A Public Safety Wireless Sensor Network: A Visible Light Communication Based Approach

Dhouha Krichen[1], Walid Abdallah[1](✉), Noureddine Boudriga[1], and Antoine Bagula[2]

[1] Communication Networks and Security Research Lab, University of Carthage, Tunis, Tunisia
dhouha.krichen@gmail.com, ab.walid@gmail.com,
noure.boudriga2@gmail.com
[2] Department of Computer Science, University of the Western Cape, Cape Town, South Africa
bagula@gmail.com

Abstract. This paper investigates the design of a wireless sensor network that employs visible light communication technology to ensure an indoor public safety application intended for toxic gas detection within critical locations such as airports. To this end, a specific architecture for the VLC-based WSN was proposed which supports mobility of sensors inside the building. Moreover, an optical encoding scheme that can provide multiple access and quality of service differentiation was developed by combining both OCDMA and WDM techniques to reduce intra and inter cell interference. The quality of service provision is based on a dynamic allocation of optical code-words with variable lengths that depend on the transmission rate requirements of different classes of sensors. To reduce interferences the allocated code-words must be orthogonal. To this end, an appropriate orthogonal code-words generation approach was presented. Finally, a simulation work was conducted to evaluate the proposed network architecture.

Keywords: Public safety network · Wsns · VLC · OCDMA · Qos provision

1 Introduction

Professional Mobile Radio (PMR) public safety networks commonly known as Terrestrial Trunked Radio (TETRA) are evolving from application-specific networks to multi-applications and multi-agencies wide area networks [1]. Moreover, the PMR are scalable and can support different volume of applications from daily control operations to main public occasions such as sport and political events. Many of public safety networks are using LTE/4G thanks to its high capability to support critical voice and data services [1]. However, those LTE-based public safety networks are facing several challenges that are mainly the high cost of the fixed infrastructure and the limited communication which is based on narrow and proprietary bands.

Besides, wireless sensor networks (WSNs) are widely investigated in monitoring applications such as target tracking in border surveillance, controlling the natural environment, and forecasting natural disasters. The ability of WSNs to control physical locations without a prior infrastructure has motivated researchers to use those networks in the context of public safety. However, the radio spectrum which is allocated to sensor

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nodes is becoming very limited creating interference with other radio systems and mainly Wi-Fi devices that are submerging indoor areas like cafes and airports. A potential solution for this problem is the integration of light-based communication technology in the indoor environment.

Indeed, visible light (VLC) is increasingly investigated as a solution instead of radio frequency (RF) communication for many indoor wireless applications. This technique can ensure ubiquitous lighting and communication simultaneously. For this reason it is considered as a potential candidate to enable wireless access in 5G mobile communication networks. Moreover, VLC offers several advantages over RF. First it has license free spectrum which provides huge communication bandwidth to deliver high data rate services. Secondly, it avoids interference with RF systems. It is also nature-friendly, safe for eyes, inexpensive, and provides high secrecy and protection against eavesdropping thanks to its narrow beam width and line of sight (LOS) transmission mode.

In this paper, we investigate the use of visible light communication technology to implement optical wireless sensor networks as a major component of a public safety network implemented in the indoor environment. The envisioned application of this network is to ensure smart surveillance within airports. The surveillance includes the detection of toxic gas within a controlled area and the report of the detected incident to a central coordinator. It is noteworthy that the central coordinator can be an entity of a cloud service that delivers ubiquitous and real time communication to public safety agencies. The designed light-based WSN architecture enables mobile and real time monitoring of critical locations in airports by optimizing LEDs and sensors deployment in specific locations such as passenger's registration points, departure and waiting rooms, hallways intersections, to provide indoor coverage and communication features. Moreover, a multiple access and quality of service provision scheme based on WDM and OCDMA using appropriate optical code generation function was presented to reduce interference among sensor nodes. The code generation approach ensures the building of a set of orthogonal code-words with variable lengths that will be allocated to communicating nodes according to their bandwidth requirements. We show that this allocation approach can provide differentiated QoS for the different classes of sensor nodes. Finally, we propose a mobility management scheme to enable the motion of sensors inside the airports while not affecting the required quality of communication inside the building. The mobility management addresses the possibility of handing over sensor nodes from a VLC cell to another while not affecting the reliability of the surveillance application.

