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Exploring Carrier Sense Multiple Access with Collision Avoidance Techniques for Resource Sharing in Broadband Power Line Communications

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Abstract

A resource sharing in power line communications (PLC) for the home network is restricted by the channel assignment techniques which decide who has the right to gain access to send data. The channel assignment techniques include contention-free and contention-based. The former requires high synchronization due to the deterministic round-trip time. Besides, contention-based utilizes CSMA/CA techniques that allow stations in a network to compete for channel access and are suitable for decentralized network topology. However, a trade-off exists between the number of stations required to gain access versus system efficiency. Whilst some research has been carried out on CSMA/CA resource sharing techniques that allow only one user to transmit, there is very little work done on multiuser access to optimize system efficiency and reduce collisions in a network. The purpose of the current study was to review the CSMA/CA techniques for resource sharing to improve system efficiency in power line communications. In carrying out this study, a systematic literature review methodology to evaluate different related works and determine the most suitable approach to allow multiuser channel access was used. The study further demonstrated the impact multichannel access has on system efficiency. In addition, the study provides recommendations for future research.

Keywords: CSMA/CA, Medium access control, OFDMA, power line, resource sharing.

Introduction

Power line communication (PLC) is one of the promising technologies which make use of the existing electrical wiring to enable data transmission for the in-home and enterprise (Cano and Malone 2014a). However, since PLC is a shared transmission medium, it is subject to various factors which may degrade performance such as the distance between communicating stations, impedance mismatch at the junctions, impulse noises, frequency selectivity, and time-varying nature (Yoon et al. 2013). Of particular concern here is that when the number of stations vying to use the shared transmission medium increases, there exists a trade-off in the efficiency of the system.

Recent studies by Chen et al. (2019) and Hao and Zhang (2020) have shown an increased interest in medium access control techniques for the IEEE 1901 and HPAV standards to accommodate data communication and smart grid applications for broadband power line communication (BPLC). However, one of the major challenges of medium access control techniques is the inefficient use of transmission medium resources. Since PLC utilizes a contention-based random-access method such as carrier sense multiple access with collision avoidance (CSMA/CA) for the

BPLC, this challenge is attributed to the compromise between the number of stations vying for channel access and the performance in terms of system efficiency or system throughput. Whilst some research has been carried out on the CSMA/CA techniques, there are limited studies on multiuser access to improve the performance of the system. Therefore, a comparative analysis of the CSMA/CA techniques for the MAC layer is required to enhance the performance of power line communications in a dense network. In this research, a systematic review methodology was adopted to scrutinize different works for resource sharing using CSMA/CA techniques for performance improvement in power line communications. Explicitly, the research 1) analyses related works on the CSMA/CA techniques for MAC layer, performance metrics, and the constraints; and 2) presents recommendations for future research.

Overview of Power Line Communication Technology

Power line communications (PLC) technology grew momentarily after the pervasive establishment of the electrical power supply distribution network and is considered one of the promising means of transferring data for home networks (Alaya and Attia 2019). The PLC operates at a carrier frequency of medium voltage (MV), low voltage (LV), and indoor voltage (IV) (Rusz et al. 2021). The low voltage (400/230V) is a three-phase transmission system that is used as the last-mile connectivity at the consumer premises (Berger 2013). Figure 1 depicts the power line technology. The power line technologies operate in two frequency bands, namely narrowband PLC (NB-PLC), with a frequency below 500 kHz, and broadband PLC (BPLC), with a frequency above 1.8 MHz. The BPLC has a much shorter range and finds its application in high-speed data transmission or last-mile connectivity.

However, power line channel has several challenges which have brought interest to the research community including frequency selective characteristics (Kale and Patra 2015), cancellation of impulse noise (Himeur and Boukabou 2017), bit error rate, channel estimation, impulse noise mitigation (Chien 2015) and medium access control (Prasad et al. 2018, De Oliveira et al. 2018). This research explores the contention-based random access CSMA/CA techniques that influence how efficiently stations transmit in a shared transmission medium to enhance the performance of the BPLC system.

