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Towards Multi-channel GTS Allocation in Visible Light Communication

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Abstract

Visible Light Communication (VLC) is a communication technology that is used to realise the data demands of futuristic Internet of Things (IoT) devices. VLC leverages the light-based infrastructure, such as LED lights, and laser light sources to enable fast and large data communication. The IEEE 802.15.7 protocol offers multiple physical layer options and Medium Access Control (MAC) sub-layer mechanisms to cater to various VLC applications. Specifically, within the MAC sub-layer, the standard provides support for contention-free communications through Guaranteed Timeslots (GTS), enabling the implementation of time-critical applications. Based on the protocol definitions, the frame structure that aids communication is rigid and fixed. This can be a problem in supporting the large data demands of IoT networks. In this paper, we propose a multi-channel GTS allocation scheme to support the large data demands of IoT applications. Based on our numerical analysis, we were able to witness almost 30% reduction in the overall delay and improved throughput using our proposed method

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***Abstract*—Visible Light Communication (VLC) is a communication technology that is used to realise the data demands of futuristic Internet of Things (IoT) devices. VLC leverages the light-based infrastructure, such as LED lights, and laser light sources to enable fast and large data communication. The IEEE 802.15.7 protocol offers multiple physical layer options and Medium Access Control (MAC) sub-layer mechanisms to cater to various VLC applications. Specifically, within the MAC sub-layer, the standard provides support for contention-free communications through Guaranteed Timeslots (GTS), enabling the implementation of time-critical applications. Based on the protocol definitions, the frame structure that aids communication is rigid and fixed. This can be a problem in supporting the large data demands of IoT networks. In this paper, we propose a multi-channel GTS allocation scheme to support the large data demands of IoT applications. Based on our numerical analysis, we were able to witness almost 30% reduction in the overall delay and improved throughput using our proposed method.**

***Index Terms*—VLC, IEEE 802.15.7, IoT**

I. Introduction

With the constant evolution in the communication medium, there has been a renewed interest in communication through light sources as they support the ever-growing data needs of modern IoT applications. Visible Light Communication (VLC) [1] is used to enable IoT (Internet of Things) by using visible light as a medium for communication between IoT devices. In this technology, data is transmitted through constant variations in the intensity of light sources such as LED, lasers and photodiodes [3]. These sources are used to receive and decode the transmitted data. VLC offers several advantages and is a promising candidate as a communication technology to realise various IoT applications.

VLC can aid the realisation of IoT on several fronts, for instance, as VLC can be integrated with existing LED lighting infrastructures, it can efficiently aid in the energy conservation of IoT deployments. The visible light spectrum is unlicensed making it feasible for the testing of data-demanding IoT applications without the need for expensive licensing [4]. VLC can achieve high data rates, making it suitable for applications like data-intensive video streaming, and high-resolution imaging. Finally, VLC does not interfere with other wireless communication technologies that use radio frequencies like WiFi, making them more secure.

IEEE 802.15.7 [5] is a communication protocol developed to realise communication in Wireless Personal Area Networks (WPANs) using visible light. It provides support towards high data rate visible light communication up to 96 Mbps with almost 300 THz of unlicensed bandwidth. Some IoT applications are critical and demand strict timeliness requirements. To support such time-critical IoT applications, the MAC layer of IEEE 802.15.7 uses a periodically synchronized superframe structure (Fig. 1), that aids in providing guaranteed bandwidth using the Guaranteed Time Slot (GTS) mechanism. However, the current superframe architecture supports a single-channel GTSs allocation similar to the IEEE 802.15.4 standard.

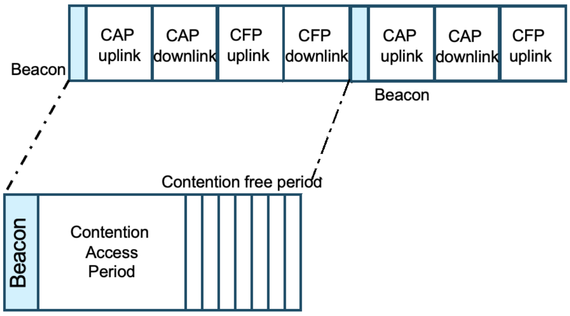

Fig. 1. The superframe structure of IEEE 802.15.7 with the contention-free period of guaranteed timeslots to realise time-critical communication in star topology-based VLC applications

Multi-channel-based GTSs allocation can immensely increase the amount of data that can be supported by the superframe [13]. Multi-channel-based GTSs allocation can be realised in several ways in the visible light spectrum. For instance, using colour division multiplexing (CDM), different LED light sources can emit unique light colours or frequencies [6]. In such a case, every colour represents a separate communication channel. The data can be modulated for every colour, and multiple channels can be used to transmit data concurrently, thus increasing the overall data capacity of the system. In this paper, we propose a multi-superframe architecture to support multi-channel GTS allocation in IEEE 802.15.7 networks.

