Visible Light Positioning: A Roadmap for International Standardization

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ABSTRACT

The widespread introduction of white LEDs for illumination provides a unique opportunity to create an indoor positioning system that is flexible, accurate, and ubiquitous. Signals transmitted by the LEDs are used to determine the position of a person or object within a room. To take full advantage of this new opportunity, it is essential that comprehensive and robust international standards are developed before a plethora of incompatible proprietary systems flood the market. In this article, we discuss the very diverse range of potential applications of these future systems and their implications for the design of a new standard. Another consideration is that the transmission of positioning signals must not compromise the primary function of the LEDs, which is energy-efficient illumination, so visible flicker must be avoided. Position information can be derived from a range of properties of the received signal, such as the power of the received signal or the angle at which the signal reaches the receiver. The suitability of different techniques for an indoor positioning system is considered. Finally, we discuss the implications each of these aspects has for the design of an effective standard.

INTRODUCTION

Positioning, also known as localization, is the process of determining the spatial position of an object or person. Accurate positioning is critical for numerous applications. The familiar Global Positioning System (GPS), originally a U.S. military system, is now in everyday use around the world, often in new and unexpected ways. Unfortunately, GPS is not suitable in many indoor situations. To obtain location information using GPS, a device must be able to receive signals from a number of GPS satellites, and this is often not possible indoors. Even when GPS positioning is available, it may not be accurate enough for many indoor applications. Despite decades of research into indoor positioning using technologies such as radio systems based on wireless local area networks (LANs), there is still no system that is cheap, accurate, and widely available [1]. The fundamental problem in radio-based systems is multipath propagation. Radio signals may reach a receiver by both direct line of sight and multiple reflected paths. This means that there is no simple and reliable way of determining the distance or direction of the transmitter from the received signal.

The widespread introduction of white LEDs for illumination provides an unprecedented opportunity for visible light positioning (VLP) to fill this gap, and form the basis for a widely available, economical, and easy-to-use indoor system. Look up in almost any building and you will be able to see multiple light fittings, demonstrating that at most indoor locations, a receiver could be designed to receive line-of-sight signals from multiple light sources. The introduction of LED lighting creates a new opportunity for creating an indoor positioning system. This was not possible with conventional lighting, but LEDs have a number of key advantages. First, LEDs can be modulated at much higher frequencies than conventional lighting, so the signals required for positioning can readily be transmitted at frequencies that do not cause visible flicker. Second, although LED lights are initially more expensive, they have a much longer lifetime, typically several years. This means that the added cost of constructing lights with the extra functionality required for positioning will be relatively smaller, and the benefits longer lasting.

There are already a number of standards for visible light communications (VLC) including IEEE 802.11 IP PHY, IEEE 802.15.7, and JEITA CP-1221. There is also one standard that is directly relevant to VLP: the JEITA CP-1222 Visible Light ID System, published in 2007, which describes a protocol for transmission of identification signals from LEDs. However, while these early standards show great foresight concerning the importance of VLC and VLP, there has since been a large body of international research on these topics, and the results of this recent research are not incorporated in these proposals [2–5]. Future standards will build on and extend the earlier standards. For example, the IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) is already considering how positioning can be incorporated in evolving camera communications standards.

VLP systems could be designed with a number of fundamentally different architectures depending on whether there is cooperation among the lights transmitting the signals and/or with the device for which the position is being determined. In this article we assume that there is no cooperation. The lights simply transmit predetermined signals. While this architecture may not provide the most accurate positioning possible, it is the simplest to install and possibly the most economical, and, we believe, if properly designed and standardized, has the greatest potential for widespread adoption.

Telecommunication standards usually specify the format of the signals to be transmitted, leaving the design of receivers to individual manufacturers. Using this principle, in the rest of the article we discuss what properties these transmitted signals should have if they are to form the basis of an indoor positioning system of the future.