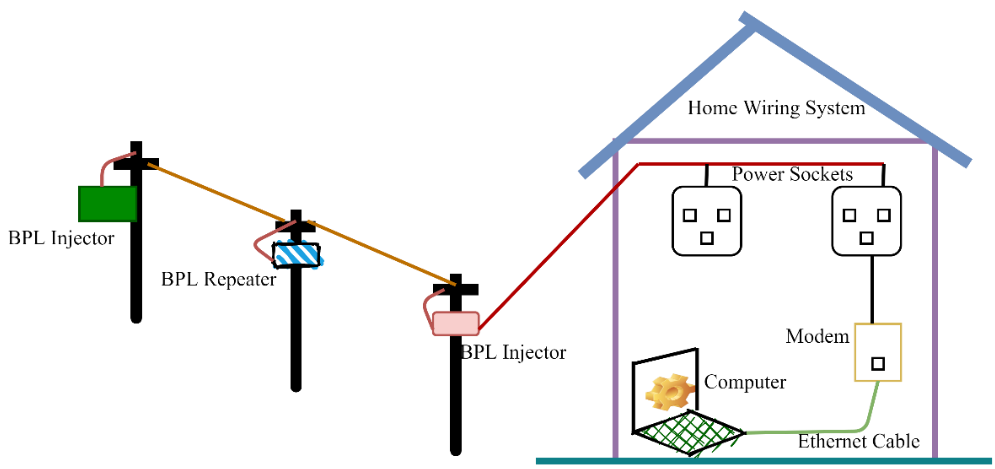

Figure 1: Power line communication technology.

The CSMA/CA techniques for power line communications

The PLC CSMA/CA technique comprises two main parts, a random backoff resolution component, and a priority resolution section. The backoff resolution is analogous to the IEEE 802.11 CSMA/CA with the only difference being the introduction of two new counters, a deferral counter (DC) and a backoff procedure counter (BPC). The CSMA/CA technique allows several stations in a network to access a shared transmission medium or a channel employing priority resolution or contention window adaptation methodology (Lin et al. 2015, Ayar and Latchman 2016). Before gaining access to the transmission medium, a station with a packet to send listens to the state of the channel and if the channel is busy, it defers its transmission. As illustrated in Figure 2, before entering a contention period, a station allocates each packet a priority tag. All packets with high priority will first utilize the channel and if it happens more than one packet is allocated high priority, enters a contention period, and perform a random backoff procedure.

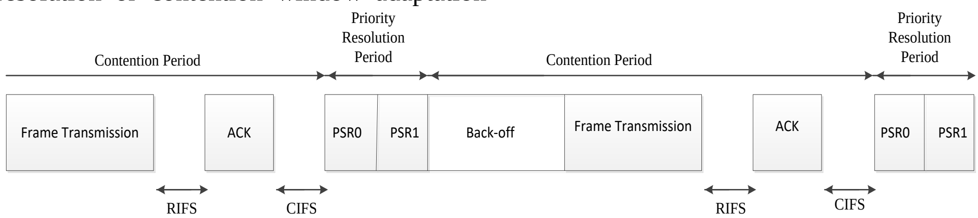

Figure 2: Channel contention sequence of events in Home Plug.

The contention-based protocol is appropriate for data communication networks in which only users with data to transmit are involved in channel contention which reduces collision by using random backoff procedures. Figure 2 defines the total successful transmission time in the contention period and the total collision time during packet transmission as follows:

$$T_s = \text{PRS0} + \text{PRS1} + T_{frame} + \text{RIFS} + \text{ACK} + \text{CIFS} \quad (1)$$

$$T_c = \text{PRS0} + \text{PRS1} + T_{frame} + \text{CIFS} \quad (2)$$

Where T_s and T_c are the total successful transmission time and total collision time, respectively; RIFS is the response interframe spacing, CIFS is the contention interframe spacing, and PRS0, PRS1 is the priority resolution times. We can further define P_b to represent the probability that a slot is sensed busy, given by

$$P_b = 1- (1-\tau)^n \quad (3)$$

Again, τ is the probability that a station transmits in each time slot, and n is the number of stations in a network.

