SafetyNet: A Universal Tracking and Security System

Christopher Browne, Thomas Ridley, Ethan Haley, Cheng Li, Cong Du
http://www.ee.ic.ac.uk/thomas.ridley11/yr2proj/default.htm

Abstract:

Accurate tracking devices are expensive, and generally for tracking only one body at a time. This poses a disadvantage if you need to locate more than one object due to the cost and the fact that a separate device or system is needed for each object. Inspired by/concerned with the high bicycle theft rate at Imperial College London, we developed the idea for a service which will provide real time tracking for many objects. The service will cater for a wide range of tracking applications, from local and portable tracking to long distance location. The service will be customisable around the basic hardware and methods, which we will outline in later sections.

This report assesses the feasibility of a tracking system for multiple bodies. It details our research on various location and communication techniques, and focuses on a theoretical implementation of a portable tracking device which can identify multiple bodies within a particular radius, and will inform the user when one of the bodies leaves the 'safe zone', indicating its distance and direction from the user. We will outline the hardware we intend to use in such an implementation and give examples of its use.

Contents:

1. Introduction

1.1 Identification of Problem

Keeping track of personal possessions and people is important to us. Loss and theft of valuable items is not uncommon nowadays, and knowing whether or not your child is safe is always a parent's major concern. One child goes missing every four minutes in the UK, almost 95,000 per year[1]. As well as children, disabled people, particularly young adults, who do not have any situational awareness or a sense of danger could get lost and very quickly find their way into trouble. In all cases, especially if they are vulnerable, it is important to look after the person and ensure they are safe, while trying not to restrict their freedom. A vulnerable person going missing puts a massive strain on the family or carers involved, and anything that could help them or the police find the missing person would be a huge benefit.

Theft of valuable or important possessions can also pose difficulties. Living and studying in London we have found first hand that bike theft is very common. Bike locks can provide considerable protection against thieves, but they can be broken or removed and the bike can still be stolen. In 2010, 115,000 bikes were reported stolen in the UK by a British crime survey conducted by the Home Office[2], but in fact over 500,000 bikes were stolen that year - a huge difference. Even when the theft is reported, it is often impossible to tell the exact time the bike was stolen, particularly if the owner had not returned within a few hours. This inaccuracy in the time of the theft greatly hinders the police's ability to find and return it.

Imperial College London provides secure bike parking areas for its students and staff; a valid college ID card is needed to enter and exit these areas. Unfortunately, the number of secure spaces is limited, and cyclists are often required to park in non-secure areas, which makes their bikes more prone to theft. Even if these bikes are locked up correctly, a large number of bikes are still stolen, with locks and cables removed with bolt cutters. An extra security system which extends to all bikes on campus could be very beneficial.

The results of our research into existing products, which is detailed in section 2.1, show that the main disadvantage of existing track and trace systems is that they are largely designed to track no more than one object at a time. This can prove expensive and inconvenient where more than one object needs to be tracked.

1.2 Proposed Solution

Our solution is to offer a service in which we implement a system that tracks the location of several objects should they leave a predefined 'safe zone'. We would be able to alter the provided equipment and systems to suit the application and needs of the customer. The basic structure of the product would involve a central terminal at the location of the 'bodies' that need to be tracked which would define the safe zone, and a small device for each body that is able to be located once it has left the safe zone. Depending on the application, further equipment and software may be required, such as a database to store information about each of the bodies being tracked, a cloud-based service to access that data, and custom interfaces at the terminal. When the body has left the safe zone, the user will be able to access the location information, which is updated periodically, and then take the appropriate action.

2. Research

In order to fully appreciate the technology on offer for our product we need to conduct research. Firstly we must look at existing products and compare them against each other to see what we can use for our proposed solution. We will take note of the hardware used, how devices find their location, communicate their location, security of data and data storage, cost for products and services

2.1 Existing Solutions

There are many tracking devices available which are designed to locate a child and inform the parent after the child has left the predefined safe zone. This is a very useful system, however it is expensive, and is only capable of tracking one child at a time, usually. These tracking devices are not cost effective for large groups of children.

Similarly, bike tracking systems such as Spybike[3] will inform the user if there is vibration or movement of the sensor after it has been activated with a small key fob. This system is also relatively expensive, and does not fit all bicycles. The cold start time is also cited as 36 seconds on average[3], which means that the location, and therefore the direction that the thief has gone will be very inaccurate for a significant amount of time after the bike is initially stolen.

The product we propose to design may be similar to the methods used in supermarkets to prevent theft of their shopping trolleys; when a trolley leaves a particular area, it is in some way disabled. There are many different technologies and solutions being used for these systems. Two examples from Carttronics[4] are their Cart Anti-theft Protection System (CAPS) and their Push-Out Protection System (POPS).

The CAPS solution is the more widely used system. It renders the cart unable to move once it crosses a boundary. This boundary is an antenna buried underground that emits a low-frequency radio signal[5]. At least one wheel of the cart is modified to contain an active circuit powered by a 9V battery. The device triggers a plastic cover to lock or unlock the wheel when it receives a particular signal; the wheel can be unlocked using a hand-held device.

The POPS solution uses technology that may be more applicable to our solution. This system is a network of radio-frequency devices that monitor the position of trolleys within a shop[6]. Trolleys are assigned a unique ID and are given permission to be taken into particular areas of the shop. If a trolley leaves an area without permission, an alarm is triggered. It may also trigger a security camera to take a snap shot or an anti-theft device on the cart, like CAPS.

As POPS is designed to track the location of trolleys, we may be able to use similar technology to track objects at a close range. However, this method would not be suitable for long range applications.

2.2 Location Techniques

Received signal strength (RSS) triangulation only has an accuracy of about 50-100 metres[7], but it does not rely on signals being strictly line of sight (LOS) as with some other techniques.. RSS requires the device to be able to receive a signal from three or more transmitters whose location is known. The signal strength of each transmitter is then compared, and the approximate position of the device relative to these transmitters is calculated. Knowing the location of the transmitters, therefore, allows us to find the location of the device. This solution becomes more accurate with an increasing number of fixed transmitters. However, RSS systems are severely affected by multipath interference[8], which is not ideal for tracking a large number of objects.

