A Comprehensive Review and Novel Strategies for Hidden Node Mitigation in IEEE 802.15.7 VLC Networks

Monica Bhutani [1] (Member IEEE), Sai Kiran Oruganti[2], Shashi Kant Gupta[3,4]

[1]Bharati Vidyapeeth's College of Engineering, Department of Electronics and Communications, New Delhi, India, monica.bhutani@bharatividyapeeth.edu, Lincoln University, pdf.monicabhutani@lincoln.edu.my

[2]Faculty of Engineering and Built Science, Lincoln University College-KL Malaysia, saisharma@lincoln.edu.my

[3]Lincoln University College, Malaysia, raj2008enator@gmail.com

[4]Centre for Research Impact & Outcome, Chitkara University Institute of Engineering and Technology. Chitkara University, Rajpura, 140401, Punjab, Índia, raj2008enator@gmail.com

Abstract

Visible Light Communication (VLC) with assigned standard IEEE 802.15.7 is a growing alternative technology to Radio frequency communication because of its wide bandwidth, intrinsic security, and unregulated spectrum. The special features of VLC, like the dependence on the line-of-sight propagation and directional light beams, contribute to its extreme vulnerability to the hidden node problem, which has an adverse effect on the network performance through intensive collisions and ineffective medium access. This paper provides a systematic overview of the current methods of dealing with hidden nodes in IEEE 802.15.7 VLC networks on the MAC layer, physical layer, and cross-layer methods. The effectiveness and the drawbacks of the existing solutions are described in detail, and it is stated that critical research gaps exist, which prevent strong and scalable implementation in dynamic VLC systems. Moreover, the novel approaches, such as a Light-Aware Hidden Node Suppression (LHNS) scheme, which aims to utilize special optical properties of VLC, can be found in this paper, to overcome the collision, and thus, to increase the throughput. The suggested methods will address the current gaps and lead to the enhancement of the state-of-the-art and contribute to a more stable and efficient VLC network. The research and recommendations provided are helpful guidelines to a researcher and practitioner towards the next-generation high-performance VLC system.

Keywords: *Artificial Intelligence, Cognitive Systems, Deep Learning, Perception-to-Action, Multimodal Integration, Attention Mechanism, Memory Emulation, Human-Like Intelligence*

1. Introduction

Since wireless high-speed connections are becoming progressively more important and the RF spectrum is saturated, Visible Light Communication (VLC) has been proposed as a possible alternative to radio frequency (RF)-based communication technologies. VLC uses unlicensed, abundant visible light to illuminate and transport data using light emitting diodes (LEDs) [1]. VLC is economically and energy-efficient in interior environments including

homes, offices, hospitals, and smart cities because to its dual purpose. IEEE 802.15.7, the first VLC standard, standardizes the physical (PHY) and medium access control (MAC) layers of short-range optical wireless communication. The standard specifies modulation techniques, frame structures, and MAC protocols for reliable data transfer in various illumination circumstances. VLC has many appealing characteristics, however light propagation limits its technical capabilities, which are outlined below: demands unobstructed line-of-sight (LOS); optical beams' high directionality causes shadowing; etc.
One of the biggest MAC layer issues in VLC networks is hidden node problem. Visual light cannot be twisted around or pass through walls, unlike RF signals, which may often pass past barriers and provide broader coverage [2].

This directional and LOS-sensitive nature increases the likelihood of hidden nodes—transmitters whose signals cannot be detected by other transmitters but can conflict at a frequent receiver. Hidden node problems cause collisions, packet loss, retransmission, poorer network throughputs, latency, and unfairness. CSMA/CA and RTS/CTS handshake protocols, standard RF-based MAC categories, have been updated for VLC with mixed success. VLC-specific restrictions such directing light signals, receiver array coverage zones, movement driven link blockages, and variable illumination levels are not met by such adjustments. Thus, unique hidden node mitigation methods tailored to VLC systems' physical and environmental features are needed urgently. Many studies have proposed alternate solutions to the VLC network hidden node problem. These include MAC protocol optimizations like carrier sensing and channel access coordination, PHY layer quality like beam steering and light intensity control, and cross-layer solutions that combine PHY and MAC protocol information to improve decision-making [3]. Projects like Hybrid VLC/RF networks combine the benefits of the technologies to establish a fallback control channel and minimize VLC MAC-level difficulties.