The contributions in this work are as follows:

- We propose a multi-superframe architecture in IEEE 802.15.7 to enable multi-channel communication
- we perform a worst-case bounds analysis for the proposed system to understand the potential of such time-critical communication mechanisms

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- We provide some in-depth numerical analysis based on our proposed model.

The rest of the paper is organised as follows, in Section II we provide some brief literature survey based on the recent works on VLC networks. In Section III, we propose our multi-channel VLC model, where we define the architecture of our proposed model and define the worst-case bounds. In Section IV, we do a numerical analysis based on the delay and compare it against the standard VLC model and finally, we conclude our paper with discussions and future scope in Section V.

II. Related work

VLC has been used in realising the Industrial Internet of Things (IIoT) where there need to be strict guarantees on delay and reliability in communication. The work in [2] presents a hybrid visible light communication (VLC)-fibre to realise communication in urban and rural areas for advanced IoT applications. In this work, they use a red light emitting diode (LED) based fiber-VLC to offer a high data rate of up to 30 Gbps. It also supports a large range of 40 km and 80 m VLC range. Researchers [7] minimize the superframe duration to impact delay violation probability. Stochastic network calculus (SNC) was used to analyse the impact of shorter superframes on delay. In our work, we use network calculus to realise the worst-case delay bounds of the multi-channel VLC network.

The work in [8] developed an exclusive unslotted CSMA/CA algorithm for a dedicated channel and evaluates the effects of collision probability, retransmission attempts, access failure probability, and normalized throughput on the network's performance during the transmission of non-real-time traffic. In our work, we focus on the contention-free period of the IEEE 802.15.7 superframe and develop a multi-channel method to analyse maximum delay and throughput.

A recent survey on VLC [9] stresses the need for MAC-specific solutions on the channel used to meet the bandwidth requirements of upcoming 6G technologies. This work highlights the need to enhance channel efficiency which can be achieved through adaptive and dynamic modifications across the entire channel, encompassing both the CAP (Contention Access Period) and CFP (Contention-Free Period) fields.

Researchers in [10], [11] provide offers a deeper perspective on OWC-based MAC layer issues, in which they point out the necessity of the MAC layer to be tailored based on application-specific demands. With the ever-growing deterministic demands and guarantees to realise IoT and 6G applications [12], [14], there is a need for scalable deterministic MAC architectures. This paper addresses this issue, by enabling multi-channel access in the GTS of the VLC superframe structure. Researchers in [15] provide a self-adaptive medium access control called SA-MAC protocol for VLC networks. By leveraging the CSMA/CA and sub-carrier orthogonality they reduce the network delay, and energy consumption while increasing throughput. However, they did not provide any deterministic bounds on the communication.

In our previous work [16], we provided the worst-case bounds analysis on the standard VLC network based on IEEE 802.15.7. The bandwidth-hungry IoT and 6G deployments can greatly benefit from the usage of multiple channels to accommodate more data. Wireless standards such as the IEEE 802.15.4 have extended support towards multichannel architecture to support the demands of IoT networks [17]. In this work, we extend our previous model by introducing multi-channel access and learning its implications on the worst-case delay and throughput of the network.

III. Multi-channel VLC model

In this work, we propose a multi-channel architecture only in the contention-free period of the VLC superframe. Providing a multi-channel architecture can extend the functionalities of the superframe to support a mesh topology with multiple transmitters connected in a decentralized manner, forming a self-configuring and interconnected network. This can be realised by splitting the guaranteed timeslots across non-overlapping channels. The typical star topology is facilitated by the superframe shown in Fig. 1 where the guaranteed communication is facilitated through 7 guaranteed timeslots spread as the contention-free period. Now through methods like CDM or time division multiplexing, it is possible to divide the guaranteed timeslots in reliance on the channels.

In Fig. 2, we present a prototype multi-channel frame structure for VLC networks. where the GTSs are spread across three colour-coded channels. This extensively increases the number of available GTSs from 7 to 21. This meets the need of data-hungry IoT applications, provided that the transmissions occur in a non-overlapping fashion across the channels. Provided the unlicensed nature of the channels in VLC, there is a possibility to incorporate more channels to meet the data demands of futuristic IoT applications.

