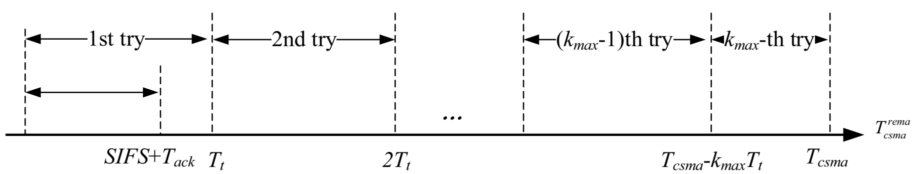


Fig. 5 Relationship between the remaining length of a CSMA/CA frame and the retransmission times of a TDMA frame

the packet. In the following, we analyze the conflict between a CSMA/CA frame and a Wi-Fi TDMA frame in details.

Let the probability that at least one CSMA/CA station transmits packets be P_{tr} and the probability that exactly one CSMA/CA packet being successfully transmitted be P_{suc}. By adopting the analysis method in [28], we have that,

$$P_{tr} = 1 - (1 - \tau)^n \tag{11}$$

$$P_{suc} = \frac{n\tau(1 - \tau)^{n-1}(1 - P_t)}{P_{tr}} \tag{12}$$

Since a CSMA/CA station listens to the channel in the backoff stage and the DIFS duration, it will freeze the timer when it senses a busy channel. Hence, the conflict can only happen during its transmission stage.

The transmission time of a CSMA/CA frame includes the backoff time, retransmit time and sending time. The probability P_c that a CSMA/CA frame conflicts with a Wi-Fi TDMA frame is expressed as follows,

$$P_c = 1 - \frac{(1 - P_{tr})\sigma + P_{tr}DIFS}{(1 - P_{tr})\sigma + P_{tr}(1 - P_{suc})T_c + P_{tr}P_{suc}T_s} \tag{13}$$

where σ is the duration of a backoff slot.

Then, the expected transmission times of a Wi-Fi TDMA packets within a frame is calculated by the follow equation,

$$E(N) = (1 - P_c) + P_c \cdot [E(k) + 1] = P_cE(k) + 1 \tag{14}$$

Therefore, the average access delay of a Wi-Fi TDMA station is,

$$E(T_{tdma}^{delay}) = \left(P_cE(k) + 1\right) \cdot T_t \tag{15}$$

6 Performance evaluation

6.1 Performance Evaluation of the Wi-Fi TDMA Delay

6.1.1 We implement the DCF (Distributed Coordination Function) and the Wi-Fi TDMA media access schemes with C++ programming

In the simulation, the network composes of the CSMA/CA station and Wi-Fi TDMA station. In total, there are one CSMA/CA AP, one Wi-Fi TDMA AP, five CSMA/CA stations and one Wi-Fi TDMA station. For the CSMA/CA stations, they work on the Basic Mode and are in saturation state. For the Wi-Fi TDMA station, it accesses the shared channel periodically. The manager could adjust the period to manage the traffic load. The Wi-Fi TDMA station and the CSMA/CA stations adopt the same physical transmit rate. The detailed configuration of the system parameters is given in Table 1.

Since the length of the Wi-Fi TDMA frame is fixed, the transmission delay of a Wi-Fi TDMA station is determined by the retransmission times. We run the simulation 10 times and evaluate the retransmission times of each frame. To demonstrate the

Table 1 Configuration of the main parameters

Parameters	Values
MAC Header	224 bits
PHY Header	192 bits
Channel Bit Rate	11 Mbit/s
CSMA/CA Slot Time	20 µs
SIFS	10 µs
DIFS	50 µs
$CW_{\min}$	31
m	6
TDMA Packet	323 bytes

accuracy of the our theoretical analysis, we compare the average retransmission times of the simulations and the theoretical retransmission times.

Let $p(i)$ be the probability of the retransmission times of a Wi-Fi TDMA frame in a single slot. According to the equations in Sect. 5, we have that,

$$p(i) = \begin{cases} 1 - P_c, & i = 1 \\ \frac{P_c(T_s - DIFS - t_{csma} + T_t)}{T_s - DIFS}, & i = 2 \\ \frac{P_c T_t}{T_s - DIFS}, & 2 < i < N_{\max} \\ \frac{P_c(t_{csma} - (N-2)T_t)}{T_s - DIFS}, & i = N_{\max} \end{cases} \tag{16}$$

Recall the parameters in Table 1, we can calculate that the transmission time of a Wi-Fi TDMA frame is $T_t = 312.4\mu s$. We set the period of a Wi-Fi TDMA frame to be 4 ms, and the length of a CSMA/CA frame to be 1500 Bytes. From Eq. (2), we have that N_{max}=5, where N_{max} is the maximum retransmission times.