Time of arrival (TOA) and time difference of arrival (TDOA) are two location techniques which can measure distances based on the time of signals arriving at the receiver from three different points, whose exact positions are known. TOA uses the absolute time of each signal compared to the time in the receiver, which requires the time of the transmitters and the receiver to be synchronized. This means that TOA localisation systems generally need data from four sources to obtain each of the unknowns (three dimensions of location, and the synchronised time).

TDOA instead takes the difference of the times sent from different transmitters to calculate the distance. This means that the receiver's time does not have to be synchronised with the transmitters', but it is less accurate than TOA. Unlike RSS systems, TOA and TDOA systems begin to accumulate errors if the signals are blocked or reflected by buildings or other structures, since this will affect the time it takes for the signal to reach the receiver. This is illustrated in Figure 1 and Figure 2. While these figures illustrate these problems in a satellite system, the errors would also be present if terrestrial signals were used.

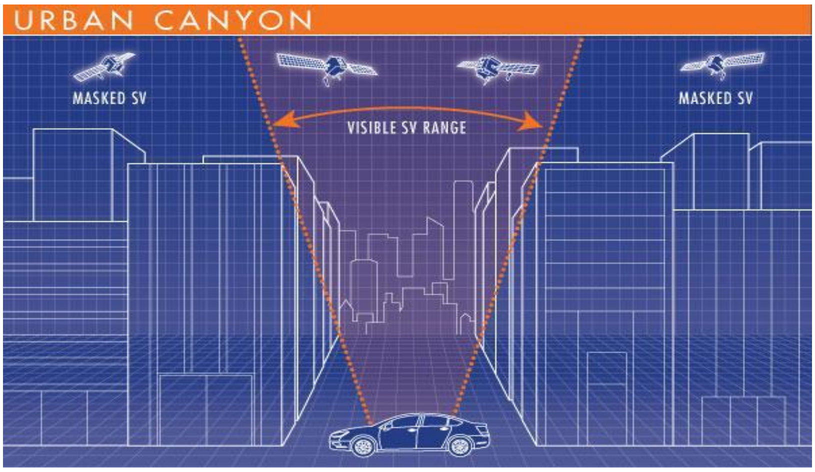


Figure 1: This diagram shows how tall buildings can block signals from GPS satellites, reducing the number of satellite signals in the receiver's LOS and reducing the accuracy of the location[9].

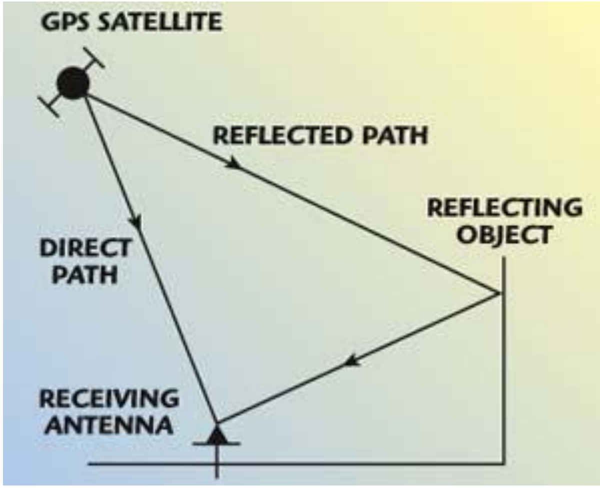


Figure 2: The GPS receiver detects signals which have been reflected off other objects, which take longer to travel from the transmitter to the receiver than the direct signals. This increase in travel time will affect the location measurement[10].

Hekimian-Williams et al.[11] have developed method for measuring distance using the phase difference of radio waves. It is possible to calculate the extra distance one wave has travelled between two antennae by comparing their phase and wavelength. Under ideal conditions, the developers have achieved an accuracy of 1.8mm. High accuracy is very desirable but this method is limited to measuring lengths up to the wavelength of the received signal. This is because after a distance greater than the one wavelength, there is no difference in phase.

2.3 Signal Sources for Communication and Location

We now must apply the techniques discussed in the previous section using available signals and services. One of the most readily available and widely used signals for localisation is GSM, a mobile network which covers almost all of the UK[12]. The most common methods involve collecting the cell ID of transmitters, whose location can be obtained by looking it up databases such as OpenCellID[13]. For an accurate location measurement, three or more mobile network transmitters are required.

A basic solution uses RSS to estimate distance from the transmitters and calculate a location. This method is very inaccurate, usually giving a range of 100m or more with the minimum three transmitters, but does not rely on the signal being LOS. Mobile networks are designed to be used by many devices simultaneously, so traffic does not normally affect the signal strength. A more advanced method uses TDOA to calculate the locations, with the positions of the transmitters again obtained using the cell ID database. However, the narrowband nature of the GSM signal causes significant multipath errors, and more complex error calculations are needed to obtain an accurate location[14]. It also suffers from the NLOS property; mobile network transmitters are terrestrial, and as such it is more difficult for signals to propagate in LOS. GSM is also an efficient and cheap way to transmit data from portable devices. It has a very long range due to providers' existing networks, and can transmit data from most locations in the UK for the same reason.

Practically every modern portable device is able to use the GPS service. It is accurate to within 3-5 metres[15] in ideal conditions but begins to lose its advantage in urban environments, where tall buildings block and reflect signals, and indoors, since virtually all of the signals are blocked. To be able to produce accurate location information, the GPS requires data from each satellite which needs to be regularly updated. The data transfer rate of GPS is sometimes as low as 50 bits per second, so this process can take upwards of 30 seconds for all observed satellites, which leads to a long time to first fix (TTFF). This would be a large problem for our concept, since we would need the bodies to be tracked immediately.

A solution to this is to use a faster network to supply GPS with up to date data quickly and regularly, even when the GPS is not active. This way, as soon as the GPS starts, it already has up to date data, and obtain a fix much more quickly. This is called assisted GPS (AGPS or A-GPS), and it most commonly used in smartphones and other smart devices[16]. Location can also be found by falling back to GSM localisation in absence of adequate GPS coverage.

Within the safe zone, it is not the precise location that will matter, but the distance from the terminal; in particular whether or not the device has left the safe zone. RFID systems are typically short range, but we need a system that operates in the range of tens of metres. RFID devices fall roughly under two types: active and passive[17].