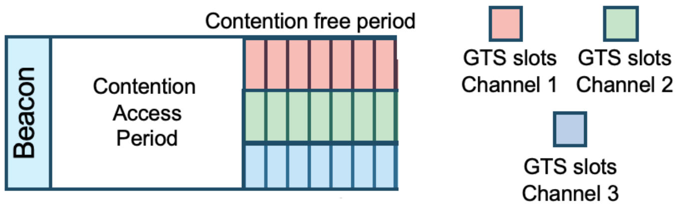

Fig. 2. Novel multi-channel architecture where the GTSs are spread across three colour-coded channels, thus increasing the overall number of GTSs from 7 to 21

In addition to increasing the overall scalability of the network, this proposed method can circumvent the single point of failure problem in the classic superframe structure because beacon scheduling and slot allocation will have to be carried out in a centralized fashion. A problem at the root of a network will be catastrophic to the entire network due to the inability to choose an alternative route. The proposed method mitigates this problem and provides the capability for peer-to-peer communications like mesh networks to choose alternative routes to reach the sink.

A. Worst-case bounds analysis of multi-channel VLC

Network Calculus is a mathematical model well adapted to controlled traffic sources to provide upper bounds on delays for traffic flows. This model is formulated for the star topology-based VLC network as it supports time-sensitive communication.

A cumulative arrival function $R(t)$ can in relevance with an arrival curve $\alpha(t) = b + r \cdot t$, where b, r, and t represent the burst rate, data rate, and time interval, respectively. This arrival function, $R(t)$, is ensured to have a minimum service curve denoted as β. The maximum delay bound for the arrival function $\alpha(t) = b + r \cdot t$, which receives a rate-latency service curve $\beta(t - T)^{+}$, where R is the bandwidth and T is the maximum latency, can be expressed as follows:

$$D_{max} = \frac{b}{R} + T \quad (1)$$

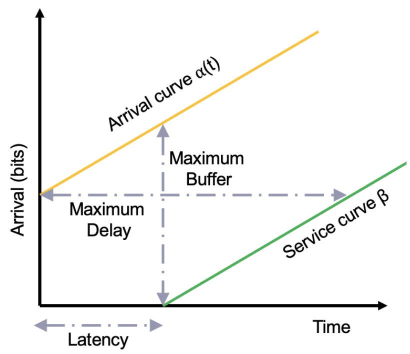

Fig. 3. fundamental (b, r) model with the arrival and service curves, along with the delay bound

The variation between the theoretical (b, r) curve and the practical model is suitable for periodic traffic that is frequently observed in Wireless Sensor Networks. Fig. 3 illustrates the fundamental (b, r) model with the arrival and service curves, along with the delay bound (represented as the maximum delay). The only change from the standard 802.15.7 is the additional inclusion of the channels to increase the quantity of the underlying GTSs. Therefore, with the beacon order (BO) and superframe order (SO) defining a VLC superframe, the common supporting parameters such as the beacon interval (BI), superframe duration (SD) and the number of optical clocks forming a superframe $baseSD$ remain the same as the standard superframe format.

$$BI = baseSD \ \times 2^{BO} optical clocks \quad (2)$$
$$for\ 0 \leq BO \leq 14$$

$$SD = baseSD \ \times 2^{SO} optical clocks \quad (3)$$
$$for\ 0 \leq SO \leq BO \leq 14$$

$$baseSD = baseSlotDuration \ \times m(T_s) \quad (4)$$

The base slot duration is the representation of the number of optical clocks that define the superframe slot when the superframe order SO is 0, this value is defined by the standard to be 60 optical clocks when SO = 0. $m(T_s)$ is the number of timeslots in the superframe. Our worst-case bounds analysis includes the time necessary to accommodate the GTS transmission, its respective acknowledgements and the CAP region where contention-based communication occurs. Let us consider three GTSs frames in each superframe, where transmission occurs across 3 different channels. Despite the communication happening in 3 GTS slots, it will not have any impact on the size of a single timeslot and it will be:

$$T_s = \frac{SD}{16} = baseSD \ \times 2^{SO-4} \quad (5)$$

Every timeslot T_s of a VLC superframe must encompass T_{data} and T_{idle}. T_{data} is the maximum duration used for data transmission in a GTS. 3 T_{data}s are utilized across 3 timeslots in the defined optical frame. T_{idle} represents the period for defining the acknowledgements and Inter Frame Spacing (IFS). VLC utilizes various Inter-Frame Spaces, including long (LIFS), short (SIFS), and reduced (RIFS). The specific values of these IFS depend on the physical layer (PHY layer) on which VLC operates. Some of the PHY layers have relatively long IFS, ranging from 40 to 400 optical clocks. The PHY layers that utilize discrete light sources do not have any IFS.