The reminder of this paper is organized as follows. Section 2 details the related work. Section 3 describes the global architecture of the proposed VLC-based public safety network. It also presents the mobility management scheme for the VLC public safety network. Section 4 describes the proposed quality of service provision scheme which is based on a dynamic allocation of optical code-words with variable length. In Sect. 5, the system performance is analyzed using a simulation work. Finally, a conclusion is drawn in Sect. 6.

2 Related Work

The Federal Communication Commission (FCC) has recently allocated a 10 MHz paired spectrum in the 700 MHz band for public safety applications [2, 3]. A unified architecture for a public safety broadband network was proposed and is based on Long Term Evolution (LTE) technology. However, the planned public safety network and existing commercial LTE networks have different characteristics. For example, the commercial networks have a more user equipment (UE) density and targets at providing different services. However, the major purpose of public safety networks is to provide immediate access to the network and a reliable communication with guaranteed quality of service. There have been many studies on public safety networks. In [4], authors developed a model for a public safety traffic under both normal and emergency scenarios. In [5], an analysis of public safety traffic on trunked land mobile radio systems was made. Indeed, it is shown that the average number of occupied channels in most cells of a commercial network is smaller compared to their capacities. In a public safety network, however, the average amount of routine traffic is much lower than that in a commercial network. In [3], a novel architecture of a cost effective broadband public safety network was developed. This architecture consists in fixed and sparsely deployed base transceiver stations (BTSs) as well as mobile BTSs. The fixed BTSs support light routine traffic, while the mobile access points are used to timely report any incident scene. This requires a deep study to determine the adequate density, placement as well as the link technologies to connect all BTSs to the fixed backhaul.

Furthermore, several research works investigated the use of WSNs for public safety purpose. In [6], authors present a general structure of an Intelligent Transport Systems (ITS) where the traffic data collection is mainly based on WSN-monitoring. A set of sensor nodes deployed throughout the roads collects and forwards measurements to a remote server which processes the data traffic and distributes this data to traffic management centers such as road control units. This collected data can be used for road safety applications. In [7], authors implemented a prototype for stadium surveillance based on wireless sensor networks. This prototype provides real time information to notify the occurrence of incidents within the stadium. Moreover, they considered security requirements that are mainly an encryption based access control and the confidentiality of the generated alert. In [8], authors address the main challenges related to resource management and context-awareness in public safety networks (PSNs) that are based on Long Term Evolution (LTE) access technology. Indeed, broadband PSNs deliver more than voice communications to first responders (police, emergency medical services, etc.). For example, PSNs ensure an integrated information database and several tools to improve the efficiency of safety applications. These tools can be either video surveillance cameras, dynamic maps or sensors. The video surveillance cameras can be used by police men to obtain more details about the scene of an incident, while the automated sensors can be used to communicate reports to firefighters or to send traffic and weather information to transportation agencies to improve road safety [9].

On the other hand, the VLC is used for several novel applications such as smart lighting, underwater communications and in-flight entertainment [10]. Furthermore, the VLC is starting to be used to ensure intelligent public safety applications. For example, in [11], authors designed a light-based architecture to enable intelligent transportation in smart cities. Moreover, they introduce issues related to the integration of the VLC technology into the networking infrastructure of the smart city. In the same context, authors in [12] introduce a VLC broadcast system which addresses LED-based traffic lights to build an intelligent transportation system. The use of VLC presents several advantages since it considers existing infrastructures and explores existing traffic lights as VLC-based road side units to build an inexpensive communication system. In addition, using VLC communication to report or prevent from road accidents enhances the road safety application because the visible light technology ensures a reliable real time communication. In this paper, we propose a communication architecture that combines VLC and WSNs capabilities to build a new communication solution for future public safety networks, especially for real time surveillance in airports.

3 A VLC-Based Wireless Sensor Network for Public Safety Control

The main objective of this work is the development of a public safety application to ensure security control in critical environments such as airports against terrorist attacks. We selected the case of the detection of toxic gas that may be spread by attackers. In this section, we describe light based toxic gas detection method by controlling reflection propriety of visible light. In addition, we describe the architecture of the VLC-based wireless sensor network intended for security control in airports and the mobility management scheme to guarantee a reliable communication to optical sensors while moving inside the building to detect security incident events related to the propagation of toxic gas.