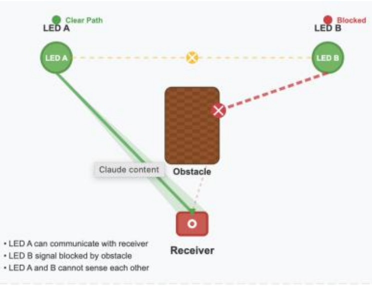

Fig.1: Hidden Node Problem in VLC Networks

Figure 1 illustrates this basic issue of a Hidden node problem that takes place in VLC networks as a result of the nature of optical communications. In contrast with radio frequency communications capable of penetrating barriers and offering omnidirectional transmission, visible light communications must follow an uninterrupted line-of-sight and exhibit very directional behaviours. Figure 2 shows a detailed taxonomy of the mitigation strategies that have been devised to help solve the hidden node issue with VLC networks. Enhanced MAC Protocol techniques centre on augmenting collision avoidance strategies that have been used on wired networks to the optical area, with light-cognizant carrier sense strategies and synchronised channel access plans that consider the directionality of VLC connections.

Fig.2: Hidden Node Mitigation Strategies for VLC Networks

The informative findings of this article are as follows:

- This paper presents a comprehensive assessment of hidden node mitigation techniques for IEEE 802.15.7 VLC networks, categorizing solutions into MAC, physical, and cross-layer domains for scholars and professionals.
- This article analyzes existing approaches, assessing strengths, shortcomings, scalability, hardware requirements, and deployment issues in indoor VLC situations, providing a critical comparison to previous surveys.
- The study introduces a novel Light-Aware Hidden Node Suppression (LHNS) technique that utilizes VLC features like directional beam, receiver field-of-view detection, and dynamic illumination mapping to minimize collisions and optimize channel availability.
- The study restructures the review and LHNS strategy, including design suggestions and open research areas for developing next-generation hidden node mitigation strategies in large-scale, dense VLC applications and mobile environments.

The rest of this paper is presented in the following way. Section 2 gives an introduction to the IEEE 802.15.7 standard and the principles of the VLC architecture of networks. In section 3, the nature and effects of the hidden node problem characteristic of VLC systems are explored. Section 4 revises the state-of-the-art mitigation techniques, which are summarised into approaches and levels of implementation. In section 5, these solutions are critically analysed and gaps in research are noticed. Section 6 presents the proposed new mitigation measures, with the idea of how they should be designed; and what benefits it may deliver. In the end, conclusions and future directions of the paper are provided in Section 7 and 8 respectively.

2. Fundamentals of IEEE 802.15.7 VLC Networks

Visible Light Communication (VLC) utilizes the visible light spectrum (380-780nm) in order to transmit wireless data and therefore presents an attractive alternative to conventional RF communication in certain environments when RF spectrum overusage, electromagnetic interference, or even security restrictions become a major challenge [4]. Along with modulation schemes such as the On-Off Keying (OOK) and the Variable Pulse Position Modulation (VPPM) as well as Color Shift Keying (CSK), onto which it is built, the IEEE 802.15.7 describe the requirements of frame formats and synchronization procedures and dimming capabilities so that data transmission is dealt with, which does not affect the illumination quality and the safety of the human eye. The standard also considers forward error correction (FEC) schemes to enhance resistance to channel degradation of; ambient light noise, multipath reflections, and shadowing.

