Cooperatively Extending the Range of Indoor Localisation

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Abstract − Whilst access to location based information has been mostly possible in the outdoor arena through the use of GPS, the provision of accurate positioning estimations and broad coverage in the indoor environment has proven somewhat problematic to deliver. Considering more time is spent in the indoor environment, the requirement for a solution is obvious. The topography of an indoor location with its many walls, doors, pillars, ceilings and floors etc. muffling the signals to\from mobile devices and their tracking devices, is one of the many barriers to implementation. Moreover the characteristically noisy behaviour of wireless devices such as Bluetooth headsets, cordless phones and microwaves can cause interference as they all operate in the same band as Wi-Fi devices. The limited range of tracking devices such as Wireless Access Points (AP), and the restrictions surrounding their positioning within a buildings' infrastructure further exacerbate this issue, these difficulties provide a fertile research area at present.

The genesis for this research is the inability of an indoor location based system (LBS) to locate devices beyond the range of the fixed tracking devices. The hypothesis advocates a solution that extends the range of Indoor LBS using Mobile Devices at the extremities of Cells that have a priori knowledge of their location, and utilizing these devices to ascertain the location of devices beyond the range of the fixed tracking device. This results in a cooperative localisation technique where participating devices come together to aid in the determination of location of devices which otherwise would be out of scope.

Keywords − Localisation; Indoor positioning; Indoor localisation; geographical positioning; wireless.

I INTRODUCTION

Localisation of devices is a fundamental enabling technology in today's world of nomadic computing, where Smart Phones, Tablets, and Laptops are not tethered to the constraints of the wired world. Data with geospatial contextualisation can be more powerful and meaningful in social media services driven applications. The concept of tracking or localising in the outdoor arena has been around now for some time. Devices that can determine exact location are relatively inexpensive. Indeed embedded GPS chips are being found in devices, from Mobile Phones to Cameras, to Tablet PC's. GPS technology works through the use of a constellation of at least 24 satellites, each orbiting the earth every 12 hours, at a height of 20200 km [1]. Standard GPS can currently provide accuracy of better than 7.8m 95% of the time [2] this level of accuracy can be further improved with the use of assisted technologies to augment the GPS System in its estimation of a location [3]. The adoption of hybrid techniques and augmented systems to further hone the precision and range of GPS has crossed realms to the Indoor Localisation arena, as can be seen in the literature [4], [5]. Even if a technology could be developed to provide the precision and range demands of modern applications, the infrastructure does not exist in today's indoor environments, nor is it required for anything other than localisation. It would therefore seem that utilizing hybrid techniques will be at the fore of any solution to the coverage and precision issues in Indoor Localisation. It is the author's opinion that Cooperative Localisation is best suited to deliver this solution, and utilising the cooperation of mobile devices is the hypothesis of this research.

With standard non-cooperative localization, mobile devices do not communicate with each other, the only communication relating to localisation is between fixed reference devices, mobile devices and localisation servers. Every mobile device needs to obtain localisation information from multiple fixed reference devices, which requires either a high number of fixed reference devices or a very large coverage area for each fixed reference device. With cooperative localization, mobile devices communicate localisation in a peer to peer fashion, removing the requirement that all mobile devices be within communication range of multiple fixed reference devices. Therefore in a cooperative localisation strategy there is no longer the need for reference devices to provide large coverage areas, or that there be a high density of fixed reference devices. Because mobile devices that need to localise can do this with other mobile devices that have a priori knowledge of their location as well as fixed reference devices, cooperative localisation can provide both increased coverage and accuracy. Cooperation within a wireless Peer To Peer infrastructure is not a new phenomenon and has been successfully implemented in standards like Bluetooth [6] and Zigbee [7] and is a proposed implementation for mobile phone networks in the coming years [8]. The most common approach used to locate devices in the Indoor arena is via the utilization of the existing IEEE 802.11 network infrastructure, which are available in most public buildings and home\office environments. These proposed approaches can offer meter level accuracy, which is generally adequate for most location aware applications, whilst also being cost-effective. One of the most used methods for localising using Wi-Fi is using scene analysis techniques [9], which involves an Initial Fingerprinting process where positions are calculated from around a building. These readings are then mapped onto a database, which is then used during the live process to plot the live readings against readings that were taken during the analysis process. Another popular method for estimating the location of a device in an indoor environment is to input the collected Received Signal Strength Indicator (RSSI) values from a Mobile Device into a positioning algorithm. The device is then located using a position estimation technique such as Triangulation, Trilateration or Multilateration.