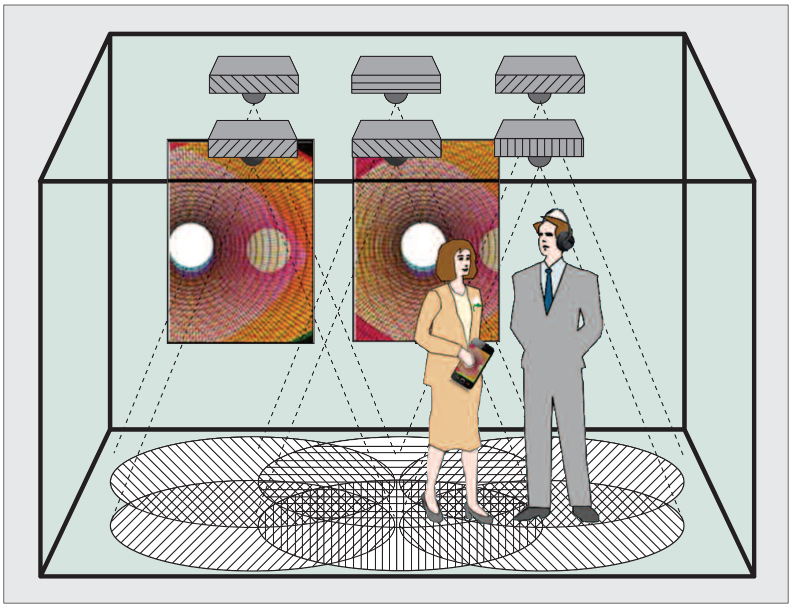

Figure 1. *Two uses of visible light positioning in an art gallery. The headset worn by the man detects its position and plays recorded information relevant to the picture in front of him. The woman is using a location-aware service on her tablet computer.*

Applications of Indoor Positioning Using Lighting LEDs

The new LED-based indoor positioning systems will have a multitude of different applications. Just as the inventors of the GPS system could never have envisaged the huge range of GPS applications currently in use, it is impossible to predict all the future uses of VLP. However, it is already obvious that there will be many different types of applications, with different constraints. These have implications for how a robust and flexible standard should be designed.

Figures 1 to 3 show four different future applications of indoor positioning, which have very different localization and communication requirements. Each figure shows a room of the future, where six light fittings are transmitting signals that can be used for localization. In Fig. 1, the man wearing headphones is listening to recorded information about the artwork in front of him. This is an automated version of the headsets currently provided by museums and other places of interest, which require a number to be entered by the user at each exhibit. In a VLP-based system, a receiver in the headset would detect the signal from the nearest LED and play the relevant commentary.

Another very important use of the new systems will be in asset tracking. Figure 2 shows an example of a system being used to track the position of a wheelchair or a portable medical device, an application that is important in hospitals. The same concept could also be used for a host of other purposes such as tracking trolleys in airports or consignments in warehouses. The receiver on the wheelchair detects the identity of the nearest LED and transmits this information using a radio system such as ZigBee or a wireless LAN to a central computer. The computer maintains a database of the identity of the LEDs and their locations. The receiver needs only to transmit information about its position intermittently, so it could be a low-power battery operated device. Note that in these first two applications, the receiver needs only to determine the *identity* of the LED, not its *position*.

The third example is a location-aware service, which is being accessed by the woman shown in Fig. 1, through a portable communication device such as a smartphone or a tablet computer. There are already many examples of applications of this kind using GPS. The use of VLP will mean that they could also be used reliably indoors. It will also enable a number of new applications, such as accurate indoor navigation based on building plans. A device on the mobile phone, possibly a camera, receives the signal from the lights. The device accesses location-based information by transmitting information about the position or identity of the nearest LED to the Internet via a radio connection. In this application, two different approaches are possible. The first requires only the identity of the nearest light; the translation of this to position information is done in a central database. The second approach is where the position of the light is determined from information transmitted by the LED itself.

The final class of application is one that requires more accurate positioning. In this case, simply knowing the identity of the nearest light is not sufficient. Figure 3 shows a mobile robot using position information to determine its path, but the same concept could be used as an aid for the visually impaired [6], or as part of a home monitoring system for the frail or elderly. Clearly the range of possible applications is huge.

