IOSR Journal of Computer Engineering (IOSR-JCE)
e-ISSN: 2278-0661,p-ISSN: 2278-8727, Volume 20, Issue 2, Ver. II (Mar. - Apr. 2018), PP 01-09
www.iosrjournals.org

A Low-Delay MAC Protocol for QoS VLC Networks

Abdullah Baz
IEEE senior member
Computer Engineering Department, College of Computer and Information Systems, Umm Al-Qura University, Saudi Arabia
Corresponding Author: Abdullah Baz

Abstract–*The Visible Lighting Communication (VLC) forms on of the enabling technology for modern and envision communication systems. Although VLC has received lots of attention from standard bodies and industrial committees to standardize its operations, most of these efforts overlooked the issues relating to Quality of Service (QoS). This paper considers such needs and introduces a novel mathematical framework to evaluate the end-to-end delay of VLC networks employing collision avoidance over carrier sensing multiple access protocol. Our model is built on near realistic assumptions in modeling which yields closed matches with simulation results. Based on the outcomes of the proposed model, this paper proposed to replace the exponential back-off mechanism of the above standard with linear back-off that results in low-delay.*

Index Terms—*IEEE 802.15.7, Visible Lighting Communication, CSMA-CA*

Date of Submission: 09-01-2018 Date of acceptance: 24-03-2018

I. Introduction

During current decades, enormous number of wireless communication systems have been devised to achieve the anytime, anywhere and anything communication paradigm. Internet of Things (IoT), 5G, Fog Computing, ZigBee, Near Field Communication (NFC), Bluetooth and Wireless Fidelity (WiFi) just to name a few. These systems generate massive data traffic, according to [1] the amount of data traversed mobile network in 2014 was about 30 times the amount of all data crossed the Internet in 2000. Furthermore, it is projected that the compound annual growth rate of mobile data could reach around 57% during the period from 2014 to 2019 and by 2020 the data volume of the Internet is going to be around 30 Exabyte per month. The key challenge towards meet these expected readings is to find the Radio Frequency (RF) spectrums that can carry them. Currently, most of licensed RF spectrums are already allocated and unlicensed RF are overcrowded [2-3] and hence facilitating wireless communication over other bands becomes one of the most active research disciplines.

Visible Light Communication (VLC) represents a new types of free space optical communication system that utilizes a visible light spectrum to deliver data wirelessly [2-4]. In VLC system, illuminations such as Light Emitting Diode (LED) and laser diode act as transmitters while photosensitive devices (like LED, image sensor and photodiodes) play the roles of receivers. The data is encoded by varying the supply current of transmitters in higher rate than human eyes can perceived [2-4]. Thereby data and lighting can be handled by the same equipment which can reduce both capital and operational expenditure significantly. Besides that, VLC can provide higher bandwidth compared to RF; since VLC operates over a wide unlicensed spectrum extending over 400 TeraHertz. Another key advantage of VLC over RF is the ability of the former to be used throughout those areas where RF is restricted, e.g., chemical plants, operating theatres and airplanes [3]. From a security perspective, VLC is preferred since visible lighting cannot penetrate through most surface which in turn eliminates the eavesdropping and interferences between spatially isolated communication systems. More importantly, owing to being visible lighting does not inference with RF signals enables integration of VLC with most current communication systems seamlessly such as Power Line Communication (PLC) or RF. Inspired by bountiful benefits of VLC, severalstandard bodies and research organizations endeavored to proliferate VLC based communication networks. Some examples are: visible light communications consortium (VLCC) [2], European Commission Home Gigabit Access (OMEGA) project [3], SLERC at University of Oxford [4] and LC at University of California [3] etc. Notwithstanding, in 2011, IEEE considered rapid importance of VLC and ratified IEEE 802.15.7 for PHY and Medium Access Control (MAC) protocols of VLC [5]. Since that multiple commercial VLC communication systems have been appeared, e.g., Light Fidelity (LiFi), LED to LED and optical camera communications. Moreover, it is anticipated that the market share for light communication to exceed $75 billion by 2023[6]. Under these circumstances, it is highly expected that majority of traffic generated by VLC is delay-sensitive data that need to be handle according to QoS policies. However, the IEEE 802.15.7 MAC standard adopt Carrier Sensing Multiple Access with Collision Avoidance (CSMA-CA) which treat all nodes evenly without distinguish between delay-sensitive and other loads.

