Adaptive Superframe Structures for Real-Time Applications in IEEE 802.15.7-Based Visible Light Communication Networks: A Comprehensive Review

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Abstract
With the introduction of Visible Light Communication (VLC), a new possibility of high-speed, secure, and interference-free wireless communications, both indoor and in real time, has presented itself. The most important standard regulating VLC is the IEEE 802.15.7, which offers medium access control (MAC) protocols designed to suit optical wireless networks. Nonetheless default superframe design in the standard might not be adequate to address the strict needs of latency, reliability and energy consumption of the real-time sensor networks. Dynamic adaptive superframe structures, which adjust the contention-based and contention-free periods allocations, have turned out to be a viable solution to these difficulties. The scenario of adaptive superframe methods on IEEE 802.15.7-based VLC networks is systematically reviewed with a focus on real-time applications. We examine dynamic GTS allocation schemes, energy-aware scheduling, speed adaptive designs and hybrid VLC RF MAC protocols. In addition, we find major bottlenecks of existing designs, including scales, synchronicity, and mobility facilitation. The paper ends with a summary of some of the existing problems along with indicating possible

areas of research that can make future VLC systems have intelligent, flexible and efficient MAC-layer solutions.

Keywords: *IEEE 802.15.7, VLC, Adaptive Superframe, Real-Time Applications, MAC Protocols, GTS Allocation, Energy Efficiency*

1. Introduction

Fast-developing wireless communication technology has imposed demands on real-time applications in industrial automation, intelligent transport systems, biomedical monitoring, and smart homes to transfer data reliably, with high speed and low latency. Visual Light Communication (VLC) is one of the latest wireless access technologies which is superior to RF. These are the unregulated bandwidth, electromagnetic interference immunity, line-of-sight, increased security, and energy efficiency when combined with the existing lighting framework. The IEEE 802.15.7 defines the physical (PHY) and the medium access control (MAC) layers that allow short-range optical wireless communication in visible light to standardise and promote VLC systems. All PHYs (Types I, II, III) are aimed at different data rates and applications. Similar in structure to IEEE 802.15.4, IEEE 802.15.7 mixes beacon-enabled operation with GTS and contention-based stages to regulate channel access applied in the MAC layer. This framework is used in the deterministic communication of time-sensitive applications.

The IEEE 802.15.7 static superframe structure is restricted to dynamic, diversified, and time-sensitive situations. In real-time sensor networks, traffic, channel parameters, and application requirements vary in real-time, resulting in unnecessarily frequent superframe element distribution, which unnecessarily wastes bandwidth, delay, and reduces QoS. The structures that are adaptive in superframes overcome these issues by varying the MAC schedule according to network and application circumstances. Bhutani et al. proposed an efficient and adaptive superframe structure of the real-time sensor networks based on the IEEE 802.15.7 [1]. They have input-inspired CAP and CFP sizes that enhance latency and energy efficiency. The adaptive structure networks the traffic load and improves the QoS of the medical monitoring and industrial sensing environment, which does require rapid, reliable communications.

Kurunathan et al. have suggested DynaVLC, a dynamical method of GTS allocation, which allows superframe-based flexibility in real time without the loss of synchronisation [2]. DynaVLC supports IEEE 802.15.7 by the dynamic GTS slot allocation according to traffic. The strategy improved the utilisation of resources and sensitivity to traffic patterns in event-driven applications or variable data rate applications. The analysis by Kurunathan, Severino, on Tovar, which presents the worst-case bounds analysis of the IEEE 802.15.7 MAC layer, reveals its deterministic behaviour advantages and limitations in most environments [3]. They illustrate the trade-offs involved in throughput, latency and energy consumption, emphasising the need of dynamic superframe scheduling. This work has improved, but the concept of adaptive superframe in VLC systems is still hindered by an obstacle and categorising available solutions in this area. We need to be able to study, analyse and synthesise the existing body of knowledge to direct future research and development because VLC is being used more and more in safety-critical and delay-sensitive applications.