As depicted in Eqn. 6, the latency T represents the duration for which a burst awaits service. It can also be represented as the time difference between the burst's arrival at the BI and the moment when the data is served. In the worst-case situation, the burst arrives at the end of the current superframe and ends up getting served at the beginning of the subsequent superframe.

$$T = BI - T_s \quad (6)$$

B. Service curve analysis of multi-channel VLC

The service provided by the network is the product of the data rate and the time at which the system receives the service. To showcase the service provided by the channel, we provide an independent service provided by the channel and the overall service representation in Fig. 4. To compute the overall service in the VLC network, we take into account the data rate, and this is achieved by multiplying the offered service with a constant data rate denoted as "D." The service allocated to the GTS, which represents the number of bits to be transmitted during a GTS within a given time interval t, is determined using Eqn. 7.

$$\beta_1 = \begin{cases} D\ ((t - (BI - T_s)))^{+}, \forall\ 0 \ \leq t \ \leq BI - \ T_{idle} \\ 0, \quad\quad otherwise \end{cases} \quad (7)$$

This value of the service curve can now be derived for N number of superframes, similar to the equation derived for the service curve for n superframes of the IEEE 802.15.7 in

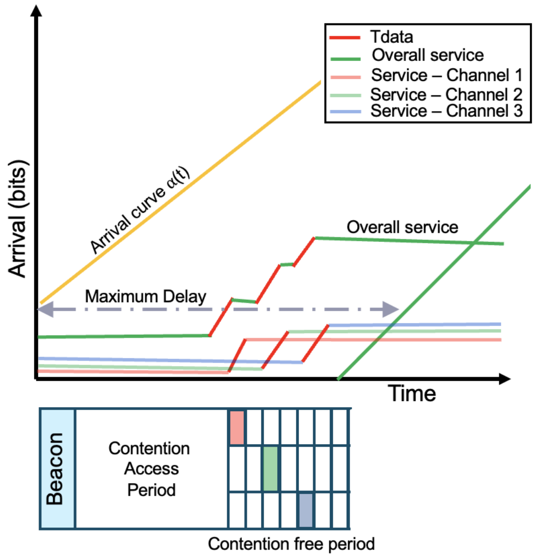

Fig. 4. Representation of the service curve, where the service of the individual channels are marked separately and the overall service can be represented by the summation of all those individual services

[16]. However, we must also consider the data transmission across every channel. Hence, When taking into account the N superframes, we also take the number of channels C where there is GTS transmitting data and multiply it across the service to define the entire service provided by the network. The service for one channel is realised by the summation of their respective data frames. This service curve that encompasses all the latencies $(n(BI - T_s))$ across the superframes acrossN_{th} superframe can be represented as:

$$\beta_N = \begin{cases} C((n-1)DT_{data} + D\left(t - (m(BI - T_s))\right)^+) \\ \forall 0 \leq t \leq (m-1)BI - T_{idle} \\ 0, \qquad otherwise \end{cases} \tag{8}$$

IV. Performance analysis

The performance analysis of our proposed method is done on two fronts. Firstly, we do a delay analysis to learn the impact on the channels over the overall delay when the data is transmitted over the GTSs over different numbers of channels. Secondly, we analyse the impact of our proposed method on the overall throughput which is the maximum amount of traffic that can be transmitted over the network at a given period of time.

A. Maximum delay bound estimation

To obtain the precise delay bound in this worst-case scenario, we can calculate the maximum horizontal deviation, denoted as $h(\alpha, \beta_{stair})$, between the arrival curve $\alpha(t) = b + r \cdot t$ and the service curve $\beta(t)$. The maximum horizontal deviation occurs at the point of intersection between the slope of $\alpha(t)$ and the burst size b.