This paper has been devoted to fill the gap of reducing delay issues for VLC networks by developing a novel MAC protocol for these networks. With the aim to consolidate proposed protocol, mathematical framework has been developed to determine the key reason for the lack of QoS measurement in standard CSMA-CA protocol. Although a number of works has been for analyzing CSMA-CA protocol for wireless networks have been introduced in the literature, e.g.[7-12] most of these models were built on the assumption that all nodes have the same packet generation distribution. Moreover, all of them use the mean-field approximations to model the behavior of saturated network (when a node is always has a packet) then investigate other packet generation patterns by assuming that a node after finishing the service of current packet generates a new packet with a certain probability. This assumption simplifies the analysis but does not account for the queuing delay that could be a major issue in delay-sensitive packets. The saturation mode is used to avoid computation changes of the channel sensing probability during the service time which makes these models do not reflect the stochastic characteristic of the CSMA-CA protocol accurately in unsaturated networks. All of these aspects make the existing model not sufficient to be used over VLC networks. The merit of our model is multifaceted; firstly: it employs statistical theorems to model the CSMA-CA operation which yields the complete Probability Mass Function (PMF) of packets service time not just its mean as done in peer works. Secondly, our model uses the queuing theorem to evaluate the delay and jitter which produces the queuing delay that has not been studied before. Thirdly, we relax the assumption about the constant sensing probability with the complete probability mass function of sensing the channel which makes our model capable to accurately predict the behaviors of the protocol. The accuracy of our model is assessed using comprehensive simulation sessions and the outcomes of this assessment exhibits its validity to predict characteristics of the network. More importantly, these outcomes are used to identify that the main reason for lack of QoS support of IEEE 802.15.7 MAC is its adoption for the Truncated Binary Exponential Back-off (TBEB) scheme. Consequently, our proposal protocol is devised to supplant TBEB with Truncated Binary Linear Back-off (TELB) scheme. Comparison between performance of VLC networks under both TBEB and TELB scheme as presented in this paper illustrates the ability of the latter to leverage the QoS issues of VLC networks.

The rest of this paper is structured as follows, section II introduces MAC mechanism of IEEE 802.15.7, section III derives the analytical modelof this contribution, and section IV presents the proposed protocol. Results and discussion are mentioned in section V while section VI concludes the work.

II. Overview of MAC Mechanism in IEEE 802.15.7

The IEEE 802.15.7 appears in 2011 to define the PHY and MAC layers VLC technology [5] over three possible topologies: star, peer-to-peer and broadcast. Generally, all topologies consist of one or more central controller also known as coordinator and a set of nodes. The main responsibilities of coordinators are to form the network and to manage communication timings and parameters across the network. In star topology, a single coordinator forms a bidirectional communications channel between itself and all other nodes. Hence a node can only communicate with the coordinator which makes this topology is appropriate for smart environment application such as: smart office and smart home etc. The peer-to-peer topology enhances connectivity of star topology by allowing any two nodes to communicate directly over bidirectional channel. This topology targets those applications require machine to machine communications e.g., phone to phone and vehicle to vehicle. The last topology defined by the IEEE 802,15,7 is the broadcast topology which differs than other topologies in that it establishes a unidirectional communication channel between a single coordinator and all other nodes. Such topology can be used to disseminate information from a central control unit to multiple recipients such as: signboard and traffic light to vehicles information systems. IEEE 802.15.7 offers three implementations for the physical layer: PHYI, PHYII and PHYII, the key differences between these implementations lie mainly in operation environments and data rates. PHYI was specified for outdoor with rate 11.6-266.6 Kbps. PHYII was defined for indoor applications using moderate data rate ranging from 1.25 Mbps up to 96 Mbps. Finally, PHYIII supports data rate of .25 Mbps up to 96 Mbpssimilar to PHYII but with multiple optical transmission and receivers.

According to IEEE 802.15.7, a coordinator synchronizes timings access the network by broadcasting a special frame dubbed beacon following by a super-frame. Each super-frame comprises two main intervals: active and inactive. During active part, all nodes are function and can communicate while during inactive portion, devices are sleeping to save energy. The active portion is partitioned into even 16 units named slots and these slots are further partitioned into two parts: contention access and contention free periods. Throughout contention access devices contend to deliver their packets using CSMA/CA. On the contrary, in contention free, certain nodes deliver their loads towards the coordinator throughout predetermined slots that were reserved during their contention. The CFP is used for delay-sensitive applications e.g., multimedia.The length of super-frame and active periods are defined using:BI and SD parameters respectively which are defined mathematically as:

$$BI = BSFD \times 2^{BO};\ 0 \le BO \le 14 \qquad (1\text{-a})$$
$$SD = BSFD \times 2^{SO};\ 0 \le SO \le BO \le 14 \qquad (1\text{-b})$$

where $BSFD$ is the optical clock frequency, BO is the interval at which beacons frames are transmitted and SO is the super-frame order.