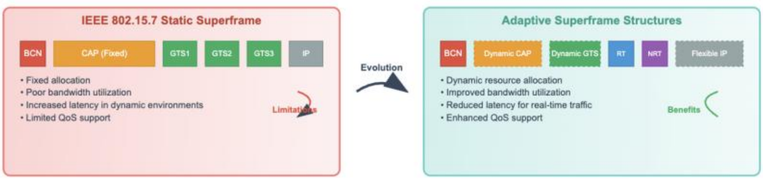

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Fig.1: Comparison between IEEE 802.15.7 static superframe structure and adaptive superframe structures for VLC networks.

Figure 1 compares the static superframe structure of the IEEE 802.15.7 with the recommended adaptive superframes techniques. The superframe components such as the beacon, contention access period, guaranteed time slots and inactive period have fixed time slot allocation. In dynamic network systems, where traffic varies, hard allocation wastes capacity, compromising latency. Adaptive superframe structures change the period duration and period allocation according to real-time network conditions and according to application needs, optimizing bandwidth usage and (QoS) to time-sensitive applications.

Fig.2: Real-time application domains benefiting from adaptive VLC superframe structures.

Figure 2 brings to the fore how adaptive superframe schemes of IEEE 802.15.7 VLC networks meet the demands of real-time applications, i.e. industrial automation, smart transportation, biomedical monitoring and smart homes. This kind of system demands low latency, high reliability and Nimble QoS- greater needs than what the static MAC designs can provide. The paper updates adaptive MAC mechanisms, their benefits, and critical issues, which can be used to guide the development of scalable, smart, and QoS-sensitive wireless communication systems, using VLC, of future generations.

There are new contributions to this paper:

- The topical article defines IEEE 802.15.7-based VLC network adaptive superframe designs according to the GTS allocation, traffic consciousness, energy efficiency, and speed adaptiveness.
- We contrast adaptive superframe algorithms in terms of latency, performance, energy and scalability.
- The article is concerned with how literature is limiting real-time applications in terms of mobility synchronisation, scale-up dynamic slot reservation, and the absence of consistent or regular evaluation conditions.
- The following study highlights recent innovations in the AI/ML-based superframe flexibility, cross-layer optimisation, and hybrid VLC-RF scheduling.

The structure of the paper is as follows. Section 2 addresses the MAC and superframe of IEEE 802.15.7. Grain-based adaptive superframe scheduling of VLC networks appears in Section 3. The approach in section 4 talks of adaptive superframe practices, including dynamic GTS allocation, energy-efficient designs, and hybrid MAC. In section 5, the major barriers to giving answers have been discussed. Section 6 sums up the conclusions of the review, whereas Section 7 gives advisory lines of research into adaptive MAC protocols of IEEE 802.15.7 VLC systems.

2. Overview of IEEE 802.15.7 Standard

To facilitate wireless communication on invisible lights, it was proposed to standardise short-range high-speed wireless communications known as the IEEE 802.15.7 standard. Visible Light Communication (VLC) is a part of Optical Wireless Communication (OWC) where data can be transported by the light-emitting diodes (LEDs), which are seen to provide beneficial features of license-free radio front, high security, and immunity to electromagnetic interferences. The standard specifies physical (PHY) and medium access control (MAC) layers, and the MAC layer implements the mechanisms used to control the access to a channel and assure the reliability of the communication [4].

2.1 Physical Layer (PHY) Overview

IEEE 802.15.7 standard provides the three different PHY types: PHY I, PHY II, and PHY III with specific application scenarios and operating conditions. PHY I is outdoor-oriented and it can manage data rates within 11.67 kbps to 266.6 kbps at On-Off Keying (OOK) and Variable Pulse Position Modulation (VPPM). PHY II is designed for indoor-only use and spans between 1.25 Mbps and 96 Mbps, whereas PHY III is less widely applied but focuses on reaching higher data rates, making use of the more complex modulation schemes like Colour Shift Keying (CSK). Table 1 indicates the most important parameters of each type of PHY defined in the standard.

Table 1: Key Characteristics of IEEE 802.15.7 PHY Types

PHY Type	Data Rate Range	Modulation Scheme	Target Environment	Wavelength Range	FEC Supported
PHY I	11.67 kbps – 266.6 kbps	OOK, VPPM	Outdoor	380–780 nm	Yes
PHY II	1.25 Mbps – 96 Mbps	OOK, VPPM	Indoor	380–780 nm	Yes
PHY III	Up to 96 Mbps+	CSK	High-speed indoor	380–780 nm	Yes

The physical layer of the standard can be flexible with respect to the lighting usage and communication needs as it is depicted in Table 1. Any type of PHY operates under the visible light (380 780 nm) and they all use Forward Error Correction (FEC) mechanisms to make transmission more reliable in a noisy medium.

