Angle of Arrival Based localization: A Better Indoor Localization Technique Over GPS

Yuqing Lin

Binghamton University

Abstract

Today's newest Global Positioning System (GPS) has a global average user range error (URE) less than 0.715 m (2.3 ft), 95% of the time. However, due to weak signal strength, multipath effects, and limited on-device computational power GPS functions well in outdoors but performs poorly in indoor environments and urban areas. This paper addresses this problem, expresses Angle of Arrival (AOA) based Optical wireless (OW) indoor localization techniques as an alternative in indoor localization field. By investigating the AOA based indoor positioning method applied Multiple Signal Classification (MUSIC) algorithm, demonstrating this indoor localization approach is reliable and efficient. This paper also analyzes the social impacts behind the indoor positioning systems from serval aspects such as real-world applications, social concerns and ethical analyses, which demonstrates this technology benefits the society as whole. This paper concludes that AOA based indoor positioning system has better performances over GPS in indoor environment.

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Introduction

Global Positioning System (GPS) has been widely used in mobile devices. Applications such as Google Map has integrated into individuals' lives. However, due to extremely weak GPS signal strengths indoor, messages such as “acquiring satellites” and “lost satellite reception” often appear in GPS- based applications.(Nirjon et al, 2014, p.1) GPS only performs normally under line-of-sight (LOS) conditions without obstructions between satellites and receivers(Bergen et al, 2017, p.1) On the other hand, after years of development, indoor localization technologies have developed a series of approaches to increase their accuracy as well as emerge into marketplaces. Recently, with the new indoor positioning feature of Bluetooth 5.1, indoor localization has attracted a lot of attention from research and industry. AOA indoor positioning technologies, as opposed to GPS, offer a more precise positioning capability in LOS conditions for mobile wireless communication devices, especially in complex indoor environments and urban areas. Meanwhile, the multiple signal classification (MUSIC) algorithm, as one of the best optimizations toward the AOA method, increases the accuracy of AOA measurement. MUSIC based AOA indoor positioning systems provide more accurate indoor tracking results than GPS, therefore better fulfill the indoor positioning demands such as asset tracking and item finding as well as increase the performance of indoor positioning-based software. Comparing the performance between MUSIC based AOA method and the GPS require background knowledge into this filed.

Background

Since 2000, the Defense Department ended their purposive degradation of GPS, civilian GPS accuracy has increased 10 times than previous generations. With 32 Global Navigation Satellite Systems (GNSS) in the Earth's orbit, GPS is capable of tracking objects within 10m positioning offsets. (Nirjon et al,2014, p.2) However the long travel distances and inevitable travel delays between Earth's surface and satellites makes GPS based systems barely decode incoming signals. Furthermore, building materials and complex building structures reduce signal strengths when penetrating through obstructions, which leads to GPS signal decoding in indoor environments more of a challenge (Chouchang Yan & Huai-Rong Shao, 2015, p.150).

In contrast to the GPS, indoor positioning technologies based on AOA method play an excellent supplemental role in the positioning filed. Implementations such as indoor navigation in shopping malls, indoor location-based advertising, asset tracking, and item finding prove indoor positioning service as a valuable and particle tool for people in everyday life. (Silicon Lab, 2019. p.10) Angle of Arrival is a measurement method capable of determining an incoming signals' direction from a signal transmitter to a signal receiver with an array of antennas. Since signal transmitters and receivers are both small and easy to implement in indoor environments, signal strengths reduction and signal distortion due to obstructions are significantly less than those resulting from GPS use (Nirjon et al,2014, p.2). Upon the AOA method, the MUSIC algorithm optimizes the AOA method, significantly increases the accuracy of the AOA result from meters offsets to only a few centimeters offsets which fulfill the accuracy requirement for indoor tracking. (Bergen et al,2017, p.2) Since this method only requires antennas and supported software, apply this technology on current mobile communication devices is practical which make indoor positioning easily accessible. In addition, by implementing this technology in industry, employees spend less time in finding missing item and become more productive. Thus, indoor localization technology benefits the entire industry around the world.