The distribution of the transmission times of a Wi-Fi TDMA frame is shown in Fig. 6. To observe how the CSMA/CA packets affect the retransmission times of the Wi-Fi TDMA frame, we vary the length of the CSMA/CA frame from 700 bytes to 1500 bytes with a step of 100 bytes. The average transmit times of a Wi-Fi TDMA frame is shown in Fig. 7.

Considering that the sending period T_p of a Wi-Fi TDMA station may affect the sending probability τ of a CSMA/CA station, it may further affect the value of P_c. In the simulations, we increase the value of T_p from 3.5 ms to 8 ms and observe the average retransmit times of a Wi-Fi TDMA frame. The results are shown in Fig. 8.

The simulation results in Figs. 6, 7 and 8 have shown that the results estimated by the proposed analysis model are nearly the same with the simulation results. The maximal differences in Figs. 6, 7 and 8 are 3%, 3.6% and 2.8%, respectively. These results have verified the accuracy of the proposed theoretical analysis model.

From Fig. 6, the probability of successfully transmitting of a Wi-Fi TDMA frame by trying just once is very low when the CSMA/CA stations are in saturated state. It happens only when the CSMA/CA station is in the backoff stage or waiting in the DIFS duration. The probability of successfully transmitting a Wi-Fi TDMA frame by trying twice is higher than the other cases. It implies that the ACK message for a Wi-Fi TDMA frame in the first try has a chance to collide with the CSMA/CA frame. Additionally, the probability of a CSMA/CA frame with large remaining length is lower than those of short remaining length. This phenomenon is in accordance with the probability of the remaining length

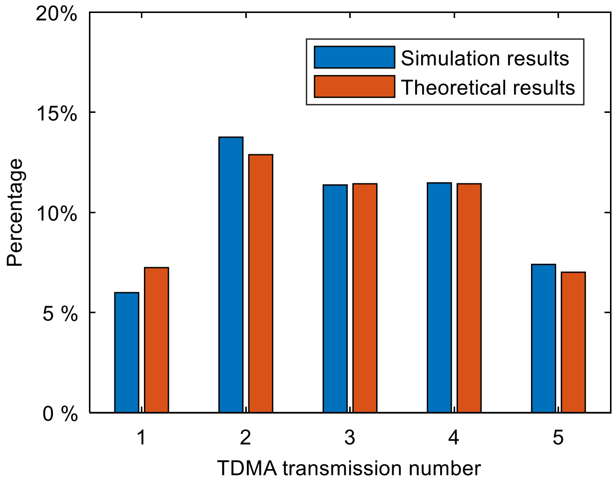


Fig. 6 The distribution of the transmit times of a TDMA frame

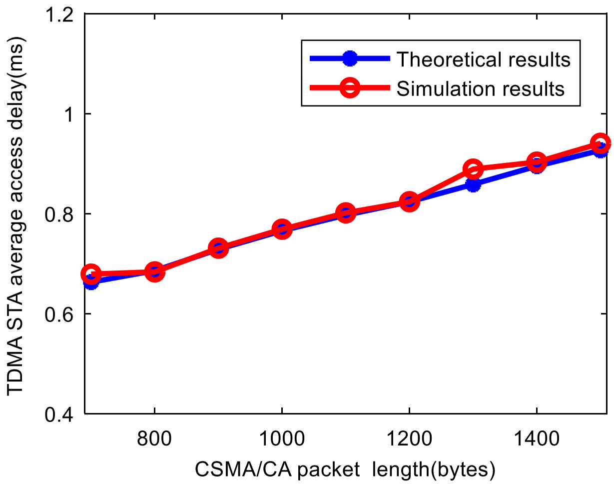


Fig. 7 The impact of the CSMA/CA frame length to the transmission times of the TDMA frame

analyzed in Sect. 5. It implies that the distribution of the remaining length of a CSMA/CA frame is uniform.