Multiuser channel access

To capitalize on multiuser resource allocation, the CSMA/CA technique is combined with the Orthogonal Frequency Division Multiple Access (OFDMA) system (Yoon et al. 2013). The main concern is that the allocation of the station to a subchannel is based on the one with the best Signal-to-Noise Ratio (SINR). Meanwhile, the power line is a frequency selective channel, which means that a station is assigned to a subchannel with constructive rather than destructive interference. Moreover, the work on multiuser access by Deng et al. (2019) proposed random massive access for smart grid applications whereby a novel Carrier Sense Multiple Access/Non-Orthogonal Multiple Access (CSMA-NOMA) methods were proposed. The scheme allows more than one user to gain access to the same time slot and frequency band which showed an improved reduction in collision rate. The adaptive modulation is the reason behind the use of OFDMA towards the achievement of frequency diversity known explicitly as multiuser diversity.

Materials and Methods

In this study, a systematic literature review method was implemented on studies related to the CSMA/CA techniques for power line communications. To identify the previously published articles on the topic under this study, the following databases and libraries were used during the search: Google Scholar, Scopus, Web of Science, IEEE Xplore, ACM, and ScienceDirect. The criteria for selecting the subjects were the keywords: MAC method for PLC, power line communications, the performance of CSMA/CA for PLC, broadband PLC, OFDMA and CSMA/CA-based BPLC. During the search, two hundred and fifty-three (253) published articles were obtained. At the screening stage, primary inclusion criteria were set for obtaining the relevant published works where the article should be based on MAC layer protocol for power line communication, adaptive layer switching, broadband PLC, the performance of CSMA/CA method for PLC and CSMA/CA and OFDMA based methods. Thereafter, 192 papers were removed from the list. The remaining 61 articles were assessed for eligibility and 36 papers were again removed to remain with 25 papers. A comprehensive analysis was performed for the 25 articles based on the performance metric and the significance of the results. Lastly, 18 articles were included for in-depth analysis of different channel access methods for power line communications. Figure 3 indicates the systematic review methodology used in this study.

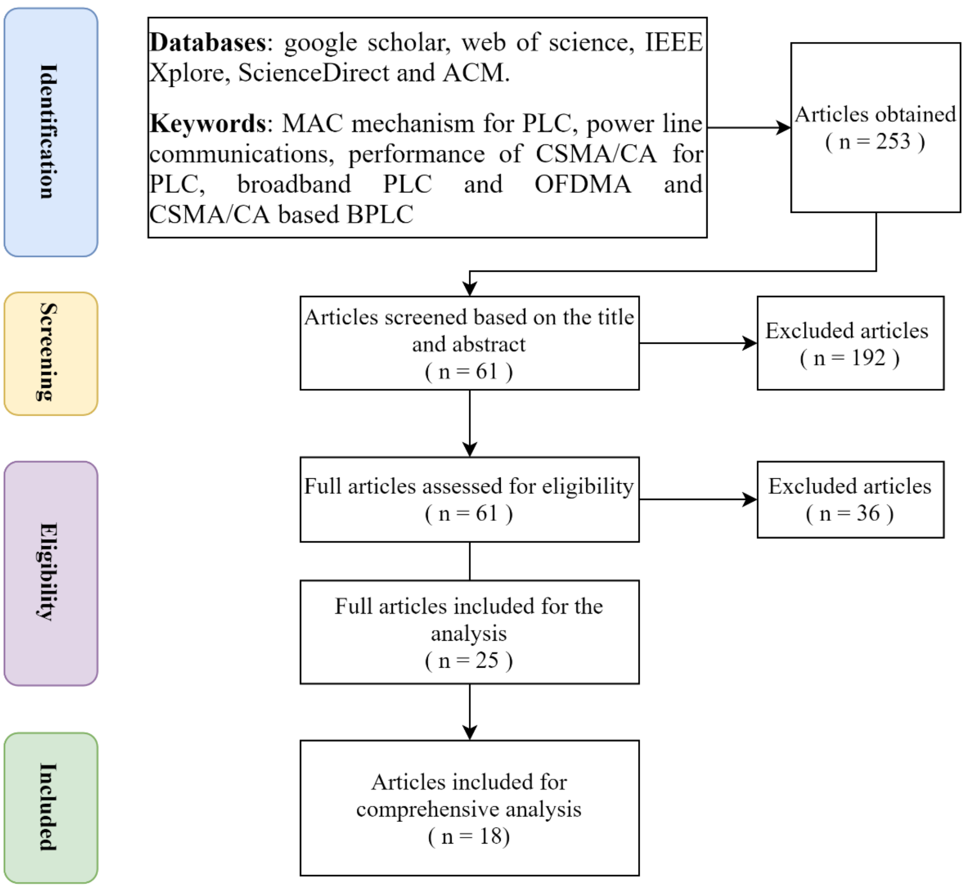

Figure 3: Flow chart of systematic review methodology.