Relate Work

Indoor localization methods are based on optical wireless (OW) system which is based on light, radio waves and electronic waves. (Bergen et al,2017, p.1) Beside of the AOA method, received signal strength (RSS) and time of arrival (TOA) are also methods capable of position tracking. (Bergen et al,2017, p.1) RSS is the simplest and one of the earliest methods in this field. A receiver based on RSS receives optical signals and determines their direction by measuring optical power. (Bergen et al,2017, p.1) However, due to optical beacons exhibit imbalances in the power levels as well as physical environment changes reflects signals and changes its signal strength, resulting position error also increase. (Bergen et al,2017, p.3)

TOA in another hand overcomes many deficiencies of RSS based positioning by measuring signal phrase and determining signal direct ion. As show in figure 1, in comparison to AOA, TOA applies trilateration on estimate signal direction, achieves as low as 0.5 cm offsets. (Bergen et al,2017, p.2) However, estimate phrase differences require high-frequency electronics, multiple receiving antenna array and precise phase synchronization, which increases implementation costs, making commercial practice much expensive (Bergen et al,2017, p.2)

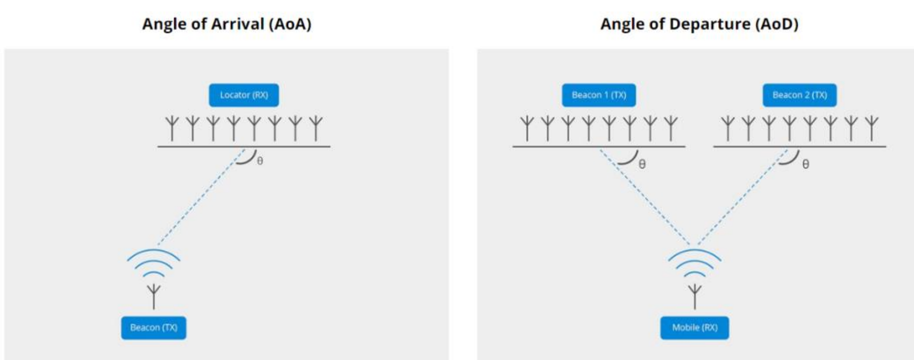

Figure 1 Bluetooth direction finding: angle of arrival (AOA) and angle of departure (AOD).

Besides indoor positioning technologies, COIN-GPS as one of the best approaches to this problem, relies on cloud computing which increases the performance from more extended signals acquisition as well as removes requirements of decoding time stamps. This approach makes decoding weak signal strengths much efficient. (Nirjon et al,2014, p.1) Although COIN-GPS has achieved an acceptable accuracy without extra infrastructures support, COIN-GPS still does not resolve the signal strengths problems in indoor environments. With more than 10 m offset, COIN-GPS still performs less than satisfactory therefore leaving GPS based indoor localization approaches remains inapplicable. (Nirjon et al,2014, p.13)

Technical Details

Typical Angle of Arrival (AOA) based optical indoor localization systems require two parts: an array of antennas and estimation algorithms (Silicon Labs, 5, 2019). According to Sauli Lehtimäki (Senior Software Engineer), an antenna array for direction finding usually has three different sets of implementations, Uniform Linear Array (ULA), Uniform Circular Array (UCA) as well as Uniform Rectangular Array (URA) (Lehtimäki, p.6, 2019). The primary distinction between these implementations is the placement of the antennas. Different algorithms require different placements of the antenna arrays. By exploiting phase difference among antenna arrays, AOA measurement method capable of processing incoming sample data as well as distinguishing signal interference and outputting correct positioning data (Yan & Shao,2015, p.151).