3.1 VLC-Based Toxic Gas Detection Approach

Optical gas detection sensors typically exploits the change in intensity in an absorbent medium or the phase change of a light beam. In the first case the sensor is called “intensity detector”. However, in the second case the sensors are called “interferometric detectors”. Actually, there exists several techniques for gas detection among them we note mainly the technique of “remote sensing” known also as “LIDAR” (Light Detection and Ranging) technique [13]. This technique measures distance by illuminating a target with a laser and analyzing the reflected light. The LIDAR measurements can be used to determine the concentration of a particular gas in the atmosphere and is typically based on Infrared (IR) light.

In this paper, we investigate the VLC technology instead of LIDAR to enable an accurate detection of some gas in the indoor atmosphere of an airport. As shown by Fig. 1, the sensors that are deployed on the floor detect the light beam of the serving VLC cells and measures the illuminance intensity of the received light. If the received luminance is far less from the value obtained in the LOS case, then the sensor triggers the second phase of the detection. During the second phase, the optical sensor captures the deviation of visible light of the serving LED. Based on the direction of a deviated light ray, the sensor uses the Descartes formula to compute the optical index of the potential new environment.

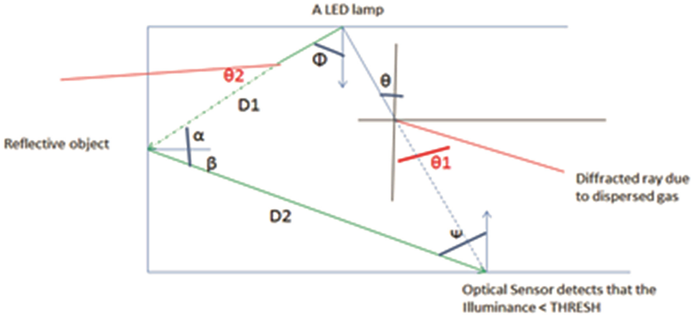

Fig. 1. VLC-based gas detection approach.

The proposed network will notify the appropriate public safety agencies about this new index indicating the emission of certain gas in the atmosphere.

3.2 Public Safety Network Architecture

The architecture of the proposed public safety network is illustrated by Fig. 2. It includes 3 main subsystems:

- The gateway which connects the VLC network to the cloud network. It is responsible for ubiquitous communication of the reported information.
- The VLC network which is composed of a set of light cells covering optical sensor nodes. The light cells are made of LEDs that are deployed in the ceiling of the airport halls and rooms to ensure visible light illuminance and communication with the optical sensor network. Moreover, each cell is allocated a single wavelength according to graph coloring technique to ensure communication with its related

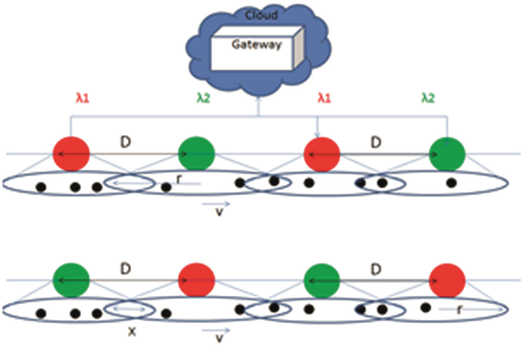

Fig. 2. Global VLC-based public safety network architecture.

nodes. It is noteworthy that graph coloring concept reduces the interference between adjacent VLC cells.
- The optical sensor nodes which are either mobile and generate heterogeneous traffic types with different quality of service requirements. Indeed, they can communicate either multimedia or data traffics.

3.3 Mobility Management

VLC systems can be classified according to their lighting modes that are mainly the "uniform lighting coverage" and "spotlighting". The first mode offers a total coverage by uniformly distributing LEDs with a wide field of view (FOV) on the ceiling. In this case, the area to cover is a wide space like hallways and aisles. The second mode is commonly used to light-up small areas like work surfaces, desktops and airplane passenger seats. Therefore, the range of VLC cells in the spotlighting mode is smaller than the range of cells in the uniform lighting mode. Moreover, the spotlighting is more appropriate for fixed users because the mobility of users is almost absent in this case. Owing to the specific properties of our network, it is more appropriate to consider mobility management only in the first lighting mode of a VLC system.