The CSMA/CA mechanism is defined technique by which nodes compete to access the shared media during the contention period. This mechanism necessaires all nodes to align their actions (e.g., Clear Channel Assessment (CCA), back-off and transmission) with the boundary of slots. A node whenever decides to send a packet sets the following two parameters: (i) Number of Back-off (NB) which tracks the number of back-off used by a node during its transmission. The minimum value of this parameter is 0 while its maximum value is set according to macMaxRABackoffs whose default value is 4 according to the standard [5]. If a node reaches the macMaxRABackoffs limit without accessing the channel, then it drops a packet and inform higher layers that the channel access failure occurred. (ii) Backoff Exponent (BE) which regulates the back-off window prior of performing CCA, the minimal and maximal values for this parameter are defined by the macMinBE(default value is 3) and macMaxBE (default value is 3) respectively. Employing these defaults yields Truncated Binary Exponential Back-off (TBEB) scheme which suffers from several defects. A flow chart for CSMA-CA mechanism is shown in figure 1.

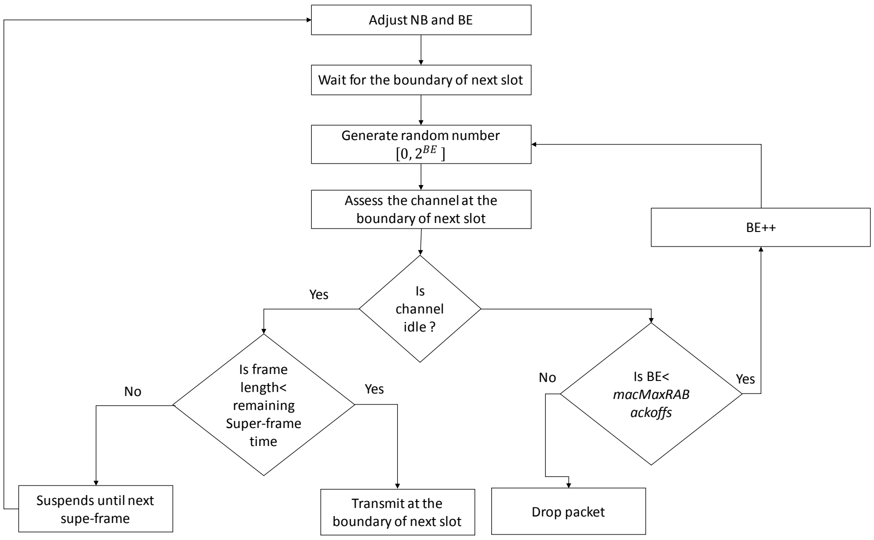


Figure 1. Flow chart for CSMA-CA mechanism.

As shown in this figure, a node after adjusting NB and BE waits for the starting of next slot and then uses uniform distribution within$[0, 2^{BE}]$ to generate backoff duration. Afterward elapsing this random duration, a node check status of the channel at the boundary of slot. If the channel is found idle, then a node computes the frame duration and compares the result with the remaining time of current superframe. If there is sufficient them then device can transmit its packet immediately, otherwise a transmission is suspended to the next superframe. on the other side, if a node assessed a busy channel then it increases the value of BE by one and repeats the accessing operation.

III. MATHEMATICAL FRAMEWORK

Here we consider N nodes sharing access a single channel using slotted CSMA-CA; each node generates packets independently and according to different distribution than other nodes. All packets are sent to the coordinator (central data collector device). This mechanism can be represented as M stages random process as shown in Fig.2 in which each stage consists of random number of back-off slots (seen as B) and a single slot for channel sensing (refer to it as C). all Bs are random periods distributed uniformly between 0 and Wi-1, where the value of Wi for all stages are W0 = 8, W1 = 16 and W2 = W3 = W4 = 32[5].