Related Works in Medium Access Control for PLC

Up to now, several studies have paid attention to the study of CSMA/CA techniques for resource sharing in power line communications. To utilize the shared medium efficiently, Chung et al. (2006) proposed an analytical model of the HomePlug MAC with CSMA/CA techniques to evaluate the performance under single channel access. The results showed variations in both throughput and delay when the number of stations increases. While Kwon et al. (2009) presented multichannel CSMA/CA for OFDMA to allow multiuser access. To capitalize on multiuser access, Dong et al. (2012) proposed an opportunistic random-access scheme using OFDMA where the channel is divided into subchannels which resulted in improved throughput and reduced collision. Moreover, the research by Liu et al. (2012) proposed adaptive contention window and data rate to improve system throughput, while the work by Vlachou et al. (2013) evaluated the fairness of among the stations gaining access to the shared medium using sliding window techniques. To improve channel access, Yoon et al. (2013) combined CSMA/CA for OFDMA techniques to improve multiuser diversity and system throughput using optimal and heuristic approaches. Moreover, Ashrafuzzaman and Fapojuwo (2014) considered the aspect of packet service time using the stochastic analytical model of CSMA/CA to analyze throughput in consideration of low data rate. The results showed that there exists strong enforcement to eliminate access discrimination in a mixed packet priority environment. However, Cano and Malone (2014b) indicated the imbalance between high priority and low priority traffic conditions as the low priority always suffers under high priority traffic conditions. Research on adaptation by Pinero-Escuer et al. (2014) proposed a cross-layer extension of the HPAV CSMA/CA method. The study focused on enhancing QoS requirements by exploiting the layers above and below to adjust the contention window size of the competing stations. The results showed that the algorithm performs better than the standard CSMA/CA method. On the other hand, Vlachou et al. (2014) put forward an analytical model to evaluate CSMA/CA techniques using a deferral counter and the performance trade-off between throughput and delay was discovered. Lin et al. (2015) proposed a contention window adaptation method that utilizes CSMA/CA parameters to generate suitable CW under the actual network situation and the results showed an improved system throughput. Recent works by Vlachou et al. (2016a) and Vlachou et al. (2016b) examined the performance of the 1901 MAC protocol in steady-state and transient environments. The results showed that the decoupling assumption is not suitable due to the coupling induced by stations.

The work by Mudriievskyi and Lehnert (2017) proposed an adaptive layer switching to reduce delay-throughput trade-off through switching between CSMA/CA and TDMA during runtime. While Ayar and Latchman (2016) studied adaptive contention window protocol to evaluate access delay and system throughput by allowing each station to adaptively find its optimal CW. In Huo et al. (2017), the author proposed a cluster and probability MAC method to eliminate channel contention by introducing probability competition to decide on station channel access. The results indicated that the scheme reduces collision among nodes and thus enhances system efficiency. Research by Ferreira et al. (2018) applied aggregation with fragment retransmission (AFR) method to analyze the control layer based on the CSMA/CA protocol. The results showed that a proper analysis of the size of the contention window under the number of competing stations and channel bandwidth has a positive effect on the MAC efficiency, throughput, and delay. The most recent work on multiuser access by Deng et al. (2019) proposed random massive access for smart grid applications whereby a novel Carrier Sense Multiple Access/Non-Orthogonal Multiple Access (CSMA-NOMA) methods were examined. The results showed that the system throughput was improved due to the decrease in collision rate in multiuser access.

However, this method comes with more computational complexities due to successive interference cancellation processes. The work by Xu et al. (2021) proposed successive interference cancellation using a multi-contention queue that reduces wasted time due to channel contention in CSMA/CA. The performance of OFDMA-based CSMA/CA techniques for multiuser access was presented by Dube and Walingo (2020) and the results showed better throughput and delay in lossy communication links.