II Review of Literature

Literature from Yang [10] and Rowe [5] reflect that Location Awareness is rapidly becoming a fundamental requirement for mobile application development. This highlights the challenges posed for ubiquitous localization of devices in the indoor arena. The main focus of this research is to develop a system that would augment an already installed and configured Indoor LBS, utilizing the Mobile Devices at the extremities of the Wi-Fi Network. These Mobile Devices will 'know' their location, and can be used to expand the coverage area of the LBS to include Devices beyond the reach of its AP's, a somewhat P2P (Peer-to-Peer) like location based solution.

Understanding one's location in an environment has long been a basic need for mankind, and although powered with the processor and sensors that man has at his disposal, along with the technological advances through the years, this need has never been fully realised. GPS provides an adequate solution to outdoor positioning at present although research is still on-going to further hone its precision and coverage. Some of the current limitations to GPS coverage include the indoor arena. The attenuation of GPS signals as they propagate the 20200 km from satellite to earth impede their ability to penetrate buildings and building materials, ruling GPS negligible as an Indoor Location Based Solution. Given that people spend most of their time in indoor situations, designers of LBSs have had to look at different ways to locate users in these GPS denied environments. This has prompted a bounty of research of new and existing technologies utilising sound [11], [12] and [13], camera vision [14], light [15] and radio frequency waves [16] and [9], to localise in indoor arenas. Most research both historical and current, into Indoor LBSs are driven by the need to provide more precise location estimation strategies. When a mobile device is beyond the range of an Indoor LBS, this requirement for precision is redundant. It is the view of the authors that satisfying the requirement to locate devices at the extremities of the range LBSs is more important in these situations.

a) Ranging Techniques

Fundamental to an Indoor LBSs ability to estimate position is its capacity to measure the range to\from Anchors and Mobile devices. The location of the receiving device relative to the transmitting device can be calculated by estimating signal metrics based on the physical waveforms transmitted during communication. Although widely employed in Indoor Location Based Solutions, these metrics are still very volatile. This volatility can be seen in literature from Lui et al., were the variances found during testing with different range readings recorded in different chipsets at the same location is highlighted [17]. The Hand-Grip body-loss effect is shown to impact ranging measurements in Rosa et al., [18]. Kaemarungsi and Krishnamurthy prove in their tests [19] that device orientation can also introduce errors when calculating signal range estimates. Generally there is no single metric that can be employed to calculate precise ranging estimations in all situations. There are key advantages and disadvantages with each technique, and sometimes a hybrid of techniques is used, as with the research in [20]. Here the authors use Time of Arrival (TOA) along with Time Difference of Arrival to calculate distance in a cooperative localisation system. Catovic and Sahinoglu calculate the Cramer Rao Bounds to show the benefits of their Received Signal Strength (RSS) Time of Arrival (TOA) ranging method [21].

Received Signal Strength Indicator (RSSI)

Possibly the most popular ranging technique used in Indoor Localisation, Received Signal Strength Indicator (RSSI) is a measurement of the voltage that exists in a transmitted radio signal, which is an indication of the power being received by the antenna. When a signal first leaves a transmitting device, the power of the signal drops or attenuates, this is true of both wired and wireless transmissions. As a radio signal propagates through the air some of its power is absorbed and the signal loses a specific amount of its strength, therefore, the higher the RSSI value (or least negative in some devices), the stronger the signal. Knowing the amount of signal loss over a given distance provides a method to calculate the distance from a transmitting device, given a Received Signal Strength.

Time of Arrival (TOA)

Time of Arrival (TOA) is another ranging technique which calculates the time it takes for a signal to travel from the transmitting device to the receiving device. The TOA is calculated using the time of transmission plus the delay that is introduced propagating the signal. The speed of a signal travelling through the air is approximately 106 times the speed of sound, as a general rule of thumb radio frequency broadcasts at a speed of 1 foot per nanosecond [22]. The distance between the transmitting device and the receiving device can therefore be calculated using the known speed of propagation and the time it took for the frame to be received as follows:

$$R = time \text{ x } speed \tag{1}$$

Where R is the distance between the receiving device and the transmitting device and is derived from time, which is the time spent by the frame travelling across the medium multiplied by speed which is the propagation speed of the signal. A major drawback of the TOA method is the fact that the clocks on the transmitting and receiving devices have to be perfectly synchronised, considering the signal travels at speeds nearing the speed of light, a small discrepancy in clocks can have a dramatic effect on the estimated positioning. Patwari et al, [22] also highlight the further issue of the time delays in the transmitter and receiver hardware and software that add to the measured distance. They go on to explain that although the insignificant delays are generally understood, discrepancy in hardware specification and response times can be another source of TOA inconsistency [22].