In Fig. 7, it shows that the retransmission times of a Wi-Fi TDMA frame increase with the increasing of the length of a CSMA/CA frame. It implies that the distribution of the CSMA/CA frame length impacts a lot on the transmission times of a Wi-Fi TDMA frame. The results in Fig. 8 have shown that the period of the Wi-Fi TDMA station hardly affects the transmission times of a Wi-Fi TDMA frame. The value of T_p has little impact on P_c even when the CSMA/CA stations are in the saturated state.

We show the times of successfully transmitting a Wi-Fi TDMA frame and the average access time (the duration between the time of the first bit is sent and the time the first bit is received) in Figs. 9 and 10, respectively. In the simulations, the length of a CSMA/CA frame is 800 bytes and the period of the Wi-Fi TDMA station is 4 ms.

In Fig. 9, it shows that the retransmission times of a Wi-Fi TDMA frame decrease when increasing the length of a Wi-Fi TDMA frame. The reason is that the difference

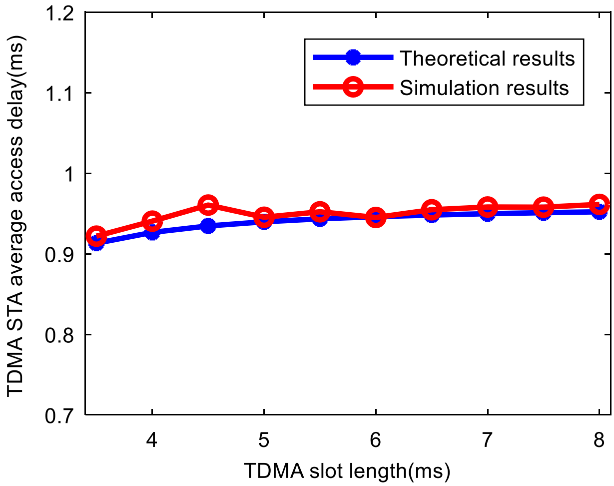


Fig. 8 The impact of the period of the TDMA station on the transmission times of the TDMA frame

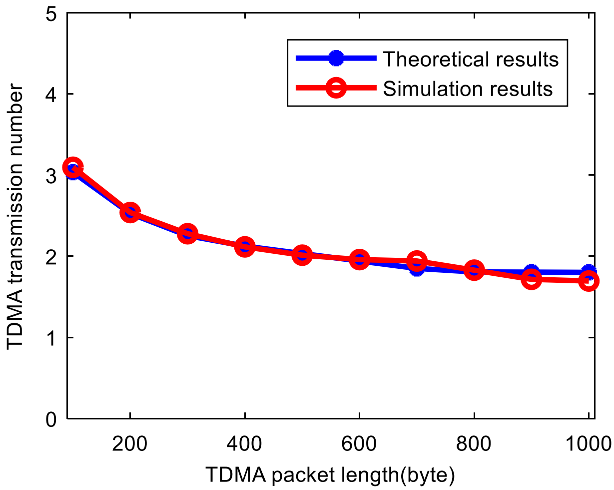


Fig. 9 The impact of the TDMA frame length on the transmit times of the TDMA frame

between the length of the Wi-Fi TDMA frame and the length of the CSMA/CA frame becomes smaller when increasing the length of the Wi-Fi TDMA frame.

Although the transmit times of a Wi-Fi TDMA frame decreases when increasing the length of a Wi-Fi TDMA frame, it shows that the average access time of a Wi-Fi TDMA frame increases with the increasing of frame length in Fig. 10. The reason is that the transmission time of a Wi-Fi TDMA frame is equal to the average transmit time multiplying with the value of T_t. When increasing the length of a Wi-Fi TDMA frame, the transmit time increases which results in the increasing of the average access time.

The differences between the values estimated by the proposed theoretical model and the simulation results are no greater than 6%. It has verified the correctness of the proposed theoretical analysis models.