A passive RFID device does not have its own power source. Instead, it is powered using induction from an active device. It can communicate both ways, but its range is extremely limited, with the largest achievable distance being approximately 3m. Active devices have their own power source, and thus can amplify a weaker signal, as well as send its own. These systems can have a range greater than 15m, which is ideal for our applications.

Wi-Fi access points are growing in number, especially in urban environments, and can provide quick location while GPS is warming up or there are insufficient satellites in view. The principle is similar to that of GSM localisation using RSS, in that each Wi-Fi access point has a unique media access control (MAC) address which can be used to determine its location. However, this information is not available as easily as cell ID information, and owners of wireless routers can opt-out of the location of their router appearing in Google's database[18], which limits the accuracy of the system. Even if the location of most access points is known, Wi-Fi positioning is only reliable in areas where there is a high density of networks, such as cities and town centres, and even then it is around twice as inaccurate as GPS. While Wi-Fi networks would be suitable for transferring data to and from a device, coverage is not guaranteed at all times, which is necessary for real time tracking.

3. System Design

The main problems that we highlighted when we considered the existing products included the fact that the accurate tracking systems were expensive and only able to track one body at a time. To solve this, we wished to create a system that is able to track multiple objects in real time. When considering applications of the technology we researched and considering environments in which our product might be used, we realised that one system would not be adequate to serve all scenarios. For this reason, we have decided to outline two different tracking systems: a portable and a long-range solution.

3.1 Long-range SafetyNet

The long-range system is designed primarily for an application which makes sure that several objects remain where they are supposed to be. Ideally, the long-range system should be able to track an object no matter how far away from the safe zone it is. This will require a network infrastructure in order to transfer data between the object, the safe zone terminal, and the end users. Location of the object is not a complex issue, as a system such as GPS or AGPS can be easily and cheaply implemented. As well as this, tracking within the safe zone can be efficiently carried out using RFID. In certain cases, it may be more efficient for the objects to be transmitting their location at all times, and define the safe zone in software.

A database of information regarding the objects to be tracked will be needed, including the ID, present and past location data, and any other necessary information, such as contact details of the owner. This database should be accessible from the internet, and there should also be a system in place to inform the system administrator and the owner if the object leaves the safe zone.

3.2 Portable SafetyNet

This system focuses much more on a scenario in which a supervisor is actively monitoring a group of objects. The hardware involved is one handheld device which creates the safe zone, and can display information about the number of objects being tracked and their distance from the device. We should calculate how far away each object is, and if it exceeds a preset value, the user will be informed, and the distance and direction of the object will be displayed on the screen.

In the following sections, we will carry out a feasibility study of the Portable SafetyNet system. We have chosen to study this over the former system because it is more localised, and we can concentrate more on specific location techniques, rather than the network infrastructure and software required in the long-range solution.

4. Distance Calculation

In our system we have a terminal and a tracker. To save power, the tracker should only transmit once it has been lost. This requires the distance calculations to be done using only the signal received from the terminal. Of the methods we found and discussed in the research section, the most reliable methods to calculate distance are TOA and TDOA. Both operate on the same principle, using the time it takes for signals to reach the device to calculate the distance d from a base-node.

$d = v\Delta t$ where v is the velocity of the signal
Δt is the time of travel of the signal

To measure the travel time a number of methods are used. The most common is timing how long it takes for a signal to be sent and returned to the device. This isn't ideal in short-range systems, and it also requires the slave device to be constantly transmitting, which consumes power. Instead, we propose a technique using synchronized clocks. The body and terminal will each have a counter triggered by an internal clock, and these will be synchronised every time the system is initialised. The terminal will send out a signal containing its current counter value. When the tracker picks up this signal, it compares the value to its own counter value. The difference between the two multiplied by the period of the clock will give the travel time.

With this technique, the measured distance is bounded by the clocks and counters in the devices. The upper limit will be the time it takes for the counter to overflow multiplied by the speed of light. A large enough counter will ensure that this distance is larger than the range of our system. Typical microcontrollers run with a clock speed of 20MHz, meaning the smallest unit of time the device could detect is the period, 50ns. Unfortunately, in 50ns light travels 15m. Our system needs to be a lot more accurate, especially when measuring the distances considered in the next section. Our solution is to have a separate clock to trigger the counter. This can be triggered at a much higher frequency.

As we will be using EM waves, $v = c = 3\text{x}10^8$ ms^{-1}. We would like to measure distances smaller than 3.5cm (this is related to the spacing of the antennae in the device, which is detailed in the next section). For d = 3.5cm, Δt = 116.7x10^{-12}s and therefore the clock frequency f = 8.6GHz, which is completely unattainable. However, we can still use this method for measuring longer distances. If we choose a minimum resolution of 2m, we only need a clock frequency of 150MHz, which is much more achievable.

Now we must use a different method for the small distances. In our research, we highlighted technique which uses the phase difference of signals received at different antenna to calculate distance[11]. This used TDOA and had millimetre accuracy, but was limited to the wavelength of the signal. We will be transmitting our signal at a frequency below 1GHz, which corresponds to a minimum wavelength, and therefore a maximum distance measurement of about 30cm. The small distances we are interested in are well below this limit.

In summary, we will use two techniques for measuring distance. The first is measuring the distances between the tracker and terminal; the travel time will be calculated by finding the difference between two different data from synchronised counters. This method's major benefit that is it is one-way, so the tracker will not have to consume power by transmitting.. To measure the much smaller distances used in the direction finding algorithm (explained further in the next section) we will use the phase difference of signals received at different antenna.