Table 1 provides a comparative analysis of the previous works that focused on the contention-based channel assignment strategy with CSMA/CA techniques to evaluate the performance of power line communications. As indicated in the table, different studies on CSMA/CA techniques show the trends in the methodological approaches to improve channel access in PLC.

Table 1: Analysis of literature based on the CSMA/CA techniques for PLC

SN	***Study***	***Mathematical tool***	***Channel assignment***	***MAC scheme***	***Methodology***	***Performance metrics***
1	Xu et al. (2021)		Multi-CQ	CSMA/CA	Successive-Interference-Aware Design	Throughput
2	Deng et al. (2019)	Markov chain	Contention-based	CSMA/CA	Multiuser channel access scheme using CSMA/NOMA method	Throughput, delay
3	Ferreira et al. (2018)	Markov chain	Contention-based	CSMA/CA	Performance of CSMA/CA under Aggregation with Fragment Retransmission scheme	Throughput and delay
4	Huo et al. (2017)		Contention free, Contention-based	TDMA, CSMA/CA	Cluster and probability competition-based MAC scheme	Throughput, delay, packet loss rate
5	Ayar and Latchman (2016)	Markov chain	Contention-based	CSMA/CA	Adaptive contention window method with prioritized traffic classes	Throughput and delay
6	Mudriievskyi and Lehnert (2017)		Contention free, Contention-based	TDMA, CSMA/CA	Combined access schemes (CSMA/CA and TDMA) with adaptive layer switching	Throughput and delay
7	Vlachou et al. (2016a)	Renewal theory	Contention-based	CSMA/CA	Decoupling assumption method using renewal theory to find fixed-point-equation	Throughput and delay and fairness
8	Vlachou et al. (2016b)	Renewal theory & Control theory	Contention-based	CSMA/CA	Decoupling assumption method using renewal theory to find fixed-point-equation	Throughput
9	Lin et al. (2015)	Markov chain	Contention-based	CSMA/CA	Adaptive contention	Throughput

Table 1: Analysis of literature based on the CSMA/CA techniques for PLC

SN	***Study***	***Mathematical tool***	***Channel assignment***	***MAC scheme***	***Methodology***	***Performance metrics***
					window scheme	
10	(Vlachou et al. (2014)	Renewal theory	Contention-based	CSMA/CA	Modelling CSMA/CA process without decoupling assumption method	Throughput
11	Pinero-Escuer et al. (2014)	Markov chain	Contention-based	CSMA/CA	Contention window adaptation of the HPAV-CSMA/CA cross-layer extension	Delay
12	Cano and Malone (2014)	Renewal theory	Contention-based	CSMA/CA	Priority resolution scheme in CSMA/CA method	Throughput
13	Ashrafuzzaman and Fapojuwo (2014)	Markov renewal theoretic	Contention-based	CSMA/CA	A stochastic model for access differentiation method of CSMA/CA scheme	Throughput and delay
14	Yoon et al. (2013)	Utility maximization theory	Contention-based	CSMA/CA, OFDMA	Multichannel CSMA/CA method based on the OFDMA	Throughput
15	Vlachou et al. (2013)	Renewal theory	Contention-based	CSMA/CA	Sliding window method to express fairness of MAC protocol	Fairness
16	Liu et al. (2012)	Markov chain	Contention-based	CSMA/CA	Adaptive contention window and data rate method for MAC protocol	Throughput
17	Dong et al. (2012)		Contention-based	OFDMA	An opportunistic random-access scheme based on OFDMA to dynamically adjust adaptive backoff time	Throughput and delay
18	Chung et al. (2006)	Markov chain	Contention-based	CSMA/CA	Performance evaluation based on priority resolution and random backoff scheme	Throughput and delay

It is apparent from the analysis that many studies selected to use contention window and backoff adaptation method to optimize stations channel access (Pinero-Escuer et al. 2014, Ayar and Latchman 2016). This method allows stations to adaptively select new contention window which leads to an improved channel access probability and hence better throughput performance. There are only a few studies that explored multichannel access by utilizing the features of CSMA/CA and OFDMA to enable more users to access the medium (Yoon et al. 2013, Deng et al. 2019). Therefore, multiuser channel access using contention-based channel assignment is crucial when the number of stations in a network increase.

