Introduction

The modern advancement in communications and mobile computing has provided users and providers alike, with plethora of opportunities. One of them is content and information sharing to and between devices in close proximity. One good example is Tweedback, a platform for live feed back between students and lecturers. This platform, developed at the University of Rostock, highlights the emphasis of indentifying devices in close proximity. This emphasis raises the need to focus on two aspects of services, localization and communication. With these two services, we can imagine a number of use cases. A good example would be the ability of two or more devices to identify their proximity and the fact that they are attending the same lecture. Another similar scenario would be for the devices to indentify the lecture room they are in and provide the user with the right content relevant to the ongoing lecture. Modern devices are equipped with resources to help them identify their location, and at the top of the list is the ubiquitous GPS service. Though, an unchallenged leader in the outdoor location service, the accuracy of GPS when used in indoor applications falls short (Chen & Kotz, 2000) of the needed accuracy for indentifying devices in a small group, like in a typical lecture room scenarios used in Tweedback. There are a number of indoor location solutions available these days, and in this thesis we discover on ways to discover devices and communicate crucial information between them. And particularly we focus on using the inaudible sound wave spectrum as a medium of communication for our system.