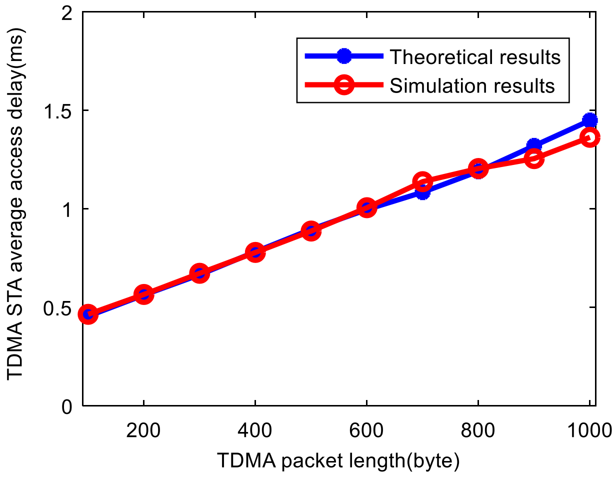


Fig. 10 The impact of the length of a TDMA frame on the access time of a TDMA frame

6.2 Performance Evaluation of the Throughput of the CSMA/CA Station

6.2.1 The Impact of the Interference from the TDMA Station

In the following, we have done numerous simulations to observe the interference. The setting of the main parameters is given in Table 1. The simulation topology is shown in Fig. 11. In the topology, there are one CSMA/CA station and one CSMA/CA AP. The CSMA/CA station are in the saturated state. The length of a CSMA/CA frame is 1500 Bytes, and the length of a Wi-Fi TDMA frame is 330 Bytes.

We run the simulations in two scenarios. In the first scenario, the Wi-Fi TDMA stations do not send packets. In the second scenario, the Wi-Fi TDMA stations send packets periodically. In Figs. 12 and 13, we vary the Wi-Fi TDMA frame duration and the periods of the Wi-Fi TDMA stations to control the interference and observe their impacts on the throughput of the CSMA/CA station.

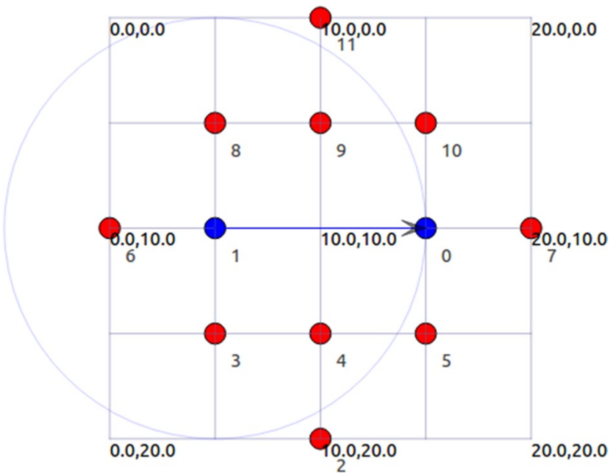


Fig. 11 Simulation topology

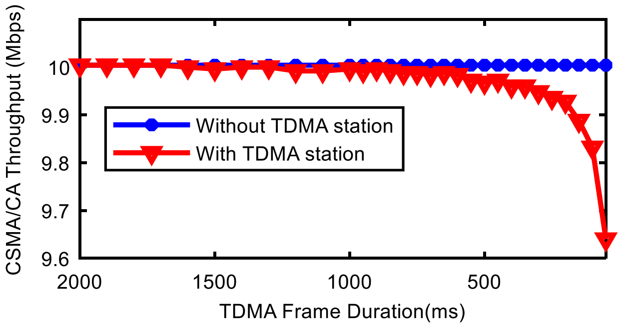
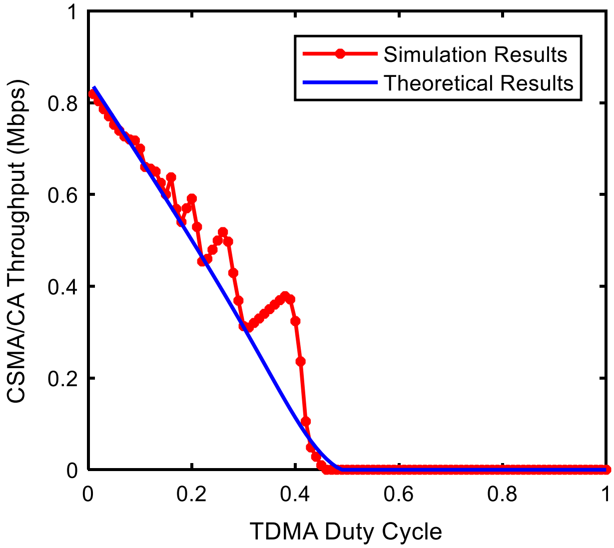


Fig. 12 Vassry the frame duration of the TDMA station

Fig. 13 CSMA/CA throughput when the length of the CSMA/CA frame is set to be 1500 Bytes



In Fig. 12, the impact of the Wi-Fi TMDA stations on the CSMA/CA station is very small when the duration of the Wi-Fi TDMA frame is larger than 500 ms. With the decreasing of the duration, the duty cycle increases. The impact on the CSMA/CA station becomes severer and results in the decreasing of the throughput.