5. Direction Finding

Our system must be able to point the user in the direction of a 'lost' device. We propose a method using the phase difference method of calculating small distances and triangulation. The master terminal will have three antennae arranged in a triangle as shown in Figure 3. These antennae will form the three base nodes. We have designed an algorithm to calculate the direction and the distance of the object relative to the terminal, which can be found in Appendix B. The calculations for this use simple trigonometry and known lengths and angles on the device:

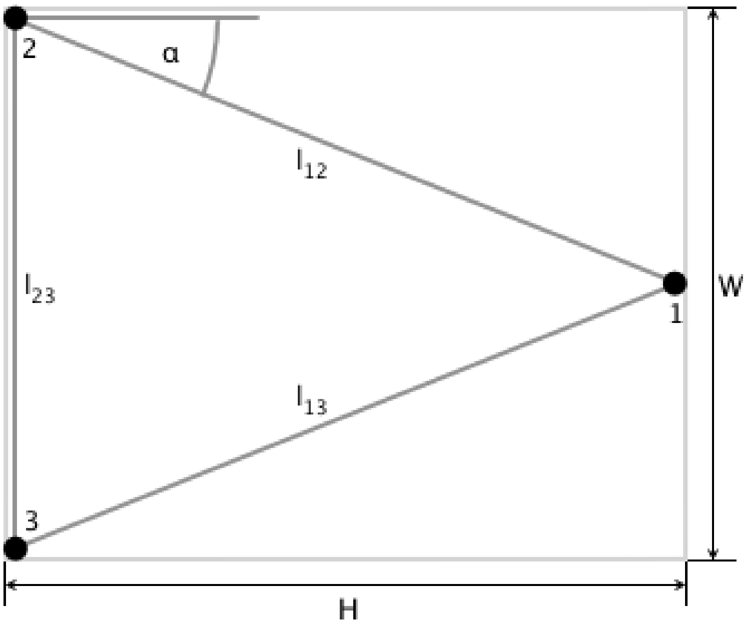
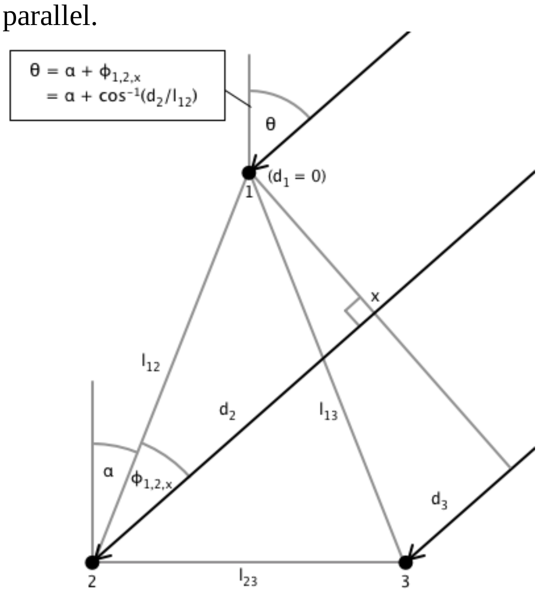


Figure 3 - Placement of antenna within the terminal device of width W and height H. l_{xy} is the distance between antenna x and y.

For a given W and H:
$l_{12} = l_{13} = (H^2 + (W/2)^2)^{1/2}$
$l_{23} = W$
$\alpha = \cos^{-1}(H/l_{12})$

Now that these parameters are defined, we can calculate the direction of the received signal. We will define the direction of the signal as the angle θ from the normal, as shown in Figure 4. A positive θ is a signal coming from the right and a negative is a signal from the left. There are some assumptions made in this model: the device geometry is known; the distances d_1, d_2 and d_3 have been calculated from the signal's travel time and phase, and the tracker is far enough away that the three incoming signal paths can be approximated as parallel.



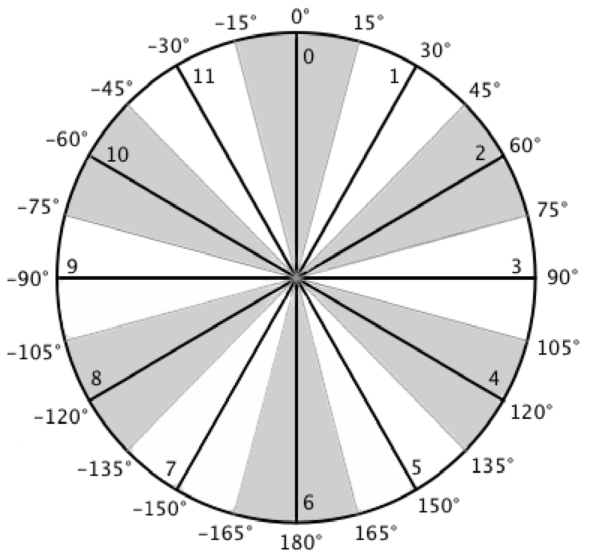


Figure 4 (left) - Calculation and example of an acute θ
Figure 5 (right) - Diagram showing discretised θ with 12 angle bins, which are regions in which the angle can fall (shown as alternating white and grey sections). In this case θ was rounded to the nearest 30°.

Using trigonometry, it is possible to calculate the direction of a signal from any angle θ. A full explanation of how θ can be calculated and a demonstrative algorithm written in C++ can be found in Appendix B. It calculates θ for a given set of values of H, W, d_1, d_2 and d_3. The output θ can be in two forms. The first is θ itself and the second is a rounded, discrete value. The latter is more useful in our system. Our aim is for the terminal to output a discrete direction to point the user in the right direction - in our case this will be in the form of an LED lighting up on a dial. The example code will output an angle number from 0 (straight ahead) to n-1, where n is the number of angle bins. Figure 5 shows an example using 12 directions where the alternating white and shaded regions show the angle bins.

6. Hardware

RFID systems generally consist of a reader and a tag. A reader consists of an antenna, controlled transceiver and a logic interface with which it would communicate with other devices or networks. Tags tend to simply consist of an antenna and a chip, which stores particular information about the tag, including its ID. Antennae for tags can be as simple as a coil of wire, and are widely available at a low cost. The transceiver is able to transform the received signal into a recognisable code[19]. As with the antennae, a wide variety is available at a low cost.

An important point to make when discussing tags is the possibility that they could be removed accidentally or purposefully. This would prevent further tracking of the object. While this not possible to prevent beyond ensuring that the tag is attached as securely as possible, we can inform the terminal when the tag has been removed. To achieve this, we simply need a small circuit in the form of a pin or a loop of wire and connect it in such a way that it must be broken to remove the tag. If the tag is still being monitored, it then begins to transmit its location, even if it is within the safe zone. This should send an immediate alert to the user so that they may take action as quickly as possible.