The rate of the number of bits sent in each BI is defined as:

$$R = \frac{T_{data}.D}{BI} \tag{9}$$

In the case of the burst size $b < D.T_{data}$, the delay is the maximum horizontal deviation between the angular point and the first stair of service. The maximum delay considering all the timeslots can be given as:

$$D_{max_n} = \frac{b}{R} + (BI - m(T_s)) \tag{10}$$

Using Eqn. 9 in 10 and considering the GTSs spread across k channels the overall delay can be defined as:

$$D_{max_n} = \frac{b.BI}{k.C.T_{data}} + (BI - m(T_s)) \tag{11}$$

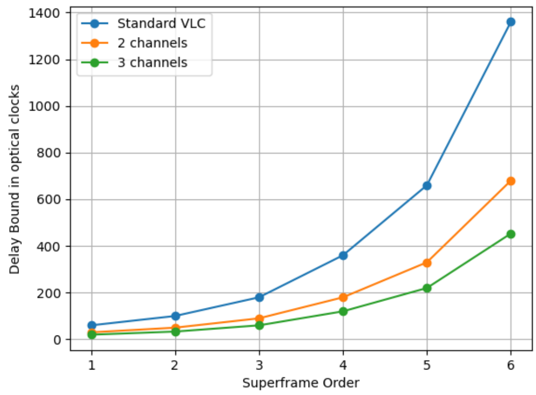

Fig. 5. Comparison of delay of the proposed method with 2 channels and 3 channels against the standard VLC superframe structure

To analyse the worst-case delay, we consider a constant burst size of 50 Mb and an arrival rate of 100 Mbps. It is clearly visible that the delay increases linearly with the increase in the superframe order. This is because with larger SO, there will be more wastage of bandwidth resulting in a larger delay. However, when more channels are available, more data can be encompassed within the GTSs slot, provided they are not overlapping, thus resulting in a reduced delay.

B. Maximum throughput evaluation

We deploy the methodology used in [16] to formulate the throughput evaluation of our proposed method. It is to be noted that the throughput is highly dependent on the inter-frame spacing that defines the interval between the data transmission.

In a typical VLC superframe frames that have a length of $aMaxSIFSFrameSize$ octets will be adjacent to a short interframe space (SIFS) period with the length $macMinSIFSPeriod$ optical clocks. On the other hand, frames with larger lengths than $aMaxSIFSFrameSize$ octets will be adjacent to a long interframe space (LIFS) period with a minimal duration of $macMinLIFSPeriod$ optical clocks. Burst frames will have minimal interframe space (RIFS) denoted as $macMinRIFSPeriod$. When the GTS is fully utilized during LIFS, SIFS and RIFS they are represented as $T_{dataLIFS}, T_{dataSIFS}$, and $T_{dataRIFS}$ respectfully.

Based on the formulation in [16], the maximum time used in data transmission can be given as:

$$T_{maxData} = \max(T_{dataLIFS}, T_{dataSIFS}, T_{dataRIFS}) \quad (12)$$

The maximum throughput of the proposed VLC network with a data rate of D and C channels can be given as:

$$Thr_{max} = \frac{T_{maxdata}}{BI} \times D \times C \quad (13)$$

For the scope of this work, we do not consider the partially used GTS where the data transmitted will be lesser than the T_{data} which is transmitted. In such a case there has to be an accountability of the wastage times along with the transmissions.

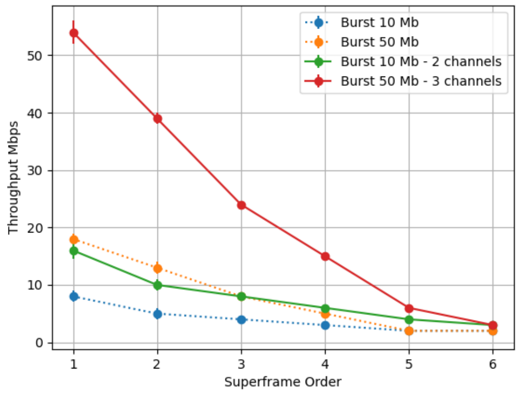

Fig. 6. Representation of the service curve, where the service of the individual channels are marked separately and the overall service can be represented by the summation of all those individual services

To analyse the throughput, we compare multiple burst sizes, it can be noticed that with 3 channels, we are able to witness almost a 30 % increase in the overall throughput. This is because with a larger amount of GTSs, more data can be accommodated. The throughput starts to diminish as the superframe order increases, this can be avoided by adaptive superframes that can resize based on the network demands.

V. Conclusion

In this paper, we proposed a multi-channel VLC superframe to meet the demands of deterministic IoT networks. We proposed a multi-superframe architecture in the standard frame of 802.15.7 to enable multi-channel communication. To accurately plan and define the bounds of the proposed network infrastructure, we did a worst-case bounds analysis using network calculus. Based on our numerical analysis, we were able to witness reduced delay by almost 30% and improved throughput. However, it must be noted that this analysis was done for a fully occupied GTS slot. There will be a wastage of bandwidth due to overfitting when fewer resources are needed by the network. In such a case, dynamic superframe architectures are needed as a viable solution.

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