Time Difference of Arrival (TDOA)

Time Difference of Arrival (TDOA) is not too dissimilar to the TOA ranging method. It employs 2 different types of transmitted signal, and the difference in time between these 2 signals is used to determine the position of the transmitting device.

$$\frac{R}{c_1} - \frac{R}{c_2} = t_1 - t_2 \tag{2}$$

In (2) c symbolizes the speed of the 2 different types of signal t represents the transmission time of the different signals propagating from the sending device to the receiving device, and R is the range or distance between the 2 devices. Takabayashi et al. [23] have proposed an algorithm using TDOA calculations to estimate the position of a device for target tracking, and argue that TDOA is a suitable ranging method to use where the number of sensors is limited. As with Time of Arrival methods, the clocks on both sending and receiving devices must be precisely synchronised.

Angle of Arrival (AOA)

With the Angle of Arrival (AOA) ranging method an array of antennas or directional antennas are used by the receiving devices to calculate the angle from which the signal was transmitted. The position of the lost device is estimated by determining the intersection of 2 or more propagation paths of the transmitted signal. The principle benefit of AOA is the fact that unlike TOA and TDOA methods, no computational load is placed on the transmitting and receiving devices to maintain clock synchronisation. AOA range estimation techniques have been extensively used in literature [24] – [26]. One of the biggest downfalls of the Angle of Arrival method is that a small error in the angle measured can lead to a catastrophic error in the positioning estimation of the lost device and this is exponentially related to the distance between the transmitting and receiving devices. Furthermore AOA based ranging techniques are vulnerable to multi path signalling errors and most implementations require Line of Sight (LOS) between sending and receiving devices.

Round Trip Time (RTT)

The Round Trip Time (RTT) range estimation technique was designed to resolve the issues of clock synchronisation that is synonymous with TOA and TDOA techniques. The Round Trip Time of a signal is calculated as follows:

$$R = \frac{(\mathrm{tRT} - \Delta\,\mathrm{x\,speed}}{2} \qquad (3)$$

t_{RT} is the time required for a signal to travel from the transmitting device via the receiving device and back to the original transmitting device again. Δt is the delay introduced by the receiving device before the signal is forwarded on, and speed is the speed of the transmitted signal. Only one device records the time taken to transmit the signal and the arrival time of the signal, thereby resolving the issue of synchronising two clocks.

b) Position Estimation Techniques

Two key components typically make up the estimation of the position of a lost device. First of all ranging techniques as discussed in the previous section, are used to estimate the distance from the transmitting device(s) to the receiving device(s). This is calculated using a metric for example the length of time it takes a signal to propagate the distance from the transmitter to the receiver. The second component is the position estimation technique, here the ranging variables, calculated using one or more ranging techniques are used with an estimation algorithm to calculate the position of the lost device. The following are three such position estimation algorithms:

Triangulation

Navigators have been using triangles to measure distance for quite some time. Triangulation is a geometric calculation used to find a position based on angles to it from *a priori* positions at either end of a line of known length.

To explain this using the cooperative paradigm, consider a distant un-localised mobile device (Device X) which is within range of two other mobile devices Mobile Device A and B illustrated in Figure 1. Mobile Devices A and B have already localised using the in-house Indoor Localisation System and are separated by a known distance (the length 'L'). The base angles from A and B to mobile device X can be calculated using AOA metrics, determined using AOA ranging techniques. The location of the mobile device can then be derived from the intersection point of the two lines drawn at their respective angles from Mobile Devices A and B. This could be further extended to provide a 3D position estimation using the known point of a third Mobile Device, Device C and the distances from it to the other Mobile Devices (Mobile Device A and Mobile Device B), along with the AOA from it to the mobile device. This could be used to calculate floor level within a building, or a specific x,y,z coordinate value in an indoor localisation system.