An alternative to using RFID, which is a transponder based communication method, would be to use technology from Short-Range Devices (SRD). These are radio frequency devices used for various wireless applications ranging from car keys to hand held voice communication. Typically these have a much longer range than RFID but each device needs to be able to generate its own high frequency carrier signal. There are restrictions on the conditions under which these devices are allowed to operate, particularly the frequency and transmission power[19].

A typical long range RFID reader uses a mains power input, which restricts the possibility of a portable/mobile system. Use of a radio transceiver reduces the required power of the reader that would be used in RFID at the cost of increasing the power at the tag's end. However, the distance that a signal needs to travel is halved, which results in a better link budget at the same power. This suits our network much better, as the available power of each device is limited by a battery.

The components required for this are a transceiver, antenna and microcontroller. There are four states that the transceiver can be in: transmit, receive, idle and sleep. In the sleep state, it can be assumed that it uses no power. The device uses most power in transmit mode. While the transceiver is receiving a message, it uses the same amount of power as it does while listening to the channel in the idle state A wake-up radio is normally used to improve efficiency by turning on the main receiver as a message is about to arrive.

To determine the maximum range of the device, we can use the Friis ground model, shown in Figure 6, which applies when the transmitter and receiver are in LOS. The range is calculated by finding the distance at which the received power is equal to the receiver sensitivity (the input signal level where the packet error rate exceeds 1%). As a rule of thumb we will assume that the maximum range indoors is going to be approximately 10% of the LOS range. Therefore, we require a range of 1-2km using the LOS equation, which is definitely achievable by portable SRDs.

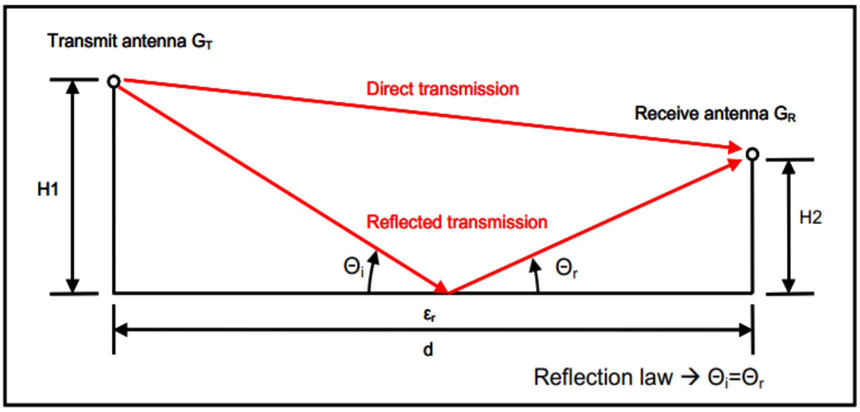


Figure 6: Diagram showing the ground reflection consideration of the Friis transmission model[20]

Since we wish to be able to transmit location data over long distances, we need to consider a small, long lasting power supply. While there are many batteries available which are cheap and long lasting, we came across an alternative solution known as a supercapacitor. These differ from normal capacitors in that they tend to have capacitance in the order of Farads, thousands of times greater than electrolytic capacitors. Unfortunately, they are not without disadvantages, and we believe that supercapacitors are not yet developed enough for us to use in our design. Instead, we have opted to use a coin cell battery, due to its long-lasting nature and voltage capability.

Typically, the working time of a coin cell battery such as CR2477 Lithium made by Panasonic[21]can be 10 hours at the maximum current of our circuit (which we estimate at 50mA). The voltage range for the system is should be within the range of 2V to 2.6 V. A single coin battery can provide 3V, which is ideal. They are also relatively cheap, with prices quoted at around £0.50 to £1.

In order to perform the distance calculations and signal processing required by our system, we need a reasonably powerful microcontroller that is easy to program. We also need to take power consumption into consideration, as well as price. We have therefore chosen the ATmega88PA-PU from ATMEL[22], which will be suitable for both the reader and the tags. The following is a brief list of our reasons for choosing it: low power consumption at when operated under normal conditions (consumption in active mode is 0.2mA, in power-down mode is 1μA, and in power-save mode is 0.75μA.); programmable with a variety of languages including C and C++, capable of 20MIPS (million instruction per second); inexpensive (£1.58 from Farnell UK for orders of over 25 units[23])

7. Example Applications

While the inspiration for SafetyNet came from tracking stolen bicycles, we have designed the full system to be as universal as possible. This section will cover a few examples of how both the Long-range and Portable versions of SafetyNet can be employed.

The first is a Bike Park that uses the Long-range SafetyNet. The Bike Park idea is intended for areas in which a large quantity of bikes may be kept, but has a high rate of theft, such as a university or business park. It is a secure environment where bikes can be stored during the day and located should they be stolen. Each bike has a tracker that is checked in and out at a terminal within the bike park area. If it has been checked in and the tracker leaves a defined safe zone around the terminal, an alert will be sent to the owner and to site security if applicable, who (via CCTV) can confirm whether a bike has been stolen. The tracker will start transmitting its location. This will be mapped and stored in an online database, where it can be accessed by the user on the SafetyNet website.

Another possible use for the Long-range SafetyNet is to monitor valuable animals or livestock. It follows the same principle as the bike park but with a much larger safe zone. There is a central terminal communicating with trackers attached to animals. If any are stolen or leave the area where they are kept they will register as having left the safe-zone and the owner will be alerted. In the meantime, the tracker will be transmitting its location, which can be used to recover the missing animal.

The Portable version SafetyNet can also be adapted for many. A guide on health and safety for school trips in the UK[24] recommends a supervisor-to-pupil ratio of between 1:6 and 1:10 depending the pupils' ages. The Portable SafetyNet system would be given to each group: a supervisor and a number of pupils. Each will be be self-contained and free to move independently of any other groups. The supervisor would have the terminal device on their person and each child within the group would have a tracker attached to them. If they leave the safe-zone around the terminal, the supervisor is alerted and the terminal device displays the direction of the missing child. This isn't just applicable to school trips: any situation in which a group of people need supervision can use this system. Another example is of a party trekking through the mountains; in adverse weather conditions, people can quickly be separated from the main group. The Portable SafetyNet would enable someone to be found quickly and safely. It is light and has a long battery life making it perfect for extended use.

Both systems we have proposed are very versatile and can be adapted to suit most needs. The designs explained in this report mostly consider the technical details concerning location. When designing the full product, the specific use must be taken into account. For example, if it is to be used on an expedition into a jungle, the hardware must be ruggedised and water-proofed.