In the following, we set the length of the TDMA frame to be 1250 Bytes (turning point in Fig. 12) and vary the duty cycle of the Wi-Fi TDMA station.

The results in Fig. 13 verified the correctness of the theoretical analysis model. The CSMA/CA throughput fluctuates when increasing the Wi-Fi TDMA duty cycle. The main reason is that: if the Wi-Fi TDMA duty cycle leads to the synchronization of the Wi-Fi TDMA slot and the CSMA/CA backoff stage, the CSMA/CA throughput will be low. Otherwise, the CSMA/CA station will have a higher throughput.

To observe the impact of the length of CSMA/CA frame on the throughput of the CSMA/CA station, we further set the length of the CSMA/CA frame to be 1250 Bytes. The comparison of the theoretical analysis and the simulation results are shown in

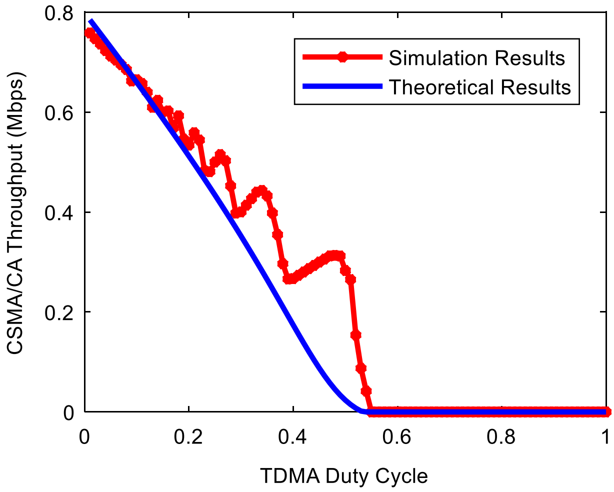


Fig. 14 CSMA/CA throughput when the length of the CSMA/CA frame is set to be 1250 Bytes

Fig. 14. The results in Fig. 14 are almost the same with those in Fig. 13. The differences are the duty cycles which results in zero CSMA/CA throughput.

From both the Figs. 13 and 14, the throughput of the CSMA/CA station decreases nearly 50% when the duty cycle of the Wi-Fi TDMA station reaches to 20%. With the increasing of the duty cycle of the Wi-Fi TDMA station, the throughput of the CSMA/CA station decreases fast. When the duty cycle of the Wi-Fi TDMA station is no greater than 10%, the throughput of the CSMA/CA station is nearly greater than 80% of the throughput without the interference of the Wi-Fi TDMA station.

6.2.2 The impact of Wi-Fi TDMA slot distribution on the CSMA/CA throughput

The slots assigned to the Wi-Fi TDMA stations could be in two ways. In Fig. 3, the slots distribute uniformly. In Fig. 15, it shows the centralized distribution way. Under these two different ways, the performances of the CSMA/CA station are different. In the following, we evaluate the throughput and delay of the CSMA/CA station.

In the simulations, we set the length of the Wi-Fi TDMA frame to be 330 Bytes and the length of the CSMA/CA station to be 1000 Bytes.

The throughput of the CSMA/CA station is shown in Fig. 16.

It shows that the throughput of the CSMA/CA station decreases generally with the increasing of the Wi-Fi TDMA duty cycle. When the Wi-Fi TDMA slots distribute uniformly, the CSMA/CA throughput decreases much faster, and the throughput fluctuates when increasing the Wi-Fi TDMA duty cycle. In the centralized distribution way, the CSMA/CA station obtains a much longer continuous duration to transmit packets. During