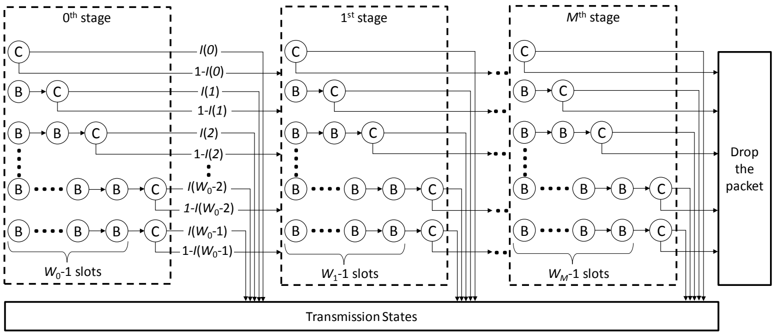


Figure 2. State transition diagram for the un-slotted CSMA-CA protocol.

Transmission commences in slot k under condition that channel is idle which happens with I(k) as shown in Fig.2. Transmission is deferred to the next stage if device finds a busy media after elapsing its back-off duration in the current stage and a packet dropped if the channel is found busy for M+1 times. Thus, the complete time required by a packet either for transmitting or dropping is a random variable, dubbed her by S.

During derivation, the following notation is used $C_i(k)$ be the Probability Mass Function (PMF) of a node being in a sensing the channel at the i^{th} stage; π_i is the probability that a node commences transmission at thei^{th} stage and $P_{B_i}^k$ is the probability of backing-off for k slots throughout the i^{th} stage that is specified by equation (2) using PMF of selection the backing-off period at the beginning of each stage:

$$P_{B_i}^k = 1/W_i \quad 0 \le k \le W_i - 1 \tag{2}$$

At all stages, a node waits for 0 Wi-1 random slots and then senses the channel for one slot. Thus, the PMF of sensing media in can be given as:

$$C_0(k) = 1/W_0 \quad 0 \le k \le W_0 - 1 \tag{3}$$

This yields a general equation for these stages as:

$$C_i(k) = \sum_{j=0}^{k-1} C_{i-1}(j) P_{B_i}^{k-j-1} \quad 0 \le k \le \left(\sum_{w=0}^{i} W_w \right) - 1 \; ; 2 \le i \le M \tag{4}$$

Using equation (4) enables us to compute the piecewise expression of the PMF of sensing the channel by the 2nd stage as:

$$P_{S_2}(k) = \frac{1}{W_0 W_1 W_2} \begin{cases} k(k-1)/2 & 0 \le k \le W_0 + 1 \\ 8k - 36 & W_0 + 2 \le k \le W_1 + 1 \\ \left(-k^2 + 49k - 334\right)/2 & W_1 + 2 \le k \le W_0 + W_1 + 1 \\ 128 & W_0 + W_1 + 2 \le k \le W_2 + 1 \\ \left(-k^2 + 65k - 800\right)/2 & W_2 + 2 \le k \le W_2 + W_0 + 1 \\ \text{-}8k + 420 & W_2 + W_0 + 2 \le k \le W_2 + W_1 + 1 \\ \left(-k^2 + 113k - 3192\right)/2, & W_2 + W_1 + 2 \le k \le W_0 + W_1 + W_2 - 1 \end{cases} \tag{5}$$

Similarly, the PMF of sensing the channel by the 3rd and 4th stages can be approximated using the central limit theorem as these stages contain multiples of identical uniform distributions. The convergence of their convolution to the normal distribution is extremely fast [8]. Here Let $\mathcal{N}(k, \square, \sigma)$ represent a Gaussian PMF with $\square$ and σ mean and standard deviation respectively, thus PMFs are:

$$C_3(k) \approx N(k, 46, 197) \quad 0 \le k \le \left(\sum_{w=0}^{3} W_w \right) - 1 \tag{6}$$

$$C_4(k) \approx N(k, 62.5, 282.25) \quad 0 \le k \le \left(\sum_{w=0}^{4} W_w \right) - 1 \tag{7}$$

Figure 3 depicts the actual distribution of sensing the channel indifferent stage.