2.2 MAC Layer and Superframe Structure

On the MAC layer, the MAC specification IEEE 802.15.7 is based on a beacon-enabled superframe design that is imperative in synchronisation of nodes in the network and coordination of communication media access [5]. Superframe is preceded by a beacon frame and comprises of 16 time-slots. These slots are separated into three major times:

- Beacon Period (BP) - sync and control information are provided here.
- Contention Access Period (CAP) -uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to enable the nodes to contend on access.
- Contention Free Period (CFP). Each CFP is a period comprising Guaranteed Time Slots (GTS) and is devoted to delay-sensitive or high-priority traffic.

Deterministic channel access is possible through the inclusion of GTS in the CFP, and this is what makes the CFP very important to real-time and latency-sensitive applications. The GTS assignment in the standard is fixed and, thus, constrains its versatility to varying network environments like changing network traffic or device mobility.

3. Adaptive Superframe Concepts

The idea of adaptive superframe frames has received much attention under IEEE 802.15.7 based Visible Light Communication (VLC) under the applications of time-critical and real-time communications [6]. The IEEE 802.15.7 uses a fixed superframe structure as its default MAC layer; this includes a beacon period (BP), a Contention Access Period (CAP) and a Contention Free Period (CFP), with Guaranteed Time Slots (GTS) within CFP to transmit delay-sensitive traffic. Although this arrangement meets a minimum of QoS (Quality of Service), it does not have the base response to changes on a network, claim of users, or application specifications. This has seen the evolution of the adaptive superframe concepts, which attempt to dynamically alter the behaviour of the MAC layer so as to have optimised performance.

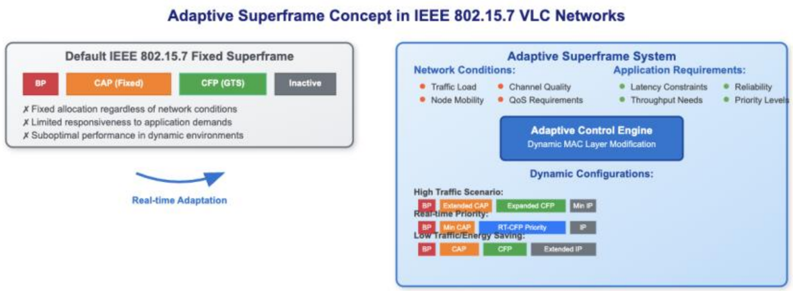

Fig.3: Adaptive superframe concept in IEEE 802.15.7-based VLC networks.

Adaptive Superframes are depicted in Figure 3, editing the transition between static MAC behaviour and dynamic MAC behaviour in IEEE 802.15.7 VLC networks. As opposed to fixed superframes where beacon period (BP), contention access period (CAP), and contention free period (CFP) are kept constant, adaptive superframes will change the length of BP, CAP, and CFP depending on the real-time conditions and demands of applications. A control engine monitors traffic load, QoS requirements and node activity to re-configure super frame elements [7]. In highly loaded conditions, CAP and CFP can be elongated, whereas idle can be lengthened in light traffic to save energy. This dynamic can be used to support more throughput, lower latencies and less energy consumption than the static allocation, but it creates problems of synchronisation, complexity and lack of compliance with the standards.

Adaptive superframes make use of the programmable parameters, including Superframe Order (SO), Beacon Order (BO), and dynamic GTS allocation, traffic prioritisation, and node activity awareness. Some of the approaches to adaptations are static-threshold-based strategies, real-time sensor. There are also methods of predicting traffic based on the history of the traffic through machine learning. Hybrid techniques will blend several methods to make it a trade between responsiveness and system stability. This is because these adaptive mechanisms come in handy, especially in fast-changing conditions such as in healthcare monitoring and industrial automation, where critical communication is essential in terms of promptness, energy conservation, and dependability. Generally, adaptive superframe frameworks improve QoS-aware scheduling as well as resource optimisation within real-time VLC networks.