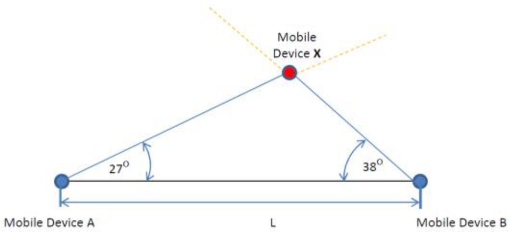
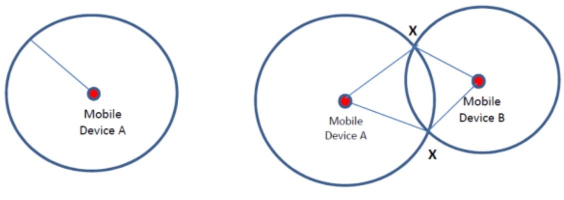


Figure 1: Calculating intersection for positioning

Trilateration

Trilateration is a key component of GPS position estimation techniques. It is a process that can estimate the position of a mobile device given the positions of at least three other objects and the distance from those objects to the mobile device. Again illustrating using a cooperative localisation example, take the basic scenario depicted below in Figure 2a, the circle depicts the distance from the Mobile Device X to the Mobile Device A. This distance would have been derived using one of the ranging techniques previously outlined, RSSI, TDOA or RTT. All we can say about the whereabouts of Mobile Device X is that it resides somewhere on the circumference of the circle that is constructed using the radius of the estimated measurement between Mobile Device X and Mobile Device A.



(a) Range from A (b) 2nd Mobile Added

Figure 2: Estimating Range

A second Mobile Device B will allow the position of X to be narrowed further as can be seen in Figure

2b. Now the ranging estimates of X have been calculated relative to Mobile Device B. Therefore considering X must be on the circumference of Mobile Devices A and B's circles there are only 2 possible positions where X might be, at the intersections of these two circles.

To calculate the exact position of X we need a third Mobile Device, Device C, when we calculate the distance from C to X and considering we already know the distance from X to A and B. We can then determine that X can only be at one specific position to match those three particular distance estimations from Mobile Device's A, B and C – the intersections of the three circles (see Figure 3).

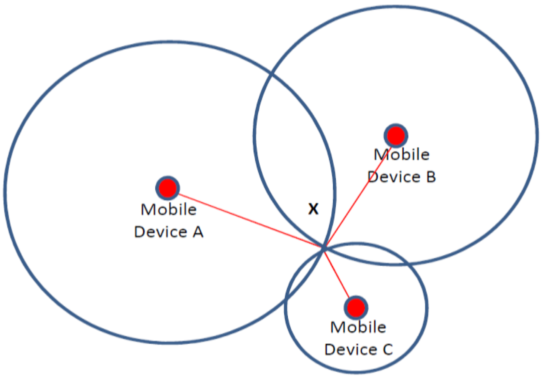


Figure 3: Trilateration example

Multilateration

Multilateration is regularly used to accurately track aircraft at airports using the Time Difference of Arrival (TDOA) ranging technique. It is somewhat similar to trilateration but where trilateration uses range measurements from three or more reference devices, Multilateration, which uses range measurements of the 'difference in distance' from two or more reference devices. Multilateration transmits signals from the reference devices at specific times. The difference in distance provides infinite position matches that correspond to measurements, these are then mapped to create a hyperbolic curve. A second hyperbolic curve is then created from the signals of further reference devices, and the intersection of these two hyperbolic curves is the estimated position of the 'lost' device. Multilateration also known as hyperbolic navigation can be reasonably easy to implement because of the lack of specific synchronisation between all reference devices, which would lend it well to the cooperative localisation environment.