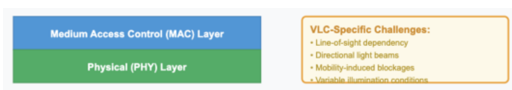

Fig.3: IEEE 802.15.7 Standard Framework and VLC-Specific Challenges

Figure 3 shows how the hidden node problem fits into the IEEE 802.15.7 short-range optical wireless communication system. The standard fixes PHY and MAC layer criteria to make VLC reliable, but optical communication has unique properties that typical RF protocols cannot manage. Line-of-sight requires unobstructed communication links between transmitters and receivers, therefore mobile users, furniture, and architectural objects can shadow VLC links. As shown in Table 1, IEEE 802.15.7 offers a wide range of application needs due to PHY modes (modulation and data rate) flexibility. It may be used for everything from low-rate outdoor signs to high-rate inside wireless personal access due to its flexibility.

Table 1: Key Features of IEEE 802.15.7 VLC PHY Modes

PHY Mode	Target Application	Modulation Schemes	Data Rate Range
PHY I	Low data rate (e.g., outdoor signage, street lighting)	OOK, VPPM	11.67 kbps – 266.6 kbps
PHY II	Moderate data rate (e.g., indoor internet access)	OOK, VPPM	1.25 Mbps – 96 Mbps
PHY III	High-speed applications (e.g., high-definition streaming)	CSK	Up to 96 Mbps

3. Hidden Node Problem in VLC Networks

Hidden node problem is the known problem of wireless networks which has a great influence on the performance and reliability of the medium access control protocols. The problem is further exacerbated in the Visible Light Communication (VLC) networks, which are principally managed in the IEEE 802.15.7 standard, owing to the distinctive qualities of the optical link, such as directionality, vulnerability to obstruction, and small coverage zones. A hidden node is a transmitter that is not inside the sensing range of any other transmitter, but whereby they may overlap at a shared receiver in case they transmit at the same period of time [6].

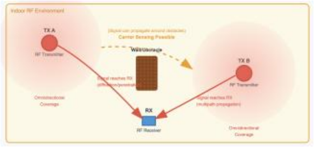

Fig.5: Hidden Node Problem in RF Networks (IEEE 802.11)

Figure 5 depicts the representation of the hidden node problem in the traditional RF wireless networks under the IEEE 802.11 standard, which proves the reason as to why this problem is more manageable than the optical communication systems. The frequency of radio waves is similarly projected in all directions in RF networks and elevates the chances of radio updates to arrive at receivers via different routes by bypassing direct line-of-sight barriers. Figure 6 shows the extreme hidden node issue of the VLC networks under the IEEE 802.15.7 standard, materializing the inherent issues that characterize optical communication as opposed to the RF systems. The LED lights are directional in nature, and thus it provides limited areas of coverage and this coverage needs clear line-of-sight to transmit a message successfully.

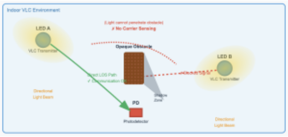

Fig.6: Hidden Node Problem in VLC Networks (IEEE 802.15.7)

The highly directional nature of the light flow is the main reason of hidden nodes in the case of VLC. In contrast to RF signals, visible light does not allow to pass through obstacles or to gain access to opaque substances like walls, furniture, or living human bodies. It makes lonesome illumination regions where a sender might fail to capture other transmission activities beyond its beam range whereas it still has the potential to cause havoc at a receiver whose situation lies within the intersection zone of two or more senders [7].

Presence of the hidden nodes causes a number of detrimental consequences to the VLC networks. The effect of hidden node collision is a corruption of frames and hence retransmission, throw-away bandwidth and latency. The high rates of collisions also compromise the effective throughput and energy efficiency of nodes to dilute the power-saving advantages of LED-based communication. As Table 2 depicts, the hidden node issue in the VLC networks is caused by the combination of various interdependent factors, including the directional beams, LOS reliance, environmental dynamics and user density.

