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Abstract

In this paper we introduce a new technology, called Lumicast, for mobile device positioning in indoor environments. The technology uses LED light fixtures to broadcast positioning signals via amplitude modulation of light in a way that does not impact the fixtures’ primary function of providing illumination. A mobile application that incorporates the Lumicast software framework can decode these Visible Light Communication signals and use them to determine the position of the mobile device. Given its compatibility with existing smartphone devices and LED lighting infrastructure, this technology is able to support a broad range of indoor positioning applications in commercial, office and industrial settings, and has been adopted by leading players in the LED lighting ecosystem such as Acuity Brands [1], [2] and GE Lighting [3].

Introduction

Over the last decade there has been a concerted effort in the technology industry to develop an accurate, reliable, and commercially viable system for indoor positioning of smartphones. The expectation has been that such a system would add a new dimension to the utility of smartphones indoors, and have a similar revolutionary effect that GPS has had on their use outdoors. Indoor positioning is of particular importance to owners of retail stores, who view mobile positioning as a means to engage with their customers and offer new shopping experiences, streamline their in-store operations, and analyze the effectiveness of the store inventory and layout. Some of the use cases include:

• Precise navigation to products on a shopping list,
• Product recommendations exactly where and when purchase decisions are made,
• Path optimization for employees conducting remerchandising,
• Fast validation of the layout of products on a shelf (a.k.a. the planogram),
• Location analytics such as aggregated dwell-times and foot traffic patterns of visitors.

For a positioning technology to be broadly adopted by consumers and, consequently, for it to fully unlock the commercial potential of location-based services, it must, above all else, provide a compelling experience to the end user. The key technical criteria that can enable this are the following.

• Accurate, stable position estimates that exhibit little jitter/noise,
• Low latency and high update rate, yielding responsiveness and smooth tracking,
• Ubiquitous coverage of the indoor venue,
• High power efficiency ensuring minimal impact on a smartphone’s battery life,
• No self-interference so that performance is not reduced in the presence of other users,
• No interference to, or from, the incumbent wireless communication systems.

To date, widespread adoption of indoor location technologies has been slow. The reasons for this are both technical and business-related. From the technical standpoint, the mainstream approaches have, in many cases, failed to achieve the key performance
metric outlined above. Systems that track the strength of RF signals, such as those transmitted by Wi-Fi access points, suffer from low accuracy and high latency caused by multipath propagation in indoor environments [4], [5]. In the case of commercial Wi-Fi positioning solutions, typical accuracy of positioning is roughly six to ten meters. If the transmitters are Bluetooth radios, the impact of multipath propagation on the narrowband signals is even more severe, creating large signal fluctuations over time [4]. Even systems based on dense deployments of Bluetooth radio transmitters can only achieve accuracies of around three to six meters, though better results are possible with fingerprinting [4], [5]. In order to get the most out of systems that track RF signals (and those that track the strength of the ambient magnetic field [9]), a fingerprint map of the signal/field strength must be created and periodically refreshed. Since this is usually done by manual surveying, the cost of maintaining the system can jeopardize the business case for the technology.

In addition to the operating cost, the business case for a positioning solution also depends on whether it can work within the constraints of hardware available on commercial smartphone devices. A technology which requires specialized hardware in the handset is always going to be at a great disadvantage, in this regard, relative to a technology that does not have such requirements and that works with millions of devices that are already available; case in point are methods that use Ultra-wideband signals (UWB) [5] for which there is no support in commercial smartphones. Not requiring new hardware in the handset is particularly important if new infrastructure is needed for the positioning system to work. Analogously, technologies which require new dedicated infrastructure are always going to be at a disadvantage relative to those that reuse the infrastructure that already serves a function in the enterprise’s venues.