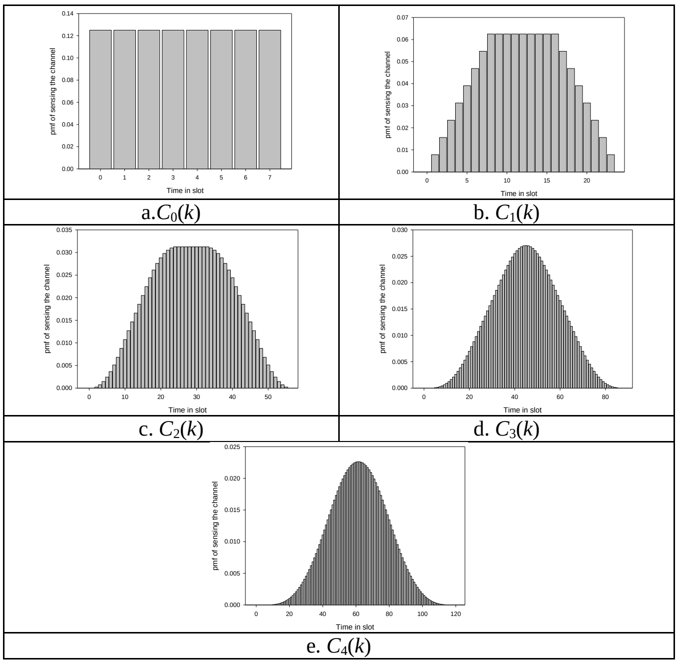


Figure 3.The probability mass function of sensing the channel in different stages.

The status of the channel in any slot can be represented as a random variable with two mutually exclusive states: idle and busy. Suppose that the probability of idle channel in slot k is I(k) which is the chance of no accessing the channel is started in slots k,…,k-L+1 (i.e., no one assesses the channel in previous slots). Thus I(k) can be given as:

$$I(k)=\prod_{l=1}^{L}\left[1-C(k-l)\right]^{N-1};C(k)=\sum_{i=0}^{M}C_i(k) \qquad (8)$$

Where C(k) represents probability of assessment the shared media in any stage. Since devices do so once per a stage, adding them is safe as they are pair-wise mutually exclusive events. Equation (9) represents all required conditions of finding an idle media; i.e. under busy channel, then it will be free after L slots on maximum, however, sensing a ideal channel will not change its status. A node can commence transmission in a stage if it finds an idle channel when it senses it during that slot. Let πi be the probability that a node commences transmission is the ith stage which can be given as:

$$\pi_i=\sum_{k=0}^{W}I(k)C(k);W=\left(\sum_{w=0}^{i}W_w\right)-1 \quad 0\le i\le M \qquad (9)$$

Based on the above, the PMF of complete service time can be given as:

$$\begin{aligned}S(k)=\pi_0C_0(k-L)+(1-\pi_0)\pi_1C_1(k-L)+......+\\+\left(\pi_M\prod_{i=1}^{M-1}(1-\pi_i)\right)C_M(k-L)+\left(\prod_{i=1}^{M}(1-\pi_i)\right)C_M(k)\end{aligned} \qquad (10)$$

The first term of S(k) accounts for the case when a device successes in sending a datagram at the zeroth stage, thus the sensing probability is shifted by L. The second term accounts for the case when a node sends its packet in the 1st stage, in this case it must find a busy channel in the 0th stage and then find an idle slot in the 1st stage. Continuing with the same procedures, other terms are found. The last term expresses the case when a packet is dropped due to failing to sense the channel in any stage, so it is not considered in the shifted version of the sensing PMF.

In terms of mathematical integrity, S(k) as given in (10) complies with the requirement of the mixture distributions [13] where the mixed distribution is the PMF of a node being in the sensing state and the mixing weight is the probability of commences transmission in each stage, since:

$$\pi_0+(1-\pi_0)\pi_1+...+\left(\pi_M\prod_{i=1}^{M-1}\pi_i\right)+\left(\prod_{i=1}^{M}(1-\pi_i)\right)=1 \qquad (11)$$

With the target to evaluate delay of multiple devices we models each node as a queue using the general queuing model where the inter-arrival distribution of packets is general independent which can be a combination of two or more distributions, the service function follows a general distribution which is given by equation (10) and the single server represents the CSMA-CA mechanism in a node. According to [14-17] the inter-departure distribution (output) model can be given as:

$$D(k) = P_E\left[X(k) * S(k)\right] + \left(1 - P_E\right) S(k) \tag{12}$$

Where P_E is the probability that a packet leaves a node with no more packets generated, and X(k) is the PMF of the time that a node spent without competition to deliver packets.