8. Conclusion

Our goal was to create a security system that would perform real time tracking of an object and alert the owner when it is not where it should be. After researching possible methods of locating an object, we realised that the constraints of the system would need to be better defined. We decided that there were two directions in which we could take the project; one for applications requiring long-range tracking, and another for a portable, short-range solution.

We felt that the portable system would be more successful after our analysis of the existing solutions and available technology. We have reached a point where we believe that we have a design that works in theory. As such, we have yet to perform testing and discover if these methods work in practice. While this is only a subset of the full service we wish to provide, it concentrates on effective location measurements, some of which could be applied to the long-range system.

9. References

[1] National Policing Improvement Agency. (2011) *Missing Persons: Data and analysis 2010/2011*.

[2] Home Office. (2012) *Crime in England and Wales: Quarterly Update to September 2011*. Report number: 978 1 84987 622 3.

[3] Integrated Trackers. *Spybike: Technical Spec*. [Online] Available from: http://www.integratedtrackers.com/GPSTrack/Spybike.jsp.

[4] Carttronics website [Online] Available from: www.carttronics.com

[5] Blender, N. *Reversing the Operation of CAPS Shopping Cart Wheel Locks*. [Online] Available from: http://www.woodmann.com/fravia/nola_wheel.htm .

[6] French, J., R., Nebolon, J., F., Harling, R., M. & Galli, D., A. (2008) *SYSTEM FOR PREVENTING SHOPPING CART PUSH-OUT THEFT*. Preventing shopping cart theft WO2008154577 (Patent).

[7] Zekavat, S., A. & Buehrer, M. (2012) *Handbook of Position Location Theory, Practice and Advances*.

[8] Pahlavan, K., Li, X. & Mäkelä, J. (2002) *Indoor Geolocation Science and Technology*. February 2002 edition.

[9] Auto Electronics. *Navigation Systems*. [Online] Available from: http://autoelectronics.com/telematics/navigation_systems/GPS_2.jpg .

[10] Microwave Journal. [Online] Available from: http://www.microwavejournal.com/legacy_assets/images/0408m32_fig01.jpg

[11] Hekimian-Williams, C., Grant, B., Xiuwen Liu, Zhenghao Zhang & Kumar, P. (2010) Accurate localization of RFID tags using phase difference. *RFID, 2010 IEEE International Conference on*. pp.89-96.

[12] Ofcom. (2012) *Infrastructure Report*. 2012 Update.

[13] OpenCellID. [Online] Available from: http://opencellid.org .

[14] Winter, J. & Wengerter, C. (2000) High resolution estimation of the time of arrival for GSM location. *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*. pp.1343-1347 vol.2.

[15] *GLOBAL POSITIONING SYSTEM STANDARD POSITIONING SERVICE PERFORMANCE STANDARD 2008*. (SI 4).

[16] Binghao Li, Jiahuang Zhang, Mumford, Peter & Dempster, Andrew G. (2011) How good is Assisted GPS? *IGNSS Symposium 2011*.

[17] Finkenzeller, K. (2012) *RFID Handbook*. 3rd edition.

[18] Google. (2011) Greater choice for wireless access point owners. Weblog. [Online] Available from: http://googleblog.blogspot.co.uk/2011/11/greater-choice-for-wireless-access.html .

[19] Karl, Holger & Willig, Andreas (2005) *Protocols and Architectures for Wireless Sensor Networks*.**[20]** Kvaksrud, T. *Range Measurements in an Open Field Environment*. [Online] Available from: http://www.ti.com/lit/an/swra169a/swra169a.pdf.

[21] Panasonic website. [Online] Available from: http://www.panasonic.com/industrial/batteries-oem/oem/primary-coin-cylindrical/br-cr.aspx

[22] ATMEL ATmega88PA datasheet [Online] Available from: http://www.atmel.com/Images/8161s.pdf

[23] Farnell UK- ATmega88PA-PU [Online] Available from: http://uk.farnell.com/atmel/atmega88pa-pu/mcu-8bit-avr-8k-flash-28pdip/dp/1715492

[24] HEALTH AND SAFETY OF PUPILS ON EDUCATIONAL VISITS [Online] Available from: http://www.bexley.gov.uk/CHttpHandler.ashx?id=5125&p=0

10. Appendices

Appendix A- comparison of positioning systems[7]

TABLE 1.2. Comparison of Positioning Systems (Part 1)

				Accuracy (m)[a]	LOS / NLOS	Environment	Power Consumption (W)[b]
Global Positioning System			**GPS**	H [20]	LOS	O	VL [26]
			AGPS	H to M [27]	LOS	O, I	VL [28]
Local Positioning System	Self-Positioning		**INS**	VH → VL[c] [12]	Both	O, I	M to H[d] [29]
	Remote Positioning	Active	**RFID**	H [14]	Both	I	VL [30]
			WLPS	varies with application	LOS	O, I	varies with application
			TCAS	L → VL[e] [31]	LOS	O	VH [32]
			WLAN	H to M [3]	Both	O, I	L [33]
		Passive	**Vision**	VH to H[f] [34]	LOS	O, I	M [35]
			Radar	VH [36]	LOS	O	H[g] [37]

				Multi- (M)/Single- (S) Node Positioning	No. of Base Stations	Dynamic (D)/ Static (S) Base Station	Absolute (A)/ Relative (R) Positioning
Global Positioning System			**GPS**	M	4[h]	D	A
			AGPS	M	4[g]	D	A
Local Positioning System	Self Positioning		**INS**	N/A	N/A	N/A	R
	Remote Positioning	Active	**RFID**	M	3	S or Known	R
			WLPS	S	1	D	R
			TCAS	S	1	D	R
			WLAN	M	3	S or Known	R
		Passive	**Vision**	S	1	D	R
			Radar	S	1	D	R

[a]Scale for accuracy of positioning systems: very high (VH), <1; high (H), 1–5; medium (M), 5–30; low (L), 30–50; very low (VL), >50.

[b]Scale for power consumption of positioning systems: very low (VL), <1; low (L), 1–10; moderate (M), 10–50; high(H), 50–200; very high (VH), >200.