In this paper, we describe a novel positioning technology that solves the technical and business challenges of the former approaches by utilizing a venue’s lighting infrastructure and the sensors available in commercial smartphone devices. The technology is based on the concept of Visible Light Communication (VLC) in which LED light fixtures broadcast positioning signals using rapid modulation of light in a way that does not affect their primary functionality of providing illumination. The positioning signals are decoded by smartphone devices using their built-in front-facing camera (image) sensors and are used to compute the device’s position in the venue.

This technology, called Lumicast, has been developed at Qualcomm Research, a division of Qualcomm Technologies, Inc. and is commercially available for licensing* as a software product of Qualcomm Technologies, Inc.

The Lumicast system is capable of achieving position accuracies on the order of ten centimeters and acquisition times of a tenth of a second, while offering unique features such as device orientation determination and positioning in three dimensions. These capabilities can provide vastly improved user experiences than possible with other commercial positioning technologies. For example, because of the system’s capability to rapidly acquire position and orientation, a quick glance at the navigation application is sufficient to orient the user relative to a map of the store (contrast this with other technologies, including GPS, using which a user must walk around for a while to get position and heading information). From the standpoint of the enterprise owner, the high position accuracy and orientation capability can offer highly granular location analytics that can yield deeper insights about the habits of visitors. Augmented reality applications can also be substantially enhanced, because accurate position and orientation priors can improve the speed, lower the false alarm rate, and increase the detection rate of computer-vision-based object recognition -- a compelling example of this is the use case of

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* Lumicast is licensed by several lighting equipment manufacturers [1], [2], [3] who are using it to offer location-based services to retail and other enterprise customers.
planogram validation in a retail store. Finally, height determination (z-axis positioning) can be used to guide forklifts and drones in warehouses and industrial facilities.

The Lumicast system is comprised of two components as illustrated in the figure and described below.

- The Lumicast signal specification which describes the coding and modulation used by LED light fixtures to transmit positioning signals. The Lumicast signal is designed to be implemented in firmware that can run on low-cost microcontrollers present in LED fixture drivers available on the market today.
- The Lumicast mobile software framework which enables a smartphone application to decode the positioning signals transmitted by LED light fixtures and determine the smartphone’s position. With the Lumicast mobile software framework developers can build location awareness into their mobile applications running on all major commercially available mobile devices and operating systems. The software also includes auxiliary positioning methods that are switched on automatically when the application is in the background state. These positioning methods use signals of opportunity, such as those transmitted by Bluetooth transmitters in the venue.

This paper is structured as follows. We will describe the Lumicast VLC system in Section 3 where we will look at how LED fixtures can simultaneously act as positioning transmitters and illumination sources and describe the operation of the image sensor in its role as a communication receiver. In Section 4 we will describe auxiliary positioning technologies, some of which are used by the Lumicast mobile software framework, and which can be used when the application is in the background state. In the same section we will also discuss how VLC can be used to improve the performance of these auxiliary systems. Finally, in Section 5 we will conclude with a look towards the future of lighting-based digital services that go beyond indoor positioning.

## 3 Positioning using Visible Light Communication

### 3.1 - The Dual Role of LEDs

In the Lumicast system, light fixtures broadcast positioning signals by modulating their light output level over time. Though the concept of using light modulation for communication has been around for a long time – optical fibers being a case-in-point – it has only recently been possible to effectively modulate the high powered light emitted by fixtures and bulbs used for general illumination [7]. The enabling technology for this is high-powered white Light Emitting Diodes (LED) which are rapidly replacing fluorescents as the lighting technology of choice for the future, thanks to their relatively high energy efficiency, low total cost of ownership, and low environmental impact [8].

In order for LED lighting to fulfill the role of a positioning infrastructure, VLC signals must be designed in a way to ensure that they do not compromise the primary function of lighting. The key design considerations are impacts on human vision, support for a broad range of dimming levels, energy efficiency, and compatibility with the existing hardware in the fixture. We look at these considerations next.