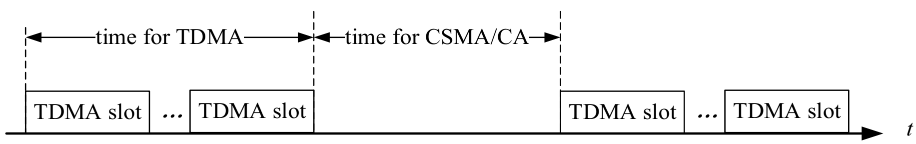


Fig. 15 The slots distribute in a centralized way

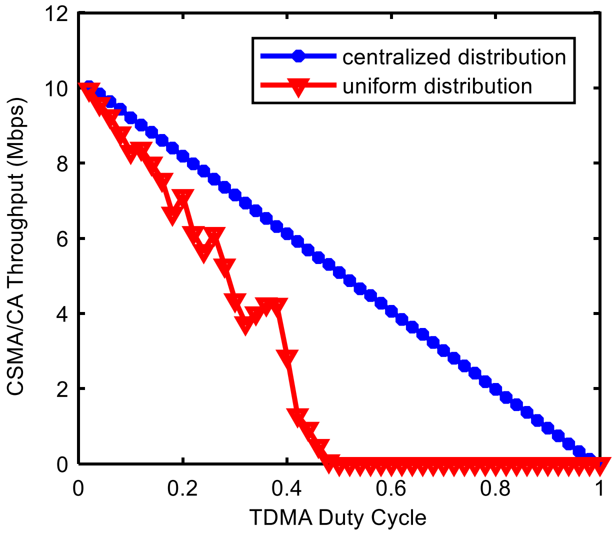


Fig. 16 The impacts of the TDMA slot distribution on the CSMA/CA throughput

the duration, there is no interference from the Wi-Fi TDMA stations. In the distributed way, the CSMA/CA station will fail to transmit a packet if the obtained duration is not large enough to transmit a packet. However, in the centralized way, the gathering of many short duration will provide a chance to successfully transmit a CSMA/CA frame. Hence, the centralized distribution of the Wi-Fi TDMA slots is better than the distributed way in terms of the CSMA/CA throughput and the stability of the throughput.

In Fig. 17, it shows the delay of the CSMA/CA station when increasing the duty cycle of the Wi-Fi TDMA frame. The delay of the CSMA/CA station is the duration between the time of the frame completely accepted by the destination and the time the frame enters the buffer of the sender in the MAC layer. The delay of the CSMA/CA station is shown in Fig. 17.

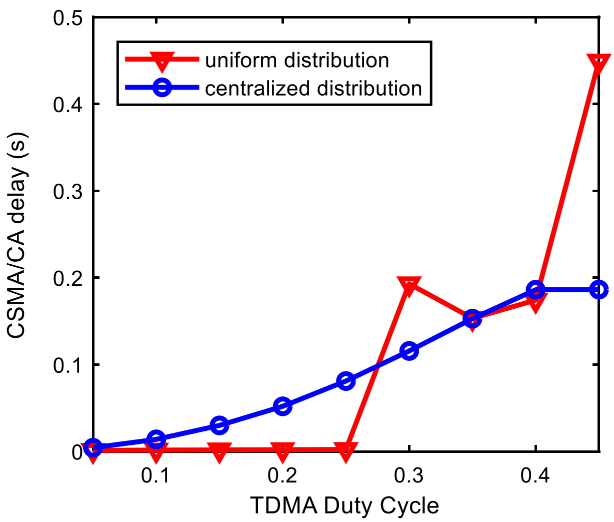


Fig. 17 The impacts of the Wi-Fi TDMA slot distribution on the CSMA/CA delay

In Fig. 17, it shows that the CSMA/CA delays under the two slot distribution ways are almost the same when the duty cycle of the Wi-Fi TDMA frame is no greater than 10%. With the increasing of the duty cycle, the sending of a CSMA/CA frame will be interrupted by many Wi-Fi TDMA slots. It will result in a much larger delay. However, in the uniform distribution method, the CSMA/CA frame waits at most one Wi-Fi TDMA slot. Hence, the delay of the CSMA/CA frame does not vary too much. However, if we keep increasing the duty cycle of the Wi-Fi TDMA station, the CSMA/CA frame will be interfered more frequently by the Wi-Fi TDMA frames since the CSMA/CA slot is very small. It will further result in the fast increasing of the CSMA/CA delay, and the delay may even be larger than that of the centralized slot distribution way. Under the situation where the distributed CSMA/CA slot is not large enough to transmit a CSMA/CA frame, the delay of the CSMA/CA station will increase infinitely.

According to the above results and analysis, the centralized distribution way has a smaller impact on the CSMA/CA station, which guarantees a much better performance for the coexistence of heterogeneous networks. However, the centralized slot distribution way may not meet the transmission period of the Wi-Fi TDMA station, and further results in longer delay of the Wi-Fi TDMA station.