[c]The initial accuracy is high (few decimeters), which changes with time due to error propagation.

[d]Depends on INS classification (stable platform system consumes high power; strapdown system consumes moderate power).

Appendix B - Direction Finding

This appendix is a further explanation of section 3.2.2 and goes through a possible method to find the direction of an incoming signal. While it isn't fully optimised for hardware, it shows the principles behind the calculations. This method will be using an antenna arrangement as shown in Figure 3 and therefore it is possible to find the direction of an incoming signal. We will define this direction as the angle θ from the normal or forward direction, where $-180° < \theta \leq 180°$. θ can be seen in Figure 4 which demonstrates Case 1: where θ is acute. In all cases θ is trivial to calculate but as the received signal moves round, the equation changes slightly, Figures B1 and B2. The distances d_1, d_2 and d_3 are defined as the extra distance travelled by an EM wave to reach its respective antenna. For example in Case 2 the wave must travel a further distance d_1 to reach antenna 1 when compared to travelling to antenna 3.

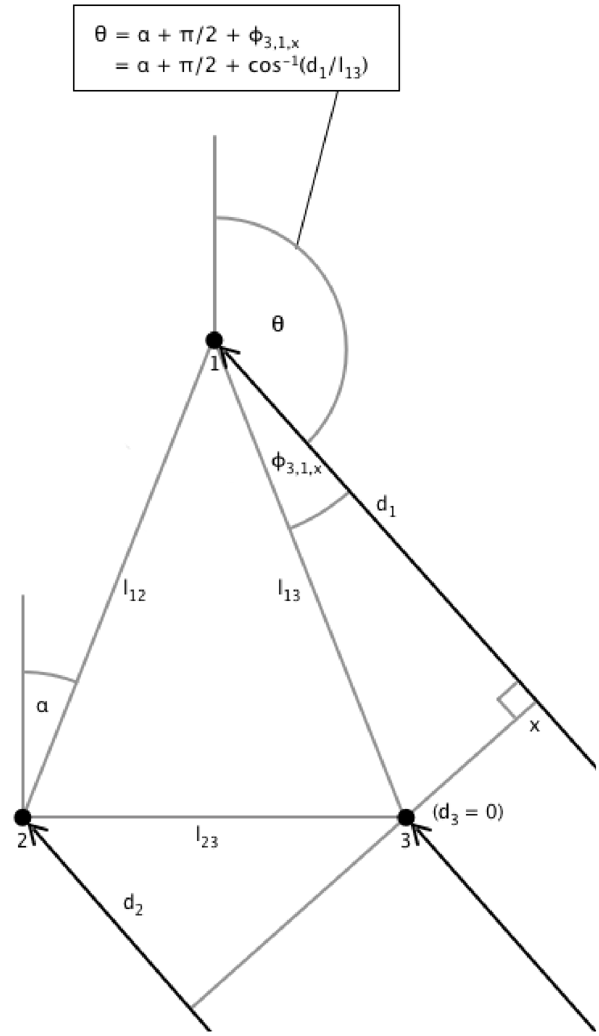


Figure B1 - Case 2: where θ is obtuse

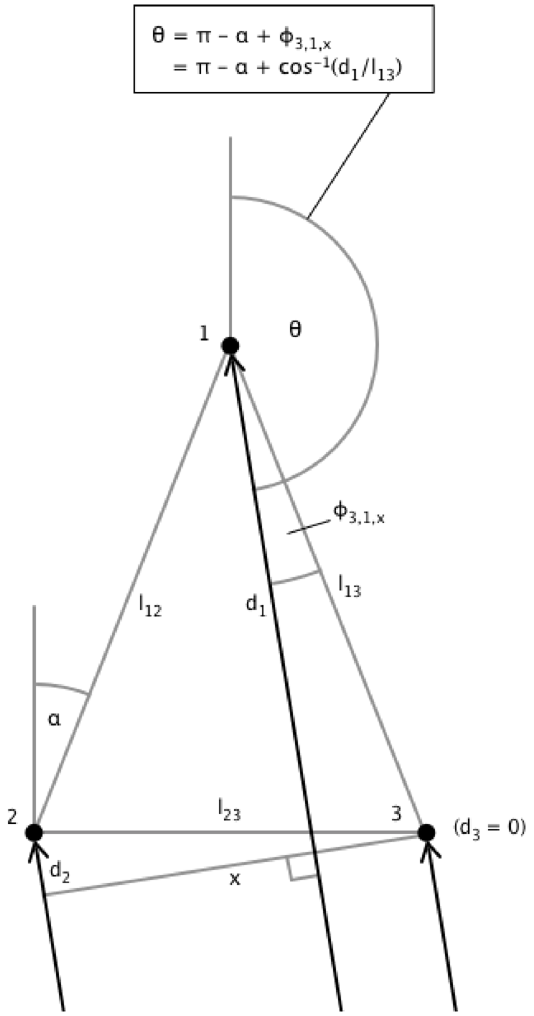


Figure B2 - Case 3: Signal is from below l_{13}

The last case is the signal coming from the left - in other words θ is negative. From the diagrams it is easy to see that switching d_2 and d_3 in the calculations will give the correct positive value, then all that is needed is to turn that value negative.

The next step is to identify the conditions for each case. Table B1 shows the conditions for each:

Case	**Condition**	**Comments**
1	assumed	We assume Case 1 unless any other conditions are satisfied
2	$d_1 > W/2$	d_1 increases with θ, at $\theta = 90°$, $d_1 = W/2$
3	$d_2 < l_{23}\sin(\alpha)$	d_2 decreases with θ, this condition coming true when d_1 and l_{13} are parallel (see Figure A3)
θ negative	$d_2 < d_3$	