In mobility scenarios, the users can maintain their connectivity with the serving cell only if the received signal is good enough. Otherwise, the connection will be disrupted. To overcome this problem of session disconnection, we propose that the light cells are overlapped such that sensors are able to continue transmitting their traffic even if they become under the coverage of the target cell. Moreover, because sensors are always covered, they are able to communicate quickly to the new cell. Thus we avoid a long disruption of communication when switching to the target cell. To enable a reliable mobility management for sensor nodes, the following assumptions are taken into consideration:

- The distance separating the VLC cells is D (m)
- The cell range is r, where $D <= 2r$
- The cells are overlapped and the overlapping distance is $x = D - 2r$
- The sensor nodes cross a lighting cell at a constant speed v (m/s)
- Each LED has a constant data rate B (kb/s)

Even though the airport hallway can be crowded with people who could be equipped with smartphones, laptops and other mobile devices, these radio-based devices cannot interfere with our system because it is based on VLC technology.

4 Optical Codeword-Based QoS Provision

In this section, we present the proposed codeword-based bandwidth allocation scheme. First, we present an overview of optical encoding based on optical code division multiple access technique. Moreover, we present the approach used for the generation of orthogonal optical codewords. Then, we detail our proposed dynamic codeword-based bandwidth allocation method for different kinds of classes of service.

4.1 Optical Coding and OCDMA Systems

A communication channel in OCDMA system is uniquely identified by a specific code rather than a wavelength as in WDM systems or a time slot in TDMA systems. One of the main advantages of using OCDMA technique is that it simplifies the network management by almost avoiding the need for channel access control to reduce collision or allocate resources. Moreover, with OCDMA there is no need for synchronization or scheduling operations as in the case of TDMA-based networks. In addition, OCDMA provides larger capacity, and the operation of admission control are less complex than in TDMA or WDM systems. Indeed, in OCDMA each bit is optically encoded by a specific pulse sequence before transmission. The optical encoding represents the data bit by a code sequence which can be in the time domain, in wavelength domain or in both domains. On the other hand, the decoding operation is implemented by an optical receiver to recover the original sequence. The optical coding is defined as the process by which a code is injected into and extracted from an optical signal.

In the time domain, the period of the data bit is splitted into very small time units called chips. However, in the wavelength domain encoding, the bits are physically presented by a unique sequence of wavelengths used during the bit period. Therefore, a two dimensional (2D) coding is the combination of wavelengths used during particular time chips. Moreover, most of the OCDMA systems use the on-off keying technique where only data bits “1” are physically presented by an optical pulse sequence. The bits “0”, however, are not presented by any signal. Even if this technique reduces the transmission power, it represents one of the most important vulnerabilities that could be exploited by eavesdroppers.

In our network we use wavelength division multiple access (WDM) to control the optical communication within each VLC cell. We note that we use white LEDs combining several wavelengths that are mainly the red, green and blue. Indeed, all the wavelengths are used for illuminating the airport hallways and rooms. However, a single wavelength is selected to be used for communication in each light cell. To mitigate the inter-cell interference, we affect monochromatic wavelengths to the different VLC cells using graph coloring technique as depicted by Fig. 2. In addition to this wavelength division, we use optical code division multiple access (OCDMA) within each cell. The OCDMA affects for each sensor a different optical code to discriminate between sensors data traffics. However, to overcome the interference problem, the codes should be orthogonal. Furthermore, the sensor nodes may have heterogeneous traffic types (multimedia and data). Thus they have different quality of service (QoS) requirements. Therefore, it is more appropriate that the code allocation process will be dynamic and takes into consideration the quality of service constraints for each sensor node.

4.2 Dynamic QoS-Based Bandwidth Provision

In this subsection we define the properties of orthogonal optical codes (OOC) and we describe our proposed orthogonal optical code generation procedure.