Characteristics of LED Lights

The design of the new VLP systems must take into account the characteristics of LEDs and the constraints imposed by the use of indoor lights as part of a positioning system. The primary function of LED lights is to provide lighting, and in particular energy-efficient lighting, so it is critical that an LED positioning standard does

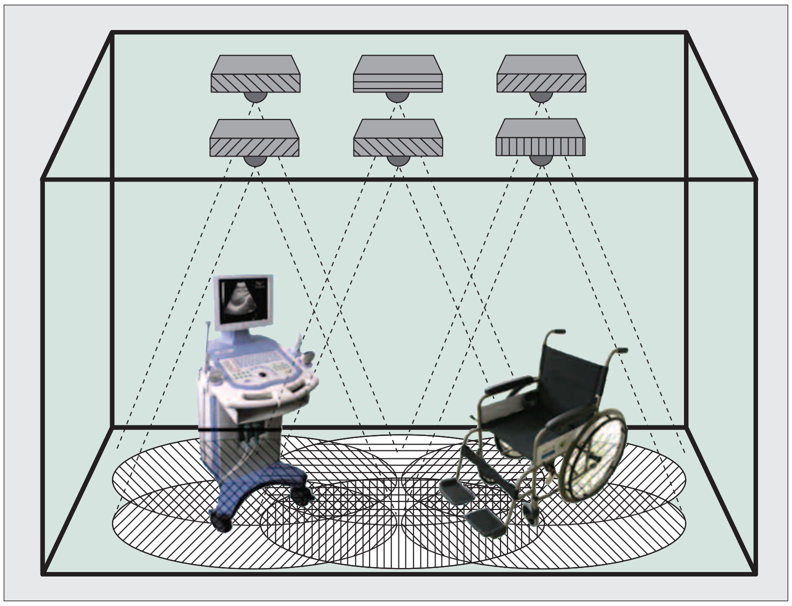

Figure 2. *Use of visible light positioning for asset tracking in a hospital to locate the positions of the trolley and the wheelchair.*

not compromise either the energy efficiency or the quality of the light. The positioning signals transmitted by the LEDs must not cause visible flicker, or detectable color changes. Many lighting systems allow the level of lighting to be adjusted, so the positioning function must be compatible with dimming as well.

Ideally the VLP standard used should be compatible with all types of lighting LEDs. There are currently two forms of white lighting LEDs. The first uses a combination of red, green, and blue LEDs to produce light that is perceived as white. The second uses a single blue LED with a phosphor coating that produces light with a broad spectrum. As both are available, it is important that any future standard should apply to both. This implies that positioning information should not be coded in the color of the light, and may also have implications for the highest frequencies at which the light can be modulated.

A major advantage of lighting-based systems is that the available bandwidth is not restricted by concerns about interference with other users in other locations. Within a room, all of the available transmission bandwidth can be dedicated to VLC and VLP. For phosphor coated LEDs, the modulation bandwidth of the broad spectrum component is typically around 2 MHz, while for the blue component this may be up to 20 MHz [7]. The amount of information that is required for localization purposes is likely to be quite modest. This means that bandwidth efficiency can be sacrificed if it results in a simpler system. For example, signals can be transmitted at frequent intervals.

There are a number of other important advantages of VLP systems. Installing them will be almost as simple as changing a lightbulb. The fittings already have a power supply for their primary lighting function, and the additional power required for the VLP function is likely to be very small, so usually no rewiring will be required. Using power line communication (PLC), it may also be possible to provide relatively high-speed data connectivity to the devices without rewiring. This is an important enabler for VLC.

Positioning Techniques for Accurate Localization

When accurate positioning is required, as in the mobile robot example of Fig. 3, the VLP receiver will use the received signals to determine the relative distance and/or direction of a number of LED transmitters. These measurements will then be combined using classical triangulation (using angle of arrival information) or trilateration (using path length or time of arrival information) to determine the position of the receiver. We now discuss a range of positioning techniques and their suitability for use with lighting LEDs.