Results and Discussion

System efficiency in single channel access scenario

The system efficiency in single-channel access is affected by the number of stations vying for opportunities to transmit packets. Different methods have been proposed to improve the performance of power line communications at the MAC level. However, most of the methods focused on how adaptively the stations may access the shared transmission medium to enhance the system efficiency.

According to Ayar and Latchman (2016), the MAC protocol efficiency may be defined as follows:

$$\eta = \frac{P_s E[N_{payload}]}{P_{idle}T_{idle}+P_sT_s+P_cT_c} \quad (4)$$

Whereas P_{idle} is the probability that at a given channel is free, Ps is a probability that a station successfully transmits a frame and T_c is the probability of collision, T_s is a time needed for successful transmission of a frame, T_c is the elapsed time due to collision occurrence, T_{idle} is a duration of idle slot time, $E[N_{payload}]$ is the average payload size of a frame. Figure 4 illustrates the relationship between system efficiency and the number of stations. As shown in the figure, when the number of contending stations in a network was less than 20, the system efficiency was about 0.39 indicating the higher performance. However, when the number of stations is greater the 20, the system efficiency drops to a minimum which reveals that in a dense network condition, there exists performance degradation. The results confirm the limitation of single-channel access where the system efficiency of the power line communication is always maximized when the number of contending stations is less.

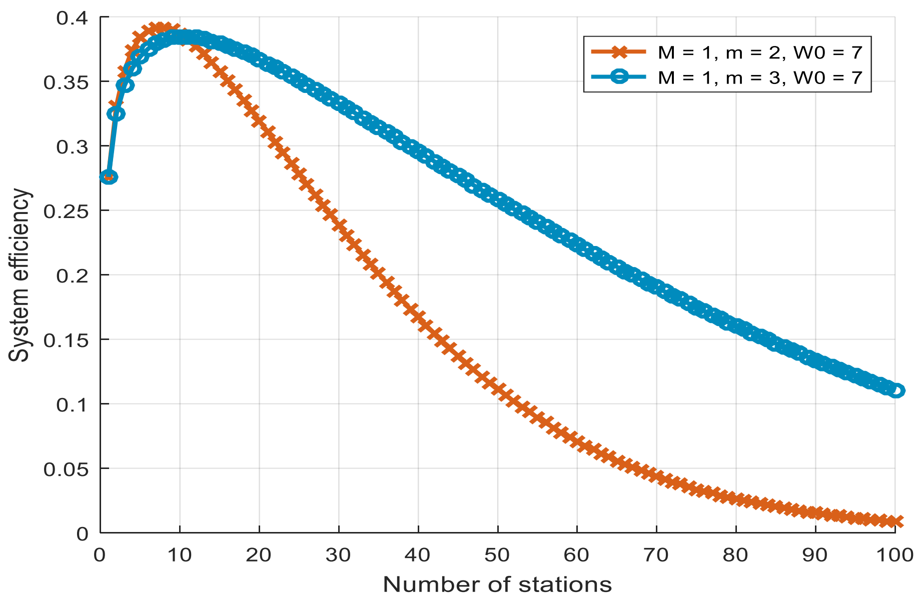

Figure 4: Relationship between system efficiency and number of stations.

Multichannel access method

Recent developments in intelligent home network devices have heightened the need for multichannel CSMA/CA for OFDMA-based access techniques to realize the usefulness of broadband power line communications (Yoon et al. 2013). The multichannel CSMA/CA method has the advantage to offer lower collision probability and high throughput even when the number of stations increases in a network. In Dong et al. (2012), the multiuser diversity in power line communications is examined. The utility function $U(.)$ was used by Yoon et al. (2013) to maximize throughput. To maximize the sum utility of the station, the author used an appropriate number of subchannels assigned to each station. Hence,

$$R_i = \sum_{j=1}^{M} I_{i,j}\, r_{i,j}\, \frac{S(N_j,M)}{N_j} \qquad (5)$$

where $r_{i,j}$ is the throughput of station i on subchannel j, and N_j represents the number of stations on subchannel j, and $N_j = \sum_{j=1}^{N} I_{i,j}$. Here the saturation throughput of the CSMA/CA protocol with n stations and m subchannels can be computed using the results in Chung et al. (2006), hence,