Table 2: Summary of Hidden Node Problem in VLC Networks

Aspect	**Description**	**Impact**	**Limitation of Traditional Solutions**
Directional Propagation	Narrow light beams create isolated coverage areas	Increases likelihood of hidden transmitters	RTS/CTS ineffective without omnidirectional signaling
LOS Requirement	Obstacles block signals completely	Sudden link loss and unpredictable collisions	No robust fallback path
Mobility & Blockage	Dynamic objects change the set of hidden nodes	Frequent changes in interference patterns	Hard to adapt with static MAC parameters
Multi-user Overlap	Overlapping beams in dense deployments	High collision probability	Conventional CSMA/CA fails to detect hidden nodes reliably

4. Existing Approaches for Hidden Node Mitigation

Various techniques have been suggested by the various researchers of solving the hidden node problem in wireless networks over the years. Nevertheless, when these are applied in VLC networks, their direct implementation must be applied with caution, since the optical channel has peculiarities. In this section, the available hidden node mitigation methods are grouped into three major categories as MAC layer protocols, physical layer techniques, and cross-layer methods. The majority of the earlier attempts to resolve hidden node problem in VLC apply MAC layer enhancements influenced by the traditional RF network mechanisms. In theory, doing so is very suitable in RF, but is impractical in VLC: the signals in the visible light are not efficient to be sent out omnidirectionally and the RTS/CTS handshaking might create flicker or mess with the lighting quality [9].

In addition to MAC-based enhancements, physical layer schemes have also been studied by a few researchers: physical layer techniques take advantage of the nature of light propagation in order to overcome interference on hidden nodes. Directed beams As an example, beam steering permits LEDs or laser diodes to alter the direction of emission, just like in the decrease of overlapping with undesired receivers [10]. Since the isolated MAC or physical layer approaches are also limited approaches, cross-layer schemes and hybrid solutions have become popular as a more comprehensive solution. These strategies combine the information of both layers and dynamically reacts to different channel conditions and user contexts. An example of this would be that Cross layer protocols can utilize real time responses by the physical layer (e.g. signal strength, blockage detection, or the level of ambient light noise) to guide MAC layer decisions about slot scheduling, contention window adaptation, or priority access.

Fig.4: Performance Impact and Mitigation Effectiveness

Figure 4 measures the overall effect of the hidden node problem on VLC network performance and shows how special mitigation measures can increase system performance. Once the suitable mitigation methods are implemented as shown by the directional line, these performance penalties are converted into better efficacy of the network. MAC level RTS/CTS and adaptive CSMA/CA give a partial fix, but these are unsuitable in high-density scenarios and with directional light propagation [11].

Table 3: Comparative Analysis of Existing Hidden Node Mitigation Techniques

Technique	Key Strengths	Main Limitations	Practical Constraints
RTS/CTS Handshaking	Simple concept, well-known in RF	Ineffective without omnidirectional broadcast; adds flicker risk	Requires extra signaling overhead
TDMA / GTS Scheduling	Predictable QoS, collision-free slots	Rigid, not suited for dynamic topologies	Needs tight time synchronization
Beam Steering	High spatial reuse, reduces overlap	Requires hardware for dynamic steering	Costly and power-hungry implementation
FoV Adaptation	Limits unintended reception, enhances privacy	Mechanically complex, latency in adaptation	Expensive optics, not standard in all receivers

Technique	Key Strengths	Main Limitations	Practical Constraints
Power Control	Limits coverage area to reduce interference	May conflict with required illumination levels	Must balance eye safety and brightness needs
Cross-Layer Protocols	Adaptive and context-aware	High coordination complexity	Computational overhead, latency concerns
Cooperative Detection	Enhances hidden node awareness	Depends on reliable inter-node signaling	Scalability and synchronization challenges

As summarised in Table 3, all types of mitigation techniques offer partial alleviation of the hidden node issue at the cost of a trade-off concerning scalability, hardware complexity, cost, and adaptability. There is no single approach that can achieve the best solution in balancing between data rate performance, user comfort, economics, and robustness to dynamic conditions common in indoor VLC network.