Many of the indoor positioning systems that are based on radio signals use received signal strength (RSS) to estimate the distance of the receiver from the transmitter. In general, as the distance between transmitter and receiver increases, the power of the received signal falls. However, the effects of objects blocking and reflecting the radio signal mean that the relationship between distance and RSS is unpredictable, limiting the accuracy of an RSS approach in radio-based systems.

Many of the papers published so far on VLP have also used RSS [8, 9]. This work has shown that if the properties of the optical channel between the transmitter and receiver, and the power of the optical power transmitted by each LED are accurately known, very accurate positioning can be achieved. Unfortunately, these conditions are unlikely to be true in practice. The transmitted optical power is very unpredictable. It will depend on the particular LED and the level of dimming. It will also vary with time, and even with factors such as how clean the light fitting is, or whether someone or something is partially blocking the path between light and receiver. Note that although the mechanisms that make RSS potentially unreliable in VLP are very different from those in radio-based systems, the overall result is the same — while rough estimates of position can be made, a number of factors limit the accuracy achievable in practice.

Time of arrival (TOA) is another technique often used in localization, and is the basis of the GPS system. However, it requires the transmitted signals to be very accurately synchronized. For example, the synchronization of the signals transmitted by GPS satellites is based on very accurate atomic clocks. This is clearly not an option for economical positioning systems based on LED lighting, so it is possible but not optimal. The need for accurate transmitter synchronization can be avoided if time difference of arrival (TDOA) rather than TOA is used. In this case, there must be at least two receivers with accurately known distance between them. The TDOA of signals reaching the two receivers gives information about the difference in path length from the transmitter. However, as the signals travel at the speed of light, and the distance between receivers in indoor applications will necessarily be small, extremely accurate time measurement is required. Localization systems based on phase of arrival (POA) and phase difference of arrival (PDOA) have similar drawbacks.

The most promising method for the new VLP systems is angle of arrival (AOA). AOA positioning is not often used in radio-based systems because there is typically no line of sight (LOS) between a transmitter and receiver, and also because of the problems caused by multipath transmission. For radio-based systems, there is often very little relationship between the AOA of the radio signal and the direction of the transmitter. The situation is very different for VLP. The receiver will virtually always have LOS to a number of lights. Although, in addition to the LOS component, the received optical signal will often have a diffuse component due to light reflected from walls and other surfaces, this component is usually very small relative to the LOS component [10], so any resulting error in AOA estimation will be relatively small. A second factor that makes AOA-based positioning very promising for VLP is that lenses with quite precise designs are economical to manufacture. This means that relatively simple optical systems can provide accurate AOA information. This is very different from radio systems where determination of accurate AOA requires sophisticated antenna systems.

The choice of positioning technique has implications for the choice of signals transmitted by the LEDs. The theoretical limits on accuracy obtainable in TOA-based systems depends on the effective bandwidth of the signal [11]. This means that, in the context of LED based systems, to achieve the highest accuracy of positioning using LEDs, as high a frequency as possible should be transmitted. One of the many advantages of AOA-based systems is that the accuracy depends on the ability to identify a given light source, not on the frequency of the modulated signal.

Another consideration in the design of an accurate positioning system is whether it is important that the position is known relative to some general coordinate system (e.g., latitude and longitude) or the position relative to, for example, the corner or edge of a room is what is required. A robot navigating along the center of a corridor may need to know where it is in a room, but not where it is in the world. A flexible, robust international standard for VLP should provide for both options.

What Information Should the LEDs Transmit?

We now discuss what information the LEDs should transmit. It is clear from the discussion of applications that there is a hierarchy of different requirements with different implementation complexities. A useful standard should incorporate these different requirements in a way that allows simple applications to be economically implemented, but does not preclude more sophisticated applications and allows for future extension as yet undreamed-of applications.