4.2.1 Definition of Optical Orthogonal Codes

We mean by optical orthogonal code a set of (0, 1) sequences of length L and weight w. The weight represents the number of ones “1” in each codeword. In addition, these orthogonal codes have auto and cross correlation properties. Let’s take the example of two code words $X = (x_1, x_2, \ldots, x_L)$ and $Y = (y_1, y_2, \ldots, y_L)$ [14]. The autocorrelation of X and the cross-correlation between X and Y should satisfy the constraints given by inequalities 1 and 2:

$$\sum_{i=1}^{L} x_i x_{i+\tau} \le \lambda_a \tag{1}$$

$$\sum_{i=1}^{L} x_i y_{i+\tau} \le \lambda_c \tag{2}$$

Where λ_a and λ_c are the auto and cross correlation constraints respectively.

4.2.2 Dynamic Codeword-Based Bandwidth Provision

In this paper, we consider sensor nodes to two types of service class, the multimedia service and the data service. To discriminate between sensors traffics in our VLC system, each node should be allocated an orthogonal optical code. For this purpose, we generated two spaces of codes of different lengths, where each space is reserved for a given type of traffic class. However, the two spaces should be orthogonal to reduce interference between nodes. Moreover, we note that the first code space has codes of length L, whereas the second code space has a length of 2L. Tables 1 and 2 give an example of codes that were used for the two spaces.

Table 1. Example of codes used in the first space.

10001000	00100001

Table 2. Example of codes used in the second space.

1000000010001000	1000000000100010

Recall that in OCDMA a bit is optically encoded by a specific pulse sequence which represents the codeword. Assume that an optical codeword has a length of L chips. Therefore, the bit duration depends on the length of this code. Consequently, the bandwidth required to send a set of bits will depend on the code length. Consequently, the shorter the code is the greater is the allocated bandwidth. Because each sensor data is encoded with a given codeword, the length of the code affects the bandwidth consumption by each sensor. We assume that B is the total bandwidth available in the system and N is the total number of sensor nodes. Consequently, each sensor node will be uniformly assigned a minimum bandwidth of B/N.

However, in our application the sensors are heterogeneous and belong to different classes of service. Therefore, they have different QoS constraints. For this purpose, it is better to allocate bandwidth to the different sensors according to their requirements. This can be done by allowing a dynamic code-word assignment during which the length of optical code-words is dynamic and depends on each senor node requirements in terms of bandwidth. For example, the codes with shorter length will be allocated to multimedia sensors and the code-words with longer length will be affected to sensors that transmit data traffic.

5 Performance Evaluation

In this section, we evaluate the performance of the proposed dynamic codeword-based bandwidth provision. A simulation model is developed by considering a case study of an airport which we aim to secure against malware behaviors. For this purpose, we consider a hallway of length 16 m and width 3 m. In the ceiling of the hallway, we deployed 8 LEDs that are separated by a uniform distance to enable a VLC communication network. In fact, each LED forms a VLC cell of a certain coverage radius. Moreover, the lamps are not used only for illuminating the hallway, but also to communicate security information to the public safety network via a cloud gateway. To save the use of wavelengths, we considered only two colors (the red and the blue) to perform the communication feature. We assume also that each LED has a data rate of 256 kbps.

On the other hand, we consider a set of sensor nodes that are deployed on the floor of the considered hallway. It is worthy to note that the sensors can be either camera nodes, smart phones equipped with cameras, or ordinary sensor nodes that are responsible for detecting suspicious events or behavior and communicate the collected information to the LEDs via VLC links. Moreover, we note that the sensors are heterogeneous and have different traffic types. For example, in our simulations we considered multimedia and data nodes. In addition, the sensors are mobile and have a constant speed. Moreover, we considered the case where the VLC cells have the same coverage radius and are overlapped. Recall that the overlapping distance is the difference between the distance separating the LEDs and the double of the radius.

To discriminate between the sensors channels in the uplink direction, each node is allocated a codeword which should be orthogonal with the other code-words of the other nodes. Because the sensors belong to heterogeneous service classes, the bandwidth allocation should be scalable. For this purpose we consider codes of dynamic code length. Because the multimedia sensor nodes are more demanding in terms of bandwidth than data nodes, we allocated codes of smaller length to the multimedia sensors. In our simulations, we used codes of length 8 for multimedia traffic transmission, whereas data traffic is encoded using codes of length 16. The simulation parameters are given by Table 3.