4. State-of-the-Art Adaptive Superframe Techniques

Some studies have further expanded the IEEE 802.15.7 MAC layer by adding an adaptive superframe structure that supports real-time applications in the Visible Light Communication (VLC) networks. Such adaptations are largely aimed at performing better in terms of parameter optimisation, e.g., GTS allocation, CAP/CFP ratio, superframe duration, and duty cycle [8]. The section provides an overview of the prominent works that have been offered in the new literature and differentiates them based on the fundamentals of innovation and application focal areas.

A very popular method to realise real-time traffic in VLC networks is Dynamic Guaranteed Time Slot (GTS) allocation. An impressive architecture is DynaVLC by Kurunathan et al. [2], a mechanism taking place in real-time to reallocate the GTS without gathering any collisions with current GTS transmissions. DynaVLC is able to respond to the changes in traffic loads and re-allocate GTS slots, thereby optimising the existing application requirements. In a related publication [6], the same concept is generalised to a multi-channel case, improving on the scalability aspect of the application with multiple channels having a concurrent flow of data on optical channels. The strategies enhance the usage of channel and packet delay on high-priority traffic.

Bhutani et al. [1, 5] have suggested the energy-efficient structure of a superframe according to real-time sensor networks based on IEEE 802.15.7 networks. Their designs set the CAP/CFP ratio according to the activity of the sensors, so that they can adaptively save power by lowering idle listening and idle transmissions. This is especially useful in bio-sensor networks where energy is a big issue and the communication is frequently event-based. Alawadhi et al. propose a duty cycle control mechanism of heterogeneous VLC networks in [9]. Their approach alters the active/sleep state of nodes in proportion to the traffic demands, and it greatly enhanced the packet delivery ratio, and less energy is consumed.

Gupta et al. [7] proposed FD-OMAC, a full-duplex VLC MAC protocol in which the adaptation of the structure of superframe occurs when simultaneous transmission and reception are needed. This adds much, thus boosting the throughput and minimising delays in access. A self-adaptive hybrid MAC in aggregated VLC and RF networks, called self-adaptive hybrid MAC, was proposed by Kucuk et al. [11]. The protocol is smart enough to hand off and hand on the RF and VLC links and redistribute superframe constituents to preserve performance in a dynamic channel environment.

Gong et al. [8] proposed a speed adaptive superframe adjustment mechanism that dynamically adapts the insertion of preambles (PI) and post processing (PP) intervals according to the mobility of devices. This adaptation contributes to the enhancement of reliability and time synchronisation in the indoor VLC network, where the speed of devices influences the quality of the signal.

Table 2: Summary of Adaptive Superframe Techniques in IEEE 802.15.7 VLC Networks

Ref.	Technique/Approach	Core Contribution	Application Focus
[1]	Adaptive CFP/CAP Adjustment	Real-time, energy-efficient scheduling	Real-time sensor networks
[2]	DynaVLC	Dynamic GTS reallocation	Delay-sensitive VLC applications
[5]	Energy-Aware Superframe	Adaptive resource allocation in bio-sensing	Biomedical monitoring

Ref.	Technique/Approach	Core Contribution	Application Focus
[6]	Multi-Channel GTS Allocation	Channel diversity and load balancing	High-density VLC deployments
[7]	FD-OMAC	Full-duplex superframe with dynamic slots	Industrial VLC systems
[8]	Speed-Adaptive Timing	PI and PP adjustment for mobility support	Mobile VLC scenarios
[9]	Duty Cycle Control	Adaptive sleep/wake cycles	Heterogeneous VLC networks
[11]	VLC–RF Hybrid MAC	Self-adaptive medium switching	Smart infrastructure

As was shown in Table 2, the considered methods show various ways of MAC layer flexibility and performance improvement of IEEE 802.15.7 VLC networks. Such solutions mostly deal with dynamic slot allocation, energy-aware scheduling, and context-based timing changes. These kinds of innovations reach great potential to address the stringent requirements of real-time applications, especially within a mobility-based, burst-driven, or hybrid-connectivity-based environment.