IV. PROPOSED PROTOCOL

The proposed mathematical model presented in the previous section has highlighted the fact that a node during its competing to access the channel increments its back-off duration exponentially each time it finds a busy channel. This in turn reduces probability of sensing channel in each stage as shown in Fig.3, the probability with which a node senses the media in the 0th stage in each slot is fixed at 0.12.While in the first stage the maximum probability is dropped by four folds to reach 0.06 and continuous to drop until reaching 0.23 in the fourth stage. Reduction of sensing probability in each stage raises the delay probable accordingly, in other meaning delaying transmission of a packet to next stage can reduce the transmission probability. This issue is due to the exponential back-off policy defined in the standard, i.e., the Truncated Binary Exponential Back-off (TBEB) enforces a node to enlarge the back-off windows with large scale which in turn deferred the transmission. This in turn makes TBEB unsuitable for QoS traffic and due to this reason, the standard protocol defined the contention free periods to cater for such traffic. However, since the contention free period is limited in length (i.e., just few slots), there is a need to find an alternative means to promotes QoS over VLC based networks.

This section proposed to replace the exponential incremental found in TBEB with liner incremental, hence its named Truncated Binary Linear Back-off (TBLB). The pseudocode of the proposed protocol is shown in Figure 4.

```
NB ← 0; LE ← 0
Wait for boundary of next slot
Generate random number [0,2LE ]
Assess the channel at boundary of next slot
If (channel is idle && frame <reaming super-frame
time)
        {Transmit packet}
Otherwise
        {delayed packet till next super-frame}
Else if channel is busy
{LE++}
Go to 3
End if
```

Figure 4 Pseudocode of the proposed protocol.

Comparing the proposed protocol with the standard protocol shown in figure 1 reveals that the main difference between them is that the proposed protocol increases the back-off duration in linear manner rather than exponentially. This can be seen in replacing back-off windows from $[0, 2^{BE}]$ by $[0, 2LE]$ where LE is defined as the linear exponent. It is worth mention that that keeping the core proposed protocol similar to the standard has a benefit that it allows our proposal to be employed to devices without needing to reprogram them differently. This in turn widens the applicability of our proposal and makes it integrate-able with those devices available in the market.

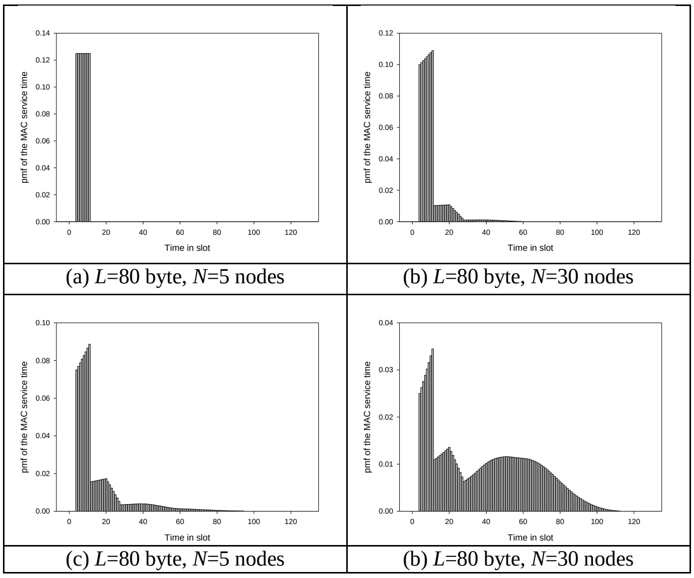
V. RESULT AND DISCUSSIONS

This work employs ns-3 simulation platform [18] whose parameters are set as shown in table I.

Table I. Key Simulation Parameters

Parameter	Value
Transmission speed	1.25Mbps
Optical clock speed	3.75MHz
Power of optical transmission	30mWatt
Physical layer operating mode	PHYII
Photo detector area	1 cm2
Photo detector responsively	0.54 A/W
Duration of CCA	8 clock cycles
Transmission-Receiving switchover time	0 clock cycles
Receiving- Transmission switchover time	8 clock cycles
Field of Vision	60°

The first step in validating accuracy of the proposed framework is to evaluate the PMF of complete service time when all nodes generate their packets with a constant rate equals 150 slots and all of packets are with same length 80 bytes. The 150 slots have been selected to eliminate the queuing delay. The results are given in Figure 5.