c) Positioning Technologies

Many different technologies have been employed to estimate position for both the indoor and outdoor environments. Each technology has its own unique characteristics making it suitable for one localisation solution over another. Range, energy efficiency, precision, implementation costs, availability in mobile devices, and Time to Fix are all attributes that need to be evaluated when deciding on a particular technology. Wi-Fi (802.11) is probably the most popular positioning technology in use today. With the proliferation of smartphone devices and the more recent widespread adoption by users of the tablet form factor, mobile users are now habitually attached to Wi- Fi enabled devices. This allows designers of Indoor LBSs to interrogate these devices to ascertain the location of their users. It also provides the ability for designers to incorporate all of the preinstalled components of a Wi-Fi infrastructure into a LBS, offering a very cost effective solution. Wi-Fi Access Points (WAP's) are strategically installed throughout a buildings infrastructure to provide mobile network coverage to users. Time based Received Signal Strength Indicator (RSSI) or Time Difference of Arrival TDOA measurement methods can be used to calculate the distance between WAP's and the Wi-Fi enabled mobile devices. There are however, environmental factors that can cause problems with Wi-Fi positioning solutions. The IEEE 802.11 specification adopts a radio frequency of 2.4 GHz, which is also the resonant frequency of water [5]. Hence an environment with a high Relative Humidity (RH) level tends to absorb more power from the radio signal than during lower RH levels. Since the human body is made up of 80% fluid, radio signals travelling around an empty hall will have a higher RSSI value than one during a busy period [4]. Environmental factors (doors, filing cabinets, suites of furniture, tables, or chairs) can affect the radio signal propagation from the APs to the target mobile devices [27].

One of the earliest Indoor LBSs was the Active Badge System [15], which positioned by sensing an Infrared (IR) signal, in an office environment. IR signals cannot penetrate walls, and do not travel far, IR LBSs therefore generally operate at room level. Because IR uses light waves IR LBSs do not suffer from interference from other RF devices, but some common devices such as TV\DVD remote controls, Plasma TV's and even direct sunlight can interfere with signals. There are IR windows on both receivers and tags and these need to remain free from dirt or obstruction to prevent them impeding the transmission and receiving of signals.

There are and have been notable location based solutions built around Radio Frequency Identification (RFID) [28], [29] and [30]. An RFID Location Based System (LBS) consists of a reader and a tag, an RFID tag is a simple device made up of an antenna and a small amount of memory, making them one of the cheapest components in any LBS.

Sanpechuda and Kovavisaruch [28] champion a hybrid solution to RFID localisation, arguing that RFID on its own cannot provide the 'optimum solution' offering examples of such in [29], where a Wi-Fi and RFID based solution is lauded. The accuracy achieved with an RFID solution can be very precise due to the limited read range of the components used. Once a reader can read a tag or a tag a reader the object to be located can be placed within the read range of the tag and reader < 1 meter. But conversely, to cover a large area requires a high density of tags\readers. The power requirement of active tags is also a major drawback where the limited lifetime of batteries can result in RFID not meeting the requirements for a lot of proposed implementations.

Ultrasound Localisation works similarly to the concept of locating using RADAR and SONAR. Systems using Ultrasound to locate in the indoor arena generally use beacons (tags) and receivers to provide a more accurate means of pinpointing the exact location of objects. Because the pulses of sound travel at a known speed – speed of sound (343.2 metres per second), then the distance to\from the transmitting\receiving devices can be determined and position estimation can be calculated via Time of Arrival (TOA). The most popular examples in literature of successful utilisation of Ultrasound as an Indoor LBS are the Active Bat System [15] and the Cricket System [11]. In [12], the authors investigate the possibility of implementing an Ultrasound Indoor LBS using mobile phone speakers and microphones to emit and receive ultrasound. One notable disadvantage of Ultrasound positioning is the fact that interference cannot be heard by the human ear leaving it difficult to troubleshoot interference issues.

Ultra-Wideband (UWB) offers a glimpse of a solution to the problem of wireless technologies coexisting in the same environment [31]. Operating in the 500MHz band, and transmitting low repetition short duration pulses, provides the unique capability to filter out reflected signals. Wymeersch et al. employ Ultra-Wideband in their SPAWN algorithm (Sum-Product Algorithm over a Wireless Network) [32], to prove that '*Cooperation among nodes has the potential to dramatically improve localisation performance*'.

Utilizing a Wireless Sensor Network (WSN) the Cortina project [33] where Zheng et. al describe it being [34], "*a distributed Real-Time Location System (RTLS) designed to track assets or people moving indoors*." Using wall-plugged wireless sensors that self-configure, self-heal and self-calibrate Cortina is a cooperative localisation system that reduces maintenance and deployment costs. People or assets wear tags that are localised using RSSI measurements from nearby reference nodes. In a novel technique the Cortina System estimates floor levels based on barometric readings from on-board sensors against readings on the wall mounted reference devices on each floor.