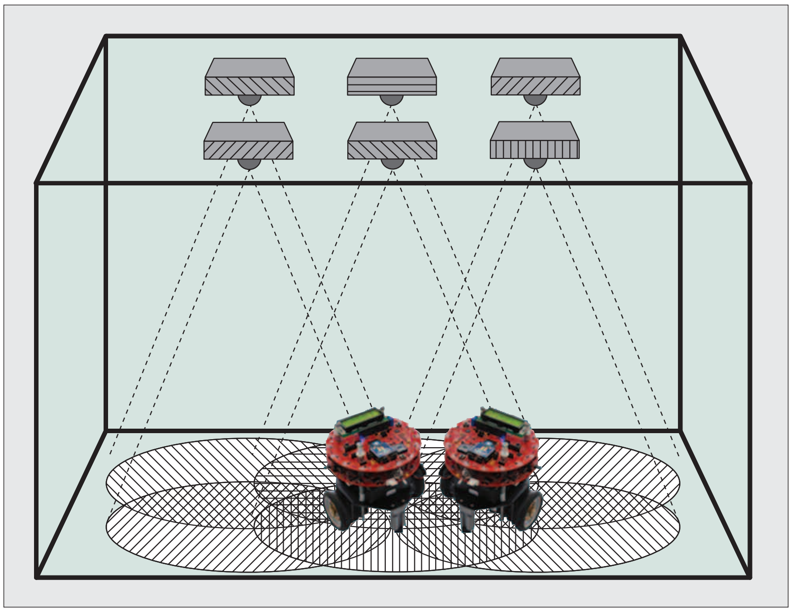

Figure 3. *Visible light positioning to give accurate positioning information for mobile robot navigation.*

A typical way to achieve flexibility in communication standards is to have a header in the transmitted sequences which indicates what type of system is being used, with the rest of the sequence providing the information required for that system. In the art gallery example, each light needs to transmit only a sequence that identifies it from among other lights in the same art gallery; the number of different required sequences is likely to be on the order of hundreds or thousands. In this case, the organization could order a set of preprogrammed lights and maintain its own database mapping light to location. The same approach could be taken for the example of asset tracking in a hospital.

For location-aware services like the third example, the receiver ideally needs to identify its actual position globally, by transmitting either a globally unique code or coordinate information. The use of a globally unique code provides some interesting possibilities. For example, during manufacture, a unique code could be programmed into each light that has this feature. The need for such a global identifier has been anticipated in other fields, and there is already an IEEE managed 64-bit global identifier, called the EUI-64 [12]. The problem, then, is how to translate this information into a location for location-aware systems. Where are these "directories," who maintains them, and who pays for them? One possibility is that, as with telephone directories, organizations could pay to have their codes held in a given directory. Another important advantage of using the EUI-64 code is that standard procedures already exist for generating IPv6 addresses from them. This means that this aspect of VLC and VLP can seamlessly be combined based on existing standards.

Another possibility that has been suggested is to use a code that contains the latitude, longitude, and height of the light. The system that has

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been suggested divides the Earth's surface into 3 m × 3 m squares [13]. Each light would transmit the appropriate code. This system has several drawbacks. One is that the light has to be programmed on site, adding a considerable degree of complexity to installation of the new light fitting; a second is that the location of each light fitting in a global coordinate system has to be determined.

The final example of application, robot navigation, requires accurate localization. As position relative to the coordinates of a room are more likely to be important than absolute coordinates, we suggest that systems of this kind are programmed at manufacture with a globally unique code which is used to identify individual lights, and that a code which gives the position in x and y distances in meters relative to, say, the most northerly corner of the room is programmed as the lights are installed.

In summary, we envisage a flexible format that encompasses a range of uses. Depending on the application, the LEDs will transmit identification codes from either a small number of codes used only within an organization or a globally unique code like the EUI-64. For applications involving VLC, the LED may also transmit an IPv6 address. In addition, in applications requiring knowledge of the position of the device in a global or local coordinate system, the LEDs will transmit information about their position using 3D global coordinates and/or a 3D local coordinate scheme relative to the corner or the edge of the room.