With the aim to measure phase difference, the system required to perform a synchronous process for frequency between frequency- agile receivers and transmitters by successfully detects and locates electric arc (Paun et al, 2015, p.2). After successfully synchronized signal phases are picked up by the receiver, depends on different frequency implementing on the different set of devices, the wavelength is calculated by

$$c = f\lambda$$

where c is the speed of light and f is the frequency of incoming signal. For most arrival angle estimation algorithms, the distance between two adjacent antennas is half of the wavelength (Lehtimäki, p.2). Therefore, when incoming signals arrive at the antenna array, different antenna in the array receives the signal at a different time frame as figure 1. The AOA measurement starts with time of arrival estimations(Tan, E.A., Chia, Y.W. & Rambabu, K.). By estimating the time frame difference of signal arrival, an azimuthal angle Φ, which indicates the transmitter's position relative to the receiver.

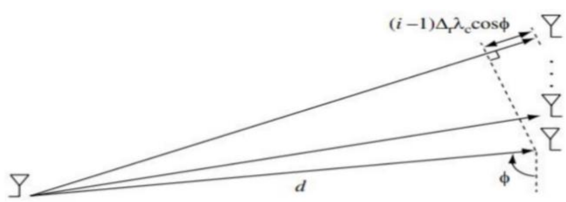

figure 2 Directional Signal Transmission in Energy Efficient Wireless Data Communications

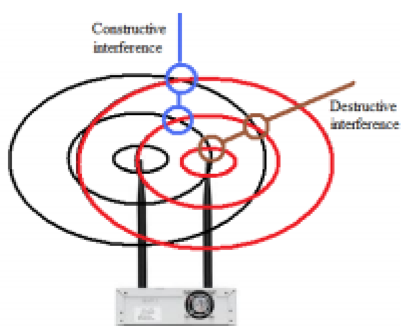

figure 3 Directional Signal Transmission in Energy Efficient Wireless Data Communications

However, this process requires a strong on broad computing power (Lehtimäki, p.8). Furthermore, when antennas are close to each other in an array, as an example shows in figure 2, signal integrity decreases due to signal mutual coupling, as well as multipath effect. To resolve these problems, one type of estimation is the MUSIC algorithm which performs subspace decomposition on the autocorrelation matrix

$$\mathrm{Rxx} = \mathrm{VAV}^{-1}$$

where A is a diagonal matrix containing eigenvalues and V contains the corresponding eigenvectors. If the receiving antenna array has N antennas, the eigenvectors of Rxx belong to the signal subspaces with N-1 eigenvectors (Lehtimäki,2019, p.11). By finding eigenvectors and inverse matrix, the algorithms return information about each ray. Based on this orthogonality information, the pseudo spectrum P is calculated by

$$P(\theta) = \frac{1}{\mathrm{a}^{\mathrm{H}}(\theta)\mathrm{VV}\text{^}\mathrm{Ha}(\,\theta\,)}$$

where the estimated angle polar θ is located at the peak value of P (Lehtimäki, 2019, p.12). With this MUSIC algorithm implements in a computing loop, it searches through all angles θ in “spatial spectrum”, which results in an excellent polar angle resolution (GIRD System, 2015, p.12). Therefore, the efficacy of AOA measurement is directly proportional to the correlation and agreement between the estimated azimuthal and angles (Bergen et al,2017, p.3).

Comparison between GPS and indoor localization system. According to Shahriar Nirjon et al. (2014), the total radiated power from GPS satellites is about 500W (or 27 dBW) (Nirjon et al,2014, p.3). Signals travelling through free space lose about 182dB, resulting -155dBW when signals research Earth’ surface (p.3). Signal strength is less than typical ambient RF noise floor (-111 dBm) (p.3). In addition, due to complex indoor environments and building materials, signal strength is further reduced by 10 to 100 times than in line of sight environments while the strength of RF noise remains the same (p.4). With this weak signal strength, GPS receivers hardly distinguish receiving signal between noises and GPS signals. Currently, although the COIN-GPS (as mentioned in the relate work section), has an accuracy within meters offsets, implementations on mobile devices remain inapplicable due to its large physical body. (p.13) On the estimation side, meters offsets leads to placing the results on other side of wall in a completely different room, which is an inefficient approach for indoor positioning applications.