The overarching benefit of using Bluetooth for Indoor Localisation is its availability in nearly every mobile device in use today. Bluetooth 4.0, now offers limited consumption of battery power and a massively increased coverage area ~200m. Kloch et al [35] investigate effects in Collaborative Indoor Localisation as an example of self-organising in ubiquitous sensing systems, using Bluetooth to correct Pedestrian Dead Reckoning (PDR) drift. They analyse the collaborative approach as a solution to the indoor localisation problem, and found that when using PDR in isolation the variance grows bigger as people are walking. But when two people both using PDR estimates come close together their single position estimates can be used together to more accurately localise devices.

III SPREAD Self-Positioning & Range Extending Augmented Devices

The proposed system Self-Positioning & Range Extending Augmented Devices (SPREAD), offers a unique contribution to research in this field in its ability to utilise Reference Devices (Mobile Device A and Mobile Device B) to determine the position of a Lost Device (Mobile Device X). Doing so extends the locating distances of an Indoor LBSs by utilizing the existing mobile infrastructure without the need for any further hardware.

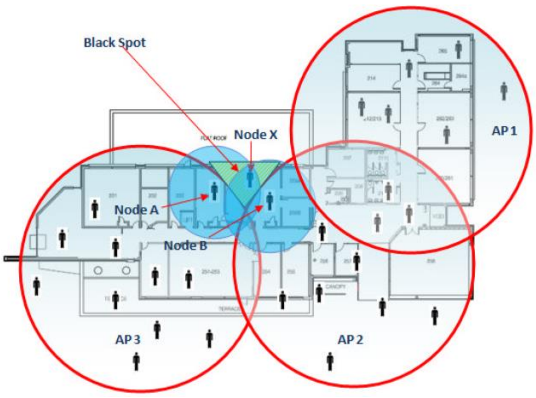


Figure 4: Building with WAP's showing coverage

Figure 4 illustrates a building with Wireless Access Points strategically placed to cover as much of the 'L' shaped building as possible, given the limitations of the range of the devices. An Indoor

Localisation System is in use in the building to determine the location of devices while they are within the range of the AP's, so almost any device within the building can be located. The 'Yellow' triangle shaped area at the front of the building, labelled as 'Black Spot' is the one area of the inside of the building that is not covered by an AP, therefore Mobile Device X's position cannot be determined using the in-house LBS. Mobile Device X will be referred to as the Lost Device as it cannot ascertain its location at this stage. Mobile Device A and Mobile Device B are located at the outer reaches of the AP's and have already been localised. Mobile Device A and Mobile Device B will therefore be referred to as Reference Device A and Reference Device B. The wireless cards on Reference Device A and B also have a range of signal and the Lost Device lies within that range. Coarse position determination can be estimated as the middle of the two overlapping coverage ranges of the mobile devices A and B. A more granular location estimation of Mobile Device X can be achieved by applying filtering techniques and location algorithms.

There are three specific scenarios where an Indoor Location System cannot locate devices and where the SPREAD system could augment with it to assist in localising devices that would not normally be found, in effect extending the range of the LBS.

1. Not enough fixed agents to accurately locate Lost Device:

In a standard LBS a specified amount of fixed agents that know their location are generally required to accurately locate 'lost' devices depending on the measurement estimation technique used. If the situation exists whereby not enough devices can 'see' the lost device, a mobile device could be used to act as a form of 'Proxy' fixed agent to assist in the localisation.

2. Lost Device is outside the building – beyond the range of the LBS:

Here Mobile Devices at the outer extremities of a buildings network can be used to locate devices outside the network, by up to 200m.

3. Indoors but beyond the range of the LBS:

There can be blind spots within any building given the aforementioned difficulties radio signals have operating within them. Mobile Devices within rooms, halls and offices in the general vicinity of these blind spots that have access to the wireless network and by default are a part of the LBS can extend the range of the LBS into the blind spot by using SPREAD.

IV CONCLUSION

There are limitations in indoor wireless location systems. Techniques to enhance this technology by extending its capability and range are to be welcomed. This research proposes to examine how cooperation between mobile devices can be used to improve localisation coverage with respect to non-cooperative techniques, and to show how the SPREAD system can be an essential ingredient of an overall Indoor LBS. Numerous collaborative and cooperative approaches have been proposed to date and the effectiveness of their strategies and technologies tested in attempts to prove their ability to enhance the precision of an Indoor LBS. But none have, as of yet proved to be able to effectively extend the range of an Indoor Localisation System. This work attempts to address this deficiency by developing a system that uses mobile agents that are themselves localised by the in situ LBS, to extend the reach of this System.

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