Types of Receiver

A standard for transmission must also consider any potential requirements of the receiver; again, a number of configurations can be envisaged. For applications where only the identity of the nearest light is to be determined, it may be possible to design receivers based on simple photodetectors with wide fields of view, followed by some signal processing that extracts the identification information. These also have the advantage of being able to detect signals at relatively high frequencies.

To determine the AOA information required for accurate positioning, an imaging receiver is required. Many consumer devices now include cameras, and it would be ideal if these could also be used as the receivers in the new systems. Unfortunately, due to the lower frequency limit imposed to avoid visible flicker, there is no bandwidth overlap with the relatively low frame rate of low-cost cameras. Signals low enough in frequency to be captured directly by the cameras would cause unacceptable flicker of the light. One partial solution, which has been proposed by a number of researchers, is to make use of the "rolling shutter" feature of typical low-cost cameras. The interaction of the modulated light and the rolling shutter result in patterns in the image that can be used to identify the transmitted signal. Other researchers have proposed solutions based on subsampling. Conventional cameras also have relatively narrow fields of view (FOVs), and this may not include enough lights to enable triangulation or trilateration. The potential of a simple wide angle lens to solve a similar problem in optical wireless communications has recently been demonstrated [14].

We predict that the accurate positioning systems of the future will use novel configurations of lenses with photodetector arrays with much lower resolution than cameras but with much wider bandwidth. Perhaps the smart phones of the future will have novel camera-like devices that are designed to serve the dual purpose of conventional camera and AOA detector for VLP. As such, it is the constraints on transmission (flicker avoidance) that impose requirements on the receiver, rather than the other way round.

Format of Transmitted Signal

In the above sections we have discussed what information should be transmitted, but not what modulation format should be used. To enable the simplest, lowest-cost systems, it is important that the modulation system used for the position information is very simple to generate and detect. Perhaps some simple signaling system based on on-off keying (OOK) or pulse position modulation (PPM) of all or a portion of the transmitted light for a short time interval could be used. As the amount of data required for the identification code is relatively small, only a small proportion of the available time and bandwidth are required. If the system is also to be used for high-speed data transmission using advanced formats such as orthogonal frequency-division multiplexing (OFDM) [15], the position information can be transmitted between data frames. In other words, the choice of modulation format for the positioning application does not need to constrain the choice for other applications as long as the overall frame format is carefully specified.

Conclusions and Future Directions

Visible light positioning is clearly an important technology for the future. In the above we have presented broad guidelines about factors that should be considered in designing a new robust and flexible standard, but there remain many unanswered questions, and there is an urgent need for research across many fields.

The theory of localization based on intensity modulated direct detection (IM/DD) LED-based systems is in its infancy, and much of the theory developed for radio systems does not apply. Unanswered questions include:

- What are the theoretical bounds on different forms of localization using IM/DD?
- How do they depend on the signal-to-noise ratio (SNR) and frequency of the transmitted signal?
- How does the accuracy of AOA-based position estimation depend on the size of the light fitting and the angle it subtends at the receiver?
- What is the required resolution of an imaging receiver?

There are also many properties of the transmitted signal to be determined, including:

- What modulation scheme should be used for the transmitted information?
- How often should the identification messages be transmitted?
- How is interference between signals from different lights managed?
- If modulation schemes such as PPM or OOK are used, should all or only a proportion of the power be modulated?
- How can VLC be integrated with VLP?

Similarly, there are many important research topics concerning the optical design of the transmitters and receivers:

- How do aspects of the design of the lighting system such as the position and directivity of the light beams affect VLP?
- Can devices be designed for the smart phones of the future, which perform the dual role of camera and receiver for an accurate positioning system?
- What are the implications for VLP of the emerging standards of lighting control, color control and bus systems for LED-based lighting control?

VLP is clearly an exciting new technology with many future applications, but there is an urgent need for cross-disciplinary research across the usually separate fields of optics, modulation theory, and localization.

Acknowledgments

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