(a) L=80 byte, N=5 nodes | (b) L=80 byte, N=30 nodes

(c) L=80 byte, N=5 nodes | (b) L=80 byte, N=30 nodes

Figure 5. PMFof the service time of different network configurations.

It can be seen from this results that the probability at which a packet complete its service after elapsing certain number of slots, e.g. a packet completes its service (leave the system) after 20 slots from its generation with about 90 % when N=5 nodes, but when N=70 the service completed with about 40%. In general, the service time of a packet increases proportionally with nodes density which is resulted from increasing sensing of busy channel with N as more nodes sharing access the channel as shown in equation (9). It is also shown service time cannot be more than 120+L, where 120 is the sum of the Wi which happens when a node backs-off for the maximum duration in each stage. Interestingly, this result can help the developer to select the appropriate packet generation rate depending on the number of nodes. More insightful results can be drawn from our model by adjusting the offset time between packet generations for each node that yields a specific QoS constraint, e.g. these results is based on adjusting the packet generating rate between nodes to reduce the probability of serving a packet by 10%. Total delay a packet experience. We assume that the mean of each node is λ following Poisson distribution. Then the total delay (queuing and service) which is denoted by D, can be computed according to the Pollaczek-Khinchine (P-K) formula as [19]:

$$D = \frac{\lambda E\left[S^2\right]}{2\left(1-\lambda E\left[S\right]\right)} \tag{13}$$

The simulated and analytical results for different traffic levels (mean values) are given in Figure 6 It is shown that the total delay increases with the mean packet generation rate as well as with number of nodes.

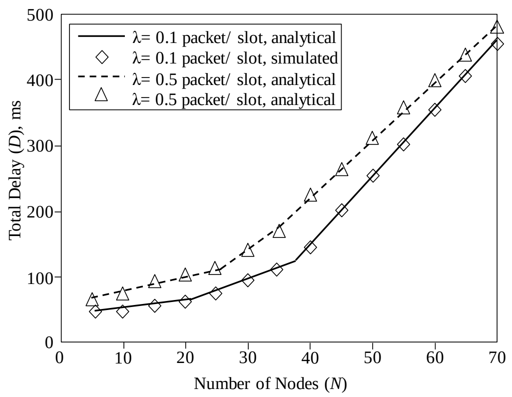


Figure 6. Total Delay for different traffic rate with M/G/1 queue model.

It is obvious from the results shown here that the main causes of increasing the service time of packets is increasing of back-off windows exponentially with the number of nodes as a result of using TBEB. These characteristic limits the applicability of the standard protocol in the area of QoS and hence we here replace TBEB with TBLB and keeping other parameters to their respect values. Figure 7 shows the total end-to-end delay against node density of TBLB and TBEB, it is obvious from these results that TBLB outperforms TBEB which in attributed mainly to being the TBLB reduces the waiting time of nodes.

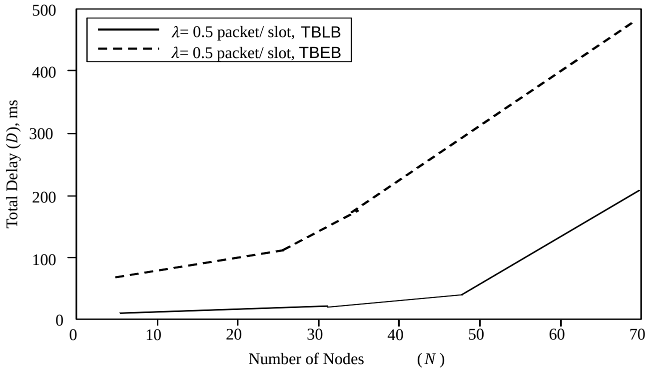


Figure 7. Total delay vs number of nodes for TBLB and TBET.

VI. CONCLUSION

This work proposed a novel mathematical framework by which service time distribution of slotted CSMA/CA as specified in IEEE 802.15.7 for VLC networks can be determined. The proposed model employed near realistic assumptions and made use them to point out the key reasons for the lack of QoS measurements in stated protocol. Based on the results of this model, this work attempted to enhance these measurements by replacing the truncated backoff incremental by linear. Comparison between these two schemes demonstrated the outperformance of linear.

ACKNOWLEDGMENT

The author would like to acknowledge and thank the Deanship of Scientific Research (DSR) at Umm Al-Qura University (Project No: 15-COM-3-2-0001, 15-COM-4-1-0001, 15-COM-4-1-0002, & 17-COM-1-01-0008) for their financial support.