Unlike linear and compact fluorescents, and because they are semiconductor devices, LED light output can be modulated at relatively high frequencies. Using modulation frequencies in the KHz range ensures that VLC signals do not cause light flicker perceptible by the human eye, while at the same time conveying information at data rates required for positioning. The design of VLC signals must also be such that the energy efficiency of the light fixture is not compromised -- this is achieved in Lumicast by using simple, binary modulation. This type of modulation is supported by the boost converters that are integral components of
dimmable LED drivers. Not only is such signaling efficient and compatible with existing driver hardware but it can also naturally coexist with the standard methods of dimming.

Lumicast signaling has been designed with these constraints in mind – using it, LED fixtures can fulfill their primary function of providing energy-efficient illumination while acting as positioning anchors.

3.2 - Fixture Identifiers and Maps

The VLC signal transmitted by each fixture conveys a unique identifier which differentiates that fixture from all other fixtures in the venue. The map of locations of the fixtures and their identifiers is created at the time the system is commissioned and is stored on a remote server. To determine their position, mobile devices must download the map and reference it every time they decode a fixture identifier from a VLC signal.

The identifier is either stored internally in the driver or is supplied from an external system, such as a Bluetooth wireless mesh network. A fixture may periodically switch to transmitting a new identifier in order to prevent unauthorized use of the positioning infrastructure. By implementing such a “rolling ID” mechanism, enterprise owners can prevent unauthorized third party mobile applications from providing location based services in their venues.

3.3 - Image Sensor as a VLC Receiver and Beamformer

The key enabling component in the handset is the CMOS image sensor which can be configured to extract a time domain VLC signal from a sequence of image frames that capture a given light fixture. The received VLC signal is demodulated and decoded by a smartphone device to produce a unique fixture identifier. Furthermore, an image sensor can in parallel extract VLC signals from images containing multiple light fixtures -- as many as are visible in the field of view of the sensor. This is important because it allows the device to use multiple independent sources of information to confirm and refine its position.

However, from the fixture identifiers alone the smartphone device can only determine its position to within a few meters. More measurement and processing must be done on the captured image frames to narrow down the device’s position to within centimeters. This is where the image sensor’s unique capacity to accurately measure the incoming light signals comes into play. Each pixel in an image sensor accumulates light energy coming from a very narrow range of physical directions, so by performing pixel-level analysis the receiver can precisely determine the direction of arrival of light from one or more fixtures. This enables the device to compute its position relative to a fixture to within a few centimeters. The signal processing technique here is analogous to “beamforming” in RF radio receivers – the difference here is that there are effectively millions of antennas so the directional accuracy is far greater than can be achieved with RF radios.
By combining an accurate estimate of its position relative to a fixture with information about the location of that fixture as
determined from the decoded identifier, the mobile device finds its global position in the venue with centimeter-level accuracy.

3.4 - Key Technological Differentiators

VLC-based positioning does not suffer from the uncertainty associated with the measurement models used by other positioning
technologies. This is because, unlike in the case of RF-signal-strength-based approaches which suffer from unpredictable
multipath signal propagation, VLC-based positioning uses only the line-of-sight path whose direction can be precisely determined
using the image sensor. From this follow some of the main advantages of this method of positioning. We will take a closer look at
other technologies in Section 4; but first we will list the key differentiators of our technology.

• **Positioning in three dimensions:** One of the key differentiators of Lumicast is that, in addition to providing the position
of the device in the horizontal plane, it also provides the position in the vertical dimension (the Z-axis). This is a direct
consequence of using direction of arrival of light, which is a three dimensional vector. Accurate height estimation
can enable a new set of use cases such as autonomous navigation and operation of drones and forklifts in warehouses
and on manufacturing floors.