On the other hand, a typical AOA OW positioning system has an excellent positioning range of 1-5 cm (Bergen et al,2017, p.2). Based on AOA and MUSIC, Mark's group proposed a better design which allows the optical receiver to optimize signal information by managing them into a 3 x 3 grid of optical beacons (p.1). As show in figure 3, each beacon has unique characteristics for identification in a 3 x 3 grid (Table is a reference to frequency and color characteristics of each beacon), which enables multiple frequencies and color channels as well as managed by onboard software. The overall positioning error is approximately 1.7 cm while the AOA error is AOA=1°(p.1). Thus, the excellent performance of their design has proved that AOA-based OW technologies are capable of emerging current positioning systems while fulfilling the demands of indoor localization applications.

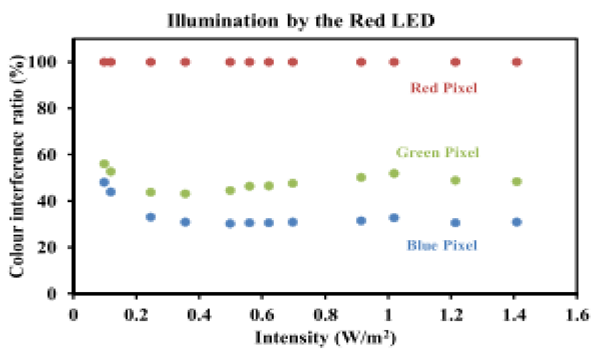

TABLE I
LOOKUP TABLE SHOWING OPTICAL BEACONS (INDEXED BY i) WITH THEIR ASSOCIATED COLOURS (LISTED IN COLUMNS) AND FREQUENCIES (STATED IN THE CELLS)

Beacon index, i	Red colour channel	Blue colour channel
1	f_1 = 40 Hz	f_2 = 80 Hz
2	f_2 = 80 Hz	f_1 = 40 Hz
3	f_2 = 80 Hz	f_1 = 40 Hz, f_2 = 80 Hz
4	f_1 = 40 Hz, f_2 = 80 Hz	f_2 = 80 Hz
5	f_1 = 40 Hz, f_2 = 80 Hz	f_1 = 40 Hz, f_2 = 80 Hz
6	f_1 = 40 Hz, f_2 = 80 Hz	f_1 = 40 Hz
7	f_1 = 40 Hz	f_1 = 40 Hz
8	f_1 = 40 Hz	f_1 = 40, f_2 = 80 Hz
9	f_2 = 80 Hz	f_2 = 80 Hz

figure 4 Design and implementation of an optical receiver for angle-of-arrival-based positioning

Applications

Asset tracking & Item finding. According to Entigral (a company sells asset tracking system), nurses waste 20-30 minutes per shift looking for missing medical equipment and supplies. Missing equipment when needed cost production downtime for employees while affecting their passion and efficiency for their work. According to Silicon Labs, Bluetooth 5.1, has solved this problem by implementing AOA-based indoor localization which allows Bluetooth connected devices directly pinpoint and locate each other. This Bluetooth-based localization technology is implemented by attaching a location tag to equipment or assets located indoors, allowing central control system or mobile phone to keep track and respond the item’s location to a query. (Silicon Lab,2019) This development not only optimize operational efficiency but also reduced the time employees spend on searching for products. Since Bluetooth technologies are itself commonly implemented on mobile devices, it also made these services easily accessible to customers.