7 Conclusion

We have proposed an efficient Wi-Fi based TDMA scheme for scenarios with stations working on different media access schemes. We have also proposed the theoretical analysis models to evaluate the delay of the Wi-Fi TDMA stations and the throughput of the typical CSMA/CA stations. Numerous simulation and theoretical results have demonstrated the effectiveness of the Wi-Fi TDMA scheme and the accuracy of the analysis models.

Acknowledgements This work was supported by the China Postdoctoral Science Foundation under Grant 2017M612503.

References

1. Song J., Han S., Mok, A. K. M., Chen D., Lucas M., Nixon M., & Pratt W. (2008) WirelessHART: Applying wireless technology in real-time industrial process control. In *IEEE real time and embedded technology and applications symposium* (pp. 377–386).
2. Zhang, W., Wei, Y. H., Leng, Q., & Han, S. (2014). A high-speed, real-time mobile gait rehabilitation system. *Xrds Crossroads the Acm Magazine for Students, 20*(3), 46–51.
3. Tramarin, Federico, Mok, Aloysius K., & Han, Song. (2019). Real-time and reliable industrial control over wireless LANs: Algorithms protocols and future directions. *Proceedings of the IEEE, 107*(6), 1027–1052.
4. Koutsiamanis, R., Papadopoulos, G. Z., Fafoutis, X., Fiore, J. M. D., Thubert, P., & Montavont, N. (2018). From best effort to deterministic packet delivery for wireless industrial IoT networks. *IEEE Transactions on Industrial Informatics, 14*(10), 4468–4480.
5. Wei, Y., Leng, Q., Chen, W., Mok, A. K., & Han, S. (2018). Schedule adaptation for ensuring reliability in RT-WiFi-based networked embedded systems. *ACM Transactions on Embedded Computing Systems, 17*(5), 1–23.
6. Xu, J., Guo, C., Zhang, H., & Yang, J. (2018). Resource allocation for real-time traffic in unreliable wireless cellular networks. *Wireless Networks, 24*(5), 1405–1418.
7. ISA100 Committee (2011). ISA-100.11a-2011 Wireless systems for industrial automation: Process control and related applications.
8. http://www.wia.org.cn/.