• **Orientation:** Another direct result of using directionality of the light vectors is that the device can determine its
orientation in the horizontal (X-Y) plane; this is also known as the device’s azimuth or yaw angle. This information is very
useful in practice because it can inform the user which way they are holding the phone (and, consequently, facing)
relative to the items in the venue. By contrast, a GPS receiver determines the heading from a time sequence of position
estimates which means that the user has to move in a certain direction before knowing which way they are going. Using
Lumicast VLC, the orientation/heading is determined as soon as the first position is computed.

• **Latency and update rate:** Typical indoor positioning systems that use RF signals require many measurements to be
taken over time and space in order to get a position fix. With Lumicast VLC, the Time to First Fix is on the order of 100
milliseconds and the update rate can be as high as 30Hz. This ensures a responsive and lively user experience for
human users and can even satisfy many of the challenging drone/robot navigation use cases.

• **Scalability:** Positioning systems that require two-way communication between a smartphone device and infrastructure
typically do not scale well as the number of mobile users and infrastructure access points increases. This is because
each smartphone-to-infrastructure communication creates interference for other smartphone devices, as they attempt
to position themselves. In the case of RTT-based positioning in Wi-Fi frequency bands, the interference can also cause a
drop in total WLAN throughput. VLC-based positioning is inherently scalable because it only uses one-way
communication hence its performance does not degrade no matter how many users and transmitters are
simultaneously active in a venue.

3.5 - The Limitations of Using the Image Sensor

Using the camera sensor as a receiver brings about one obvious limitation: if the field-of-view of the camera is obstructed, no
signal can be received and hence no position can be computed. Under normal, active usage scenarios – i.e., when the application
is in the foreground and user is looking at the screen – the probability of signal/positioning outage due to obstructions or signal
dead-zones is very low. However, if the smartphone is placed in a pocket or purse, positioning outage will certainly occur.
Even though the vast majority of use cases of indoor positioning for smartphone devices involve the active usage of the device by
the user – such as navigation and location-based search -- there are some use cases which would be enhanced if positioning could
work when the phone is on stand-by and is not being actively handled by the user. For example, tracking a visitor’s movements in
a retail store for purposes of location analytics or disseminating location-based promotions/coupons, all while the phone is in the
pocket/purse. Since VLC cannot be used to address these use cases, other positioning systems must be brought to bear. In the next section we will take a look at some of these alternate positioning systems and discuss ways in which VLC-based positioning can enhance their performance.

### 4 Background Positioning

When the mobile application is in the foreground and the smartphone is being actively used by the user, VLC can achieve superior positioning performance. To address the challenge of positioning while the application is in the background, the Lumicast mobile software framework relies on other methods of positioning. In this section, we will review some of the technologies that are a good fit for this scenario. We will also discuss the fundamental issues they face and show how each of them can be enhanced by VLC-based positioning to achieve new levels of performance and scalability.

It is imperative to note the implications of background positioning on privacy and user experience, however. Firstly, the user must be explicitly asked to “opt-in” to the background positioning service by the application. While this is also the case with foreground positioning, it is naturally much less obvious that background positioning is running when it is enabled. Secondly, the mobile application must not create a noticeable drain on the phone’s battery since the user expects their device’s stand-by time to not be compromised by any application. Moreover, the background positioning system must be accurate enough to not cause too many false alarms in the cases where mobile alerts and notifications are issued by the application. Any system that provides background positioning must take these considerations into account.

#### 4.1 - Received RF Signal Strength

RF signals, such as those transmitted by Wi-Fi APs or Bluetooth radios, are a natural choice for use in background positioning because most RF signals can be reliably received even when the device is in a user’s pocket or purse. RF-signal-strength-based approaches work by comparing the received signal strength values to predicted signal strengths at every location in the venue. As mentioned earlier in this paper, it is practically impossible to accurately predict, or model, the RF signal strength because of the multipath nature of signal propagation. Received RF signals are sums of many individual ray components, each of which has a different physical path through the environment. Predicting these paths is extremely difficult to do accurately, even if the position of every object in the environment is known. Moreover, signal propagation changes whenever there is motion of people or objects in the environment, or whenever there are changes in the way the device is held or worn by the user. The net effects are biases and noise in the position estimates.