5. Challenges and Open Issues

The use of A-SF in IEEE 802.15.7 VLC networks has great potential for improving the real-time performance, although their practical contribution has a number of challenges [10]. Another important matter is synchronisation because some dynamic changes to the superframe structure, like alteration of CAP, CFP, or GTS sections, need consistent communication among all nodes. Also, reconfigurability can be frequent to the level of desynchronization, hence, loss of data or loss of latency. Also, overload on computation and communication is an issue as the nodes need to evaluate the traffic and channels continuously, particularly where resources are scarce. Bandwidth can also be tested by control signalling to help adaptation. Another key challenge is scalability, since methods that scale well in small networks can perform poorly in dense deployments, where dynamic slot assignment can become complicated and centralised coordination can provide a bottleneck. In the same line, mobility and dynamic topologies that become more critical in the context of mobile VLC applications introduce additional problems associated with link reliability and frequent node reassociation that the existing adaptive schemes do not consider in most cases.

In multi-user and hybrid VLC-RF Scenarios, the two-fold complexity of interference and coexistence introduces the necessity of smart control of resources in order to prevent collision, as well as cross-technology interference. Furthermore, a lack of homogeneous systems of evaluation restricts cross-study comparisons and progress in general, and there ought to be integrated standardised benchmarking platforms. Finally, there is a great number of proposed adaptations, which are incompatible with IEEE 802.15.7 specifications and therefore may have problems with interoperability [11]. The broader requirement of solutions is achieved by designing flexible, backwards-compatible solutions with adherence to or guidance for future revisions of standards.

Table 3: Summary of Key Challenges and Open Issues in Adaptive Superframe Structures for IEEE 802.15.7 VLC Networks

Challenge	Description	Implications
Synchronization Overhead	Difficulty maintaining time alignment with frequent superframe adjustments	Packet loss, increased latency, reduced QoS
Computational Complexity	Real-time evaluation of traffic/load metrics adds processing burden	Limits applicability in resource-constrained devices
Communication Overhead	Extra control messages for dynamic coordination	Reduces effective throughput, increases energy consumption
Scalability in Dense Networks	Difficulty managing superframe dynamics in large node populations	GTS contention, reduced determinism, performance bottlenecks
Mobility Support	Lack of robust mechanisms for dynamic topology and handoffs	Link instability, session drops, re-synchronization delays
Interference and Coexistence	Difficulty ensuring clean VLC signals in hybrid or multi-user environments	Increased BER, reduced reliability
Lack of Standardized Evaluation	Inconsistent test methodologies across studies	Hinders reproducibility and cross-comparison of solutions
Standard Compliance	Deviation from IEEE 802.15.7 specifications in some proposed solutions	Limits interoperability and adoption in real-world deployments

The design of adaptive superframe structures of the IEEE 802.15.7 VLC networks faces several critical challenges as defined in Table 3. They include such technical concerns as synchronisation and computational overhead, as well as more comprehensive aspects such as scalability, support of mobility, and adherence to standards. Furthermore, a lack of a standardised evaluation framework prevents the ease with which it is possible to benchmark proposed solutions objectively [12-13]. It is in these aspects that these obstacles must be overcome to support powerful and real-time VLC systems capable of adapting to the changing needs of smart environments, smart healthcare, and industrial automation.

6. Conclusion

The paper is a comprehensive review of adaptive superframe protocols in IEEE 802.15.7 VLC networks and why it is significant in IEEE 802.15.7 VLC networks supporting real-time applications. Dynamic GTS allocation and energy-efficient scheduling, as well as a hybrid MAC protocol, are some of the key techniques reviewed that enhance latency, throughput, and power efficiency. All these developments, however, set requirements of difficulties in synchronisation, scalability and adherence to standards. Research indicates that there is a need to have strong standardised adaptive MAC solutions. It defines the existing trends in the research area and the open questions, hoping that these types of questions can be utilised in future works to realise the design of intelligent, scalable, and QoS-aware VLC communication systems.

7. Future Research Directions

Effective asynchronous protocols to organise predictive superframe scheduling should be studied in AI/ML-based adaptive MAC protocols in consideration of real-time traffic and mobility. The responsiveness and energy efficiency can be enhanced by the inclusion of PHY and MAC layers in cross-layer optimization. Provision of distributed adaptation mechanisms to enable scaling of dense networks is also necessary. The development of adaptive superframe management interoperable frameworks should be the priority of standardization activities. Lastly, testing environments and realistic models are necessary to prove theoretically proposed solutions in real-life circumstances.

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