Table B1 - Boundary conditions for each θ calculation

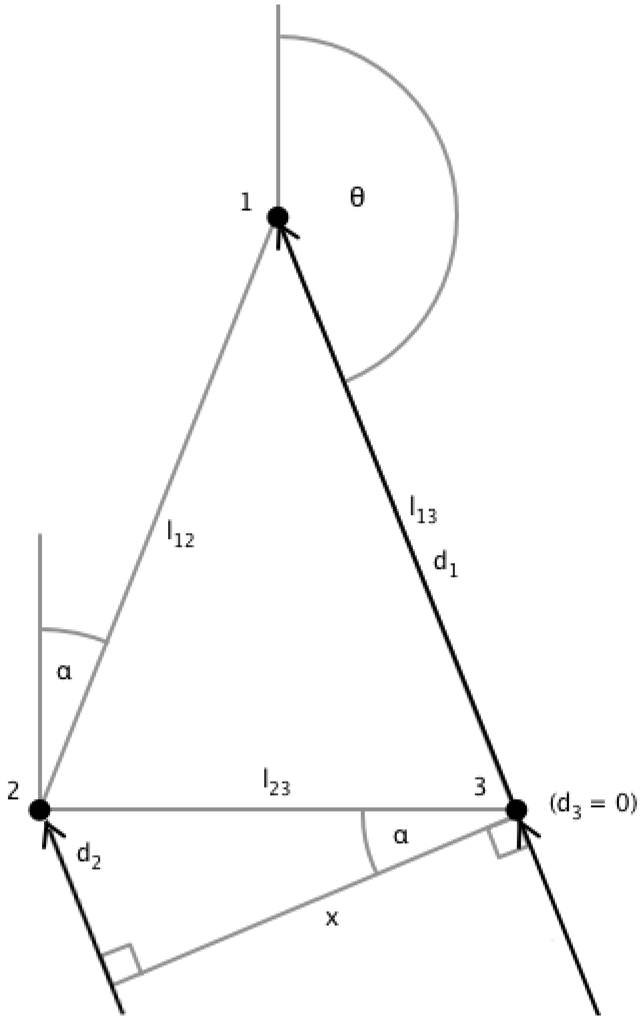


Figure A3 - Boundary condition for Case 3

The following is an example of how this algorithm can be implement. In this case it is written in C++. It is meant to demonstrate the concepts explained above, taking a set of values for d_1, d_2 and d_3 and from them, find the direction of the received signal. The output, Figure A4, is both the accurate calculation of θ and the discrete direction as explained in Figure 5.

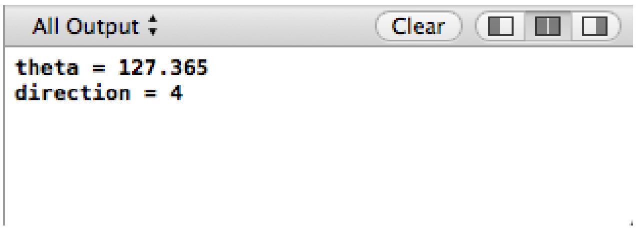


Figure A4 – Output from direction finding algorithm – using same d values as in the code below

Direction Finding Algorithm:

```
//  GP_DirectionFindingAlgorithm

#include <iostream>
#include <math.h>
#include <stdlib.h>
#define PI 3.14159265
using namespace std;

//global variables
double H = 12, W = 7;
double l12, l13, l23, alpha;

double acuteTheta (double, double, double);
double obtuseTheta (double, double, double);
int thetaDirection (double, int);

int main()
{
    double d1=11.6615425, d2=4.24823312, d3=0;  //127.365
    double theta;  //the received signal angle relative to the normal
    int numberOfDirections=12, direction;  //discrete number of direction
lights
    bool thetaPositive;  //theta positive if right of normal, negative if
left got normal

    l12 = sqrt(H*H + (W/2)*(W/2));
    l13 = l12;
    l23 = W;
    alpha = acos(H/l12)*180/PI;

    //determine if signal is coming from left or right by checking the extra
time it takes to get to either antenna 2 or 3
    if (d2 == d3) { //signal straight ahead or behind
        if (d2 > d1) {
            theta = 0;
            direction = 0;
        } else {
            theta = 180;
            direction = 6;
        }
        cout << "theta = " << theta << endl;
        cin.get();
        return 0;
    } else if (d2 > d3) //signal coming from right
        thetaPositive = true;
    else                //signal coming from left
        thetaPositive = false;

    //determine if signal is coming from the front (i.e. theta acute) or from
behind (theta obtuse)
    if (d1 == W/2) {        //if coming directly from right or left
        theta = 90;
            if (!thetaPositive)
                theta = -theta;
    } else if (d1 < W/2) {  //theta acute
        if (thetaPositive)
            theta = acuteTheta(d1,d2,d3);
        else {  //account for -ve theta
            theta = acuteTheta(d1,d3,d2);
            theta = -theta;
        }
    } else {                //theta obtuse
        if (thetaPositive)
            theta = obtuseTheta(d1,d2,d3);
```

```
        else {  //account for -ve theta
            theta = obtuseTheta(d1,d3,d2);
            theta = -theta;
        }
    }
    //get direction number from theta
    direction = thetaDirection(theta, numberOfDirections);
    cout << "theta = " << theta << endl << "direction = " << direction <<
endl;
    cin.get();
}

double acuteTheta (double d1, double d2, double d3) {
    //this function will calculate theta for a given d1, d2 and d3 when theta
is acute
    //this is d1, d2, d3 as defined with +ve theta, for -ve theta d2 and d3
are switched in the calculations
    double theta;
    theta = alpha + (acos(d2/l12)*180/PI);  //l12 = l13 so it works for both
+ve and -ve theta
    return theta;
}

double obtuseTheta (double d1, double d2, double d3) {
    //this function will calculate theta for a given d1, d2 and d3 when theta
is obtuse
    //as with the acuteTheta function: this is d1, d2, d3 as defined with +ve
theta
    double theta;
    //do slightly different calculations if the d1 line is below the d13 line
    if (d2 > (l23 * sin(alpha*PI/180))) {
        theta = alpha + 90 + (acos(d1/l13)*180/PI);
    } else {
        theta = 180 - alpha + (acos(d1/l13)*180/PI);
    }
    return theta;
}

int thetaDirection (double theta, int numberOfDirections) {
    //this function will return the discrete direction number for a given
theta and number of direction
    double directionInterval;
    double direction;

    directionInterval = 360/(numberOfDirections);
    direction = theta/directionInterval;
    //if direction not integer, round
    if ((direction - int(direction)) < 0.5) //round down
        direction = int(direction);
    else  //round up
        direction = int(direction) + 1;

    if(direction < 0)
        direction = direction + numberOfDirections;

    return int(direction);
}
```