To minimize the impact of the multipath, the fingerprint map of the venue must be frequently refreshed, as mentioned in the introduction, which is not only costly but also highly error-prone if done by manual surveying. Using Lumicast, this process can be vastly improved. Positions from VLC are effectively “ground-truths” and can be used, whenever available, to build more accurate fingerprint maps. This process can occur automatically as users move through the venue while using VLC-based positioning. In this way, the foreground mode can be opportunistically used to improve the accuracy of the background positioning system. Furthermore, if the machine learning algorithm for building the fingerprint map runs on a remote server, all the mobile
devices can contribute data to it. Such an approach can dramatically improve the accuracy and reduce the time and cost of building fingerprint maps.

4.2 - Magnetic Field Strength

Another positioning method which suffers from similar technical challenges is the one based on the measurement of the ambient spatial magnetic field in the indoor environment. The main challenge here is that surveying must be done with an even greater accuracy because the ambient magnetic field is even more difficult to model than RF signal propagation [9]. Measurement biases in the sensor are also notoriously difficult to remove as they change as a function of the level of the ambient magnetic field. Compensation for these biases typically requires the user to handle the smartphone in a prescribed way, and even then the best accuracy is on the order of several meters.

Just as in the case of methods based on RF-signal strength, using VLC-based positions as ground positions for the creation of magnetic field fingerprint maps can substantially improve the performance of the system as well as the time and cost of system commissioning. Furthermore, because Lumicast VLC completes the six degree of freedom description of the pose in space of the device, directional information about the magnetic field can be obtained which can be useful in calibrating the magnetic sensor biases.

4.3 - Sensor-Based Dead-Rekoning

There are methods that rely on the device’s internal inertial sensors to estimate its position relative to the last known position fix. These approaches suffer from errors that build-up over time due to the measurement biases that are inevitably present in low-cost MEMS sensors that are used in mobile devices today. In order to minimize the effect of error build-up, or drift, the time over which the sensors are used in a stand-alone mode must be kept to a minimum. This is where VLC-based positioning can help -- by providing occasional position fixes when the application is in the foreground, the sensor-based dead-reckoning system can be periodically reset and calibrated.

We note that all of the positioning methods listed above can be combined together. In fact, VLC can be simultaneously used to train and calibrate each of these systems simultaneously. Since all of the sources of measurements are independent, combining the systems can only improve the overall performance.

5 Lighting as Platform for Digital Services

In this paper, we introduced a novel positioning system that leverages lighting as an infrastructure of positioning transmitters. There are several key reasons why light fixtures are an excellent choice of positioning transmitters and all of them stem from their primary role as providers of illumination:

- They are powered from the mains (and don’t require battery replacement cycles),
- They provide wall-to-wall coverage of the venue,
- They are densely deployed,
- They have excellent line-of-sight view of the environment,
- They can easily be mapped, and are rarely moved.

Incidentally, these are the same properties that make the lighting infrastructure an attractive target for installation of sensors and
radios that could constitute, together with the software running on mobile devices and the cloud, a complete end-to-end platform for delivering a new class of services. Though positioning would be their cornerstone, such services would also include the determination of the state and context of people and objects with the goal of creating physical environments that are sensitive and responsive to the needs and desires of its occupants. This broad class of services has been known as Ambient Intelligence in the technology community for a number of years [10] and recently the lighting industry has taken the first steps in this direction by, for example, integrating camera sensors into outdoor light fixtures to support various use cases including parking spot finding [11]. Though it is very early days for systems of this type, the future seems very promising. Given the natural market acceleration to LED lighting for a number of other compelling reasons, the wide availability and low cost of sensors and radios, and the proliferation of mobile technology in the consumer market, it seems that a dawn of a new era of distributing computing is on the horizon.

6 References