$$S(n,m) = \frac{P_{tr}(n)P_s(n)T_{(payload)}(m)}{(1-P_{tr}(n))\delta + P_{tr}(n)(P_s(n)T_s+(1-P_s(n))T_C)} \qquad (6)$$

where $P_{tr}(n)$ and $P_s(n)$ denote the probabilities that at least a station transmits and that a station successfully transmits in the case of n stations, respectively. While $T_{payload}(m)$, δ, T_c and T_s represent payload transmission time, idle slot, successful transmission, and collision time, respectively. Figure 5 shows the relationship between system efficiency and the number of stations in a multichannel scenario. As illustrated in the figure, when M = 1 and W0 = 7, the system operates under single channel access and the system efficiency was 39% when the number of competing stations in a network is less than 10. Nevertheless, as the number of stations increased from 15 to 100, the system efficiency dropped to 1% due to collisions in a single channel access scenario and the improvement is 20 times when compared with a single channel for 100 users. The size of the contention window in multichannel access affects the system efficiency when the number of stations is less than 20. This is because some of the subchannels may be free which leads to wasted resources and directly reduces the system efficiency. For instance, in Figure 5, the system efficiency is maintained at close to 23% regardless of the number of contending stations.

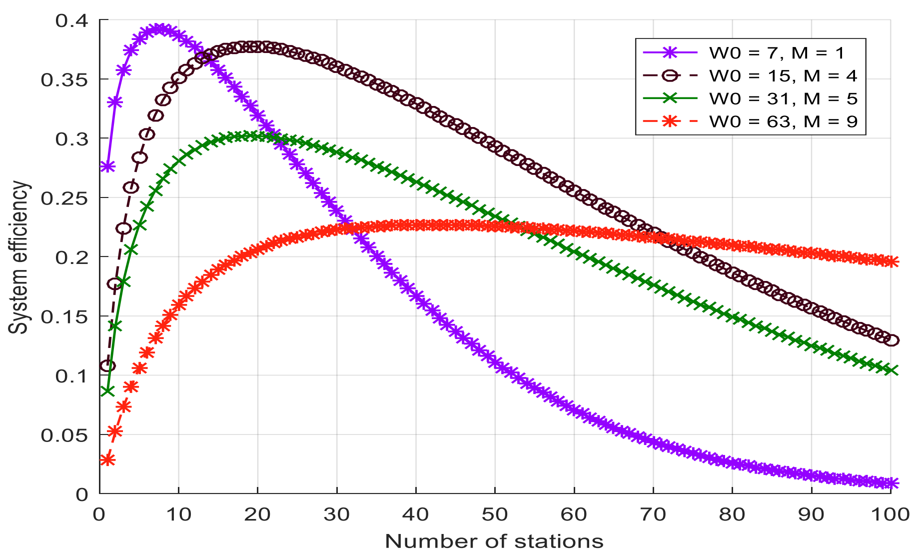

Figure 5: Relationship between system efficiency and the number of stations.

Conclusion

The purpose of the current study was to review the CSMA/CA approaches for resource sharing in power line communications. Also, the study explored the impact of the CSMA/CA techniques on the system efficiency for PLC. The performance of both single-channel and multichannel access methods at the MAC layer was studied for comparative analysis. A systematic review approach was adopted in this study to analyze various CSMA/CA techniques and performance results under different scenarios. Additionally, 18 studies were chosen to further analyze the system efficiency, delay, and other performance metrics against the number of contending stations in a network. Analysis of the results presented in MATLAB demonstrated that the performance of the system under the single-channel access technique decreases the system efficiency (system throughput) when the number of contending stations increases. The results of the present study also show that the channel or bandwidth is a scarce resource that requires proper techniques to optimize the performance of the system. It was also shown that there has been a limited number of studies that considered multichannel access approaches towards optimizing this scarce resource, especially under heavy loads. Moreover, the results of this study indicate that when the number of competing stations increases greatly reduces the system efficiency. It was also shown that, under the multichannel scenario, the system efficiency is improved even when the number of stations increases due to the availability of resources. However, the fewer number of stations in the multichannel scenario leads to wastage of resources which has an impact on reducing the system efficiency. Further research might explore the mechanisms to improve resource utilization with low network loads in the multichannel scenario.

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