Figure 4 shows the variation of the average transmission delay in function of the number of sensors that are deployed on the hallway for the two types of traffic. We note by average transmission delay the average time between the first sending of the message and the reception of the proper acknowledgment. As it is shown by the curve, the average transmission delay is an increasing function of the number of sensors due to the interference problem. For data traffic, the transmission delay varies from 7 to 19 ms.

Table 3. Simulation parameters.

Parameter	Value
Code length of multimedia service	8
Code length of data service	16
Data rate (kb/s)	256
Number of Leds	8
Number of wavelengths	2
Distance separating the LEDs (m)	4
Cell range (m)	2
Height of the hallway (m)	3
Number of sensors in the hallway	5,10,15,20,25
Speed of sensors (m/s)	2

However, for multimedia traffic it remains under 10 ms. In fact, with a short code length, multimedia traffic is able to transmit more bits than data traffic. This is because the encoded data for both traffics has the same chip duration but not the same bit duration. We notice that the delay of data traffic is almost two times the delay of multimedia traffic. This can be explained by two reasons. Firstly, multimedia codes have half the length of data codes. Therefore, multimedia sensors transmit with more important data rate. Secondly, multimedia nodes have the priority to transmit in case of interference.

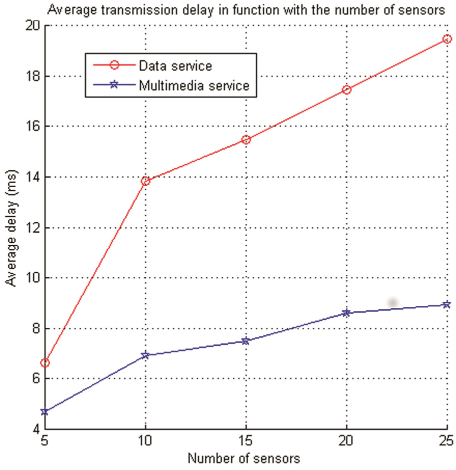

Fig. 4. Average transmission delay in function of number of sensors.

Figure 5 shows the variation of the success rate in function of the number of sensors that are deployed on the hallway for two types of traffic. We note by success rate the rate of packets that were successfully transmitted and acknowledged. As it is shown by the curve, the success rate is a decreasing function of the number of sensors. This is because the interference becomes more important with additional nodes. For data traffic, the success rate decreases from 100 % to 77 %. However, for multimedia traffic it decreases from 100 to 75 %. Indeed, as the multimedia sensors are more demanding in terms of QoS, they are allocated codes with shorter length to allow more bit rate. Because the length of codes of multimedia sensors is half the one of data codes, then the allocated bit rate to multimedia nodes will be the double. This is the reason why the success rate of multimedia service is higher than the one obtained with data service. In addition, we note that the delivery ratio is kept under 75 % which is an acceptable rate. This is ensured thanks to code orthogonality allowing the discrimination between traffics of sensors, which in turn will mitigate the interference problem.

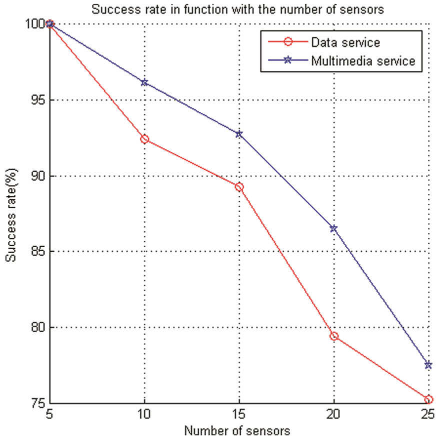

Fig. 5. Success rate in function pf number of sensors

6 Conclusion

In this paper we investigated the use optical WSNs with VLC technology to ensure an indoor public safety application within airports. In addition, we designed an appropriate architecture of the VLC-based WSN. Moreover, we choose a QoS-aware multiple access scheme combining both OCDMA and WDM techniques where codes are dynamically allocated to different sensors according to their requirements in terms of QoS. Finally, simulation results show that the proposed scheme can satisfy QoS constraints by reducing transmission delays and ensuring acceptable success rates. We intend to focus on the nodes energy consumption issue in future works.

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