Location-based social networks (LBSNs). Social networking applications such as Facebook, and Instagram, provide Internet-based applications or web-services for people to interact with other that socially relevant to them. In the past decade, LBSNs as a new type of social network based on localization technologies, has emerged. LBSNs allow people to share their favor places with others or find interesting places. Moustafa Elhamshary (a PhD student at Egypt-Japan University), Anas Basalamah (an assistant professor at Umm Ai Qura University), and Moustafa Youssef (an associate professor at Alexandria University) published *A Fine-grained Indoor Location-based Social Network*. According to this paper, the primary interaction between LBSNs and users is checking venues of a chosen location and sharing with peers. Due to the limitation of phone screens, results from queries are usually sorted into a list of places by rank. Regardless of the ranking algorithms, most implementations rely on accurate localization (Elhamshary, Basalamah, &Youssef 2016, p1). However, due to the poor GPS's performances in None-line-of-slight condition, search results usually locate venues in other places within a certain amount of distances range, which is inefficient when users only want to learn about their current location. Given that, on average, users spend about 89% of their time indoors, inaccurate LBSNs solution leads to a worse user experience. (p.1) In comparison to the GPS approach , the AOA based indoor localization system improves LBSNs' performance by interacting users' mobile devices with Bluetooth and WiFi technologies that preinstall, read ahead and label all venues' information inside the building.(p.2) With this method applied to large public places, such as shopping malls and libraries, users can quickly locate the nearest recommended venues in a mall.

Ethical analysis. Although indoor localization technology enhances the performance of LBSNs and fulfills the demands of accurate indoor localization tracking, it also increases the risks of personal privacy. Since indoor technologies rely heavily on data communication between personal devices and optical wave transmitters, backtrack personal positions through wireless communication channels is possible. Despite of that, from the viewpoint of utilitarianism, John Stuart Mill supports the idea of making indoor localization technologies easily accessible because it provides benefits to the entire human race. The applications of indoor localization technology in asset tracking and LBSN reduce the cost to companies, save employee's time in item finding as well as provide a great convenience to users for searching venues. Therefore, popularizing indoor localization applications increases the utility of all people and benefits entire society.

Furthermore, from the viewpoint of deontological theory, Immanuel Kant believes the measurement of good or bad to an action depends on motivations when people first carrying out the action. Since the goal of developing this technology benefits the society, helps people become more productive while fulfills the demands in this area, the motivation of carrying out popularizing indoor localization applications as an action is morally right.

In positive right point of view, people have the right to have better localization service on their mobile devices. Employers have the right to require employees to use this indoor localization applications during working hours for reducing negative side effects. Employers also have the right to increase their profits while indoor positioning system helps employees become more productive which increases companies’ productivity and eventually lead to more profits. Therefore, popularizing indoor localization services fulfills the demand of people’s positive rights. In contract to positive right, people have negative right to ensure their privacy. High accuracy localization applications increase risks of leaking personal private location information. On the contrary, increase security on both user side and optical wave transmitter side resolve this problem and ensure. Consequently, with supports from both utilitarianism and deontological theory as well as demand of people positive right, developing and popularizing indoor positioning technology are ethical right and necessary.

Conclusion

After analyzing technical details and applications such as asset tracking, item finding, and improving LBSN for AOA based indoor localization technology, a conclusion is formed. Due to poor signal strength, travel delay and multipath effects, GPS is inapplicable to work indoors. However, since average people spend 89% of their time indoors, the demands for indoor tracking applications have increased. The AOA based indoor positioning system, as opposed to GPS, implements the MUSIC algorithm, measuring arrival signal phases' differences, provides accuracy as low as a 1.7cm offset for indoor positioning; this improves positioning-based applications while enables indoor tracking applications. With installing both transmitters and receivers in a fixed short distance range, the AOA method minimizes the negative effects for positioning performance such as signal strength attenuation and time delays due to long travel distance. Meanwhile, on the software level, implementing MUSIC algorithms to perform a subspace decomposition on autocorrelation matrix, achieves a high accuracy angle estimation. Since indoor localization has better performance than GPS indoors, in utilitarian point of view, as this technology benefits the entire society, engineers should first reevaluate their localization-based projects, adapt to the system in a needs-based. Meanwhile, engineers should also develop more applications on various platforms to expand this benefit. On the other side, computer professionals should continue to optimize and improve the system's security and protect possible user's privacy information leaks from happening in the first place. Furthermore, the indoor positioning technology draws a promising blueprint in utilizing the advantages of both GPS and indoor positioning system, developing a full-scale localization system capable of cover entire

Earth's surfaces and provide more precise positioning measurements as reflected from current dissatisfied GPS's performances.

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