9. Branz F., Pezzutto M., Antonello R, Tramarin F., & Schenato L. (2019). Drive-by-Wi-Fi: Testing 1 kHz control experiments over wireless. In *2019 18th European control conference (ECC)*, Naples, Italy (pp. 2990–2995).
10. Rao A., & Stoica I. (2005). An overlay MAC layer for 802.11 networks. In: *Proceedings of the 3rd international conference on Mobile systems, applications, and services* (pp. 135–148).
11. Leffler S. (2009). TDMA for long distance wireless networks. In *Computer laboratory seminar,* University of Cambridge (pp. 1–10).
12. Dhekne A., Uchat N., Raman, B. (2009). Implementation and evaluation of a TDMA MAC for WiFi-based rural mesh networks. In: The 3rd ACM workshop on networked systems for developing regions (pp. 1–6).
13. Sevani V., Raman B., & Piyush J. (2014). Implementation-based evaluation of a full-fledged multihop TDMA-MAC for WiFi Mesh networks. In: *IEEE transactions on mobile computing* (Vol. 13, No. 2, pp. 392–406).
14. Hussain, I., Sarma, N., & Saikia, D. K. (2014). TDMA MAC protocols for WiFi-based long distance networks: a survey. *International Journal of Computer Applications, 94*(19), 1–8.
15. Jin, X., Kong, F., Kong, L., Liu, W., & Zeng, P. (2017). Reliability and temporality optimization for multiple coexisting wireless HART networks in industrial environments. *IEEE Transactions on Industrial Electronics, 64*(8), 6591–6602.
16. Yang, D., Xu, Y., & Gidlund, M. (2011). Wireless coexistence between IEEE 802.11- and IEEE 802.15.4-based networks: A survey. *International Journal of Distributed Sensor Networks, 3,* 876–879.
17. Bartolomeu, P., Alam, M., Ferreira, J., & Fonseca, J. (2016). Survey on low power real-time wireless MAC protocols. *Journal of Network and Computer Applications, 75,* 293–316.
18. Kim, J., Jeon, W., Park, K., & Choi, J. P. (2018). Coexistence of full-duplex-based IEEE 802.15.4 and IEEE 802.11. *IEEE Transactions on Industrial Informatics, 14*(12), 5389–5399.
19. Sahoo, P., Pattanaik, S., & Wu, S. (2017). A reliable data transmission model for IEEE 802.15.4e enabled wireless sensor network under WiFi interference. *Sensors, 17,* 1320.
20. Chiasserini, C., & Rao, R. R. (2003). Coexistence mechanisms for interference mitigation in the 2.4-GHz ISM band. *IEEE Transactions on Wireless Communications, 2*(5), 964–975.
21. Zhang X., & Shin K. G. (2010). Enabling coexistence of heterogeneous wireless systems: Case for ZigBee and WiFi. In *MOBIHOC* (pp. 1–11).
22. Guo P., Cao J., Zhang K., & Liu X. (2014). Enhancing ZigBee throughput under WiFi interference using real-time adaptive coding. In *IEEE INFOCOM* (pp. 2858–2866).
23. Lee T. H., Hsieh M. C., Chang L. H., Chiang H. S., Wen C. H., & Yap K. M. (2014). Avoiding collisions between IEEE 802.11 and IEEE 802.15.4 using coexistence inter-frame space. In *Lecture notes in electrical engineering* (vol. 260, pp. 1185–1193).
24. Bhandari, S., & Moh, S. (2016). A priority-based adaptive MAC protocol for wireless body area networks. *Sensors, 16*(3), 401–416.
25. Guan Z., & Melodia T. (2016). CU-LTE: Spectrally-efficient and fair coexistence between LTE and Wi-Fi in unlicensed bands. In *IEEE INFOCOM* (pp. 1–9).
26. Yun S., Qiu L. (2015). Supporting WiFi and LTE co-existence. In *IEEE INFOCOM* (pp. 810–818).
27. Almeida E., Cavalcante A. M., Paiva R., Chaves F., Abinader F., Vieira R., Choudhury S., Tuomaala E., & Doppler K. (2013). Enabling LTE/WiFi coexistence by LTE blank subframe allocation. In *IEEE ICC* (pp. 5083–5088).
28. Xu Z., Wu Z., Chen F., & Gong Y. (2017). Analyzing the WiFi access probability in LTE-U/WiFi coexistence networks. In *IEEE Globecom workshops (GC Wkshps)*, Singapore (pp. 1–5).
29. Alabdel Abass A. A., Kumbhkar R., Mandayam N. B., & Gajic Z. (2019). WiFi/LTE-U Coexistence: An Evolutionary Game Approach. In *IEEE transactions on cognitive communications and networking* (vol. 5, no. 1, pp. 44–58).
30. Rezha, F. P., & Shin, S. Y. (2014). Performance analysis of ISA100.11a under interference from an IEEE 802.11b wireless network. *IEEE Transactions on Industrial Informatics, 10*(2), 919–927.
31. Wei Y. (2016). Real-time communication platform for wireless cyber-physical applications. *The University of Texas at Austin*.
32. Bianchi, G. (2000). Performance analysis of the IEEE802.11 distributed coordination function. *IEEE Journal on Selected Areas in Communications, 18*(3), 535–547.
33. Yazid, M., Ksentini, A., Bouallouche-Medjkoune, L., & Aïssani, D. (2014). Performance Analysis of the TXOP sharing mechanism in the VHT IEEE 802.11 ac WLANs. *IEEE Communications Letters, 18*(9), 1599–1602.
34. Hu, Z., Wen, X., Li, Z., Lu, Z., & Jing, W. (2015). Modeling the TXOP sharing mechanism of IEEE 802.11 ac enhanced distributed channel access in non-saturated conditions. *IEEE Communications Letters, 19*(9), 1576–1579.

35. Guglielmo D., Anastasi G., & Conti M. (2014). A localized slot allocation algorithm for wireless sensor network. In *12th annual mediterranean ad hoc networking workshop (MED-HOC-NET)* (pp. 89–96).
36. Liu, J., Dai, H., & Chen, W. (2015). On throughput maximization of time division multiple access with energy harvesting users. *IEEE Transactions on Vehicular Technology, 65*(4), 2457–2470.
37. Yang H., & Sikdar B. (2007). Performance analysis of polling based TDMA MAC protocols with sleep and wakeup cycles. In *ICC* (pp. 241–246).
38. Khader O., Willig A., & Wolisz A. (2010). Wireless HART TDMA protocol performance evaluation using response surface methodology. In *International conference on broadband and wireless computing, communication and applications (BWCCA)* (pp. 197–206).

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