5. Proposed Novel Strategies

In continuation with the critical examination of the current existing hidden node mitigation strategies, the proposed paper proposes a new Light-Aware Hidden Node Suppression (LHNS) framework. The suggested method is specific to IEEE 802.15.7 VLC networks, so it can use the peculiarities of visible light to overcome the limitations of the traditional RF-based approaches [12]. LHNS amalgamates three interdependent solutions: intelligent control of beam management, dynamic context-aware MAC modification and cooperative sensing among nodes. The first item of LHNS is devoted to adaptive beam shaping and steering. In contrast to fixed beam systems, LHNS-enabled transmitters are electronically steered light sources, or that the optical beam can be continuously oriented to direct the communication beam towards the appropriate receiver. This reduces the physical redundancy amongst other receivers and hence, reduces the chances of having a

The second underlying strategy is a context-sensitive MAC layer that varies its contention and scheduling behaviour according to current environmental circumstances in real-time. Each node can approximate local blockage incidents, user density and possible hidden node dangers, by incorporating lightweight sensors or getting feedback on signal quality. In case a high collision probability is felt, the MAC layer dynamically changes its contention window size, transmission priority, or slot assignments in order to reduce collisions.

Collaborative awareness among the nodes is encouraged by the third LHNS pillar. A conventional VLC system is designed in such a way that nodes mostly act independently and only with local information. LHNS improves on this by supporting nodes to exchange low metadata, e.g. current transmission state or sensed collisions, via low-rate uplink RF channels or piggybacked VLC control frames. The suggested LHNS framework consolidates the three synergetic approaches to the hidden node problem utilised to address the problem from various perspectives, as shown in Table 4.

Table 4: Key Features of the Proposed LHNS Framework

LHNS Component	Core Function	Benefit	Improvement Over Existing Methods
Intelligent Beam Management	Dynamic beam steering and adaptive beamwidth	Reduces spatial overlap, better alignment	Outperforms static beams; low collision rate
Context-Aware MAC	Real-time sensing-based MAC adaptation	Flexible slot allocation, responsive contention control	Better than rigid TDMA/GTS; adapts to mobility
Collaborative Sensing	Node-to-node sharing of status info	Enhances hidden node detection accuracy	Overcomes limits of isolated local sensing

6. Conclusion

This study reviews the hidden node problem of VLC networks using IEEE 802.15.7, analyzes the drawbacks of present MAC and physical layer protocols, and highlights optical medium-specific challenges. RTS/CTS, TDMA, and beam steering reduce hidden node interference, but they cannot guarantee network reliability with moving nodes and high illumination. Our new Light-Aware Hidden Node Suppression (LHNS) system uses intelligent beam management, context-aware MAC modification, and node cooperation in sensing to fill these gaps. With simple complexity and IEEE 802.15.7 compatibility, LHNS considerably reduces hidden node collision through spatial controllability of light and lightweight collaboration. Following thorough analysis and conceptual validation, this study shows that LHNS addresses fundamental limitations of earlier techniques and recommends a durable, expandable route for additional VLC implementations. VLC is evolving as an addition to RF communication; therefore, hidden node alleviation will be crucial to realizing its full potential in high-capacity wireless networks in the future.

7. Future Research Directions

Although the presented LHNS framework offers a potentially workable solution, there exist many research directions that are open. In the future, low-cost, real-time beam steering the systems and adaptive optics that could be easily integrated into VLC devices of quality suitable to consumers should be developed. The context-awareness and prediction accuracy will also be improved in case of hidden node situations when an efficient machine learning algorithm, which applies to resource-constrained VLC nodes, is used.

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