REFERENCES

[1] Cisco Networks, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020," [Online], https://www.cisco.com/c/dam/m/en_in/innovation/enterprise/assets/mobile-white-paper-c11-520862.pdf, accessed on 29th of January 2018.

[2] P. H. Pathak, X. Feng, P. Hu and P. Mohapatra, "Visible Light Communication, Networking, and Sensing: A Survey, Potential and Challenges," in IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2047-2077, Fourthquarter 2015.

[3] D. Karunatilaka, F. Zafar, V. Kalavally and R. Parthiban, "LED Based Indoor Visible Light Communications: State of the Art," in IEEE Communications Surveys & Tutorials, vol. 17, no. 3, pp. 1649-1678, thirdquarter 2015.

[4] G. M. Saridis, D. Alexandropoulos, G. Zervas and D. Simeonidou, "Survey and Evaluation of Space Division Multiplexing: From Technologies to Optical Networks," in IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2136-2156, Fourthquarter 2015.

[5] IEEE Standard for Local and Metropolitan Area Networks--Part 15.7: Short-Range Wireless Optical Communication Using Visible Light," in IEEE Std 802.15.7-2011 , vol., no., pp.1-309, Sept. 6 2011.

[6] IEEE 802.11-17/0962r3, An overview on high speed optical wireless/light communications, [online], http://ieee802.org/802_tutorials/2017-07/11-17-0962-03-00lc-An-Overview-on-High-Speed-Optical-Wireless-Light.pdf, accessed on 29th of January, 2018.

[7] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," in IEEE Journal on Selected Areas in Communications, vol. 18, no. 3, pp. 535-547, March 2000.

[8] MikkoKohvakka, Mauri Kuorilehto, Marko Hännikäinen, and Timo D. Hämäläinen. 2006. “Performance analysis of IEEE 802.15.4 and ZigBee for large-scale wireless sensor network applications”. In Proceedings of the 3rd ACM international workshop on Performance evaluation of wireless ad hoc, sensor and ubiquitous networks (PE-WASUN '06). ACM, New York, NY, USA, 48-57.

[9] F. Chen, N. Wang, R. German and F. Dressler, "Performance Evaluation of IEEE 802.15.4 LR-WPAN for Industrial Applications," 2008 Fifth Annual Conference on Wireless on Demand Network Systems and Services, Garmisch-Partenkirchen, 2008, pp. 89-96.

[10] J. Zheng, M. J. Lee, "A Comprehensive Performance Study of IEEE 802.15.4", Sensor Network Operations IEEE, pp. 218-237, 2006.

[11] A. Faridi et al., "Comprehensive Evaluation of the IEEE 802.15.4 MAC Layer Performance with Retransmissions," in IEEE Transactions on Vehicular Technology, vol. 59, no. 8, pp. 3917-3932, Oct. 2010.

[12] Zhifeng Tao, S. Panwar, Daqing Gu and Jinyun Zhang, "Performance analysis and a proposed improvement for the IEEE 802.15.4 contention access period," IEEE Wireless Communications and Networking Conference, 2006. WCNC 2006., Las Vegas, NV, 2006, pp. 1811-1818.

[13] B. Everitt, Finite Mixture Distributions, Monographs on Statistics and Applied Probability, Springer Science & Business Media, 2013.

[14] R. Boucherie and N. Dijk, Queueing Networks: A Fundamental Approach, Springer Science & Business Media, 2010.
[15] G. Bolch, G. Stefan, M. Hermann, S.T. Kishor, "Queueing networks and Markov chains", John Wiley & Sons, 1998.
[16] T. Qiu, F. Xia, L. Feng, G. Wu, B. Jin, "Queueing theory-based path delay analysis of wireless sensor networks", Advances in Electrical and Computer Engineering, vol. 11, no. 2, 2011.
[17] A. Melikov, A. Rustamov, "Queuing management in wireless sensor networks for QoS measurement", Wireless Sensor Network, vol. 4, pp. 211-218, 2012.
[18] D. Gross, C.M. Harris, Fundamental of Queuing Theory, Wiley Inter-Science, 1998.
[19] L. Kleinrock, Queuing System: Theory. John Wiley & Sons, 1976.

AbdullahBaz "A Low-Delay MAC Protocol for QoS VLC Networks." IOSR Journal of Computer Engineering (IOSR-JCE) 20.2 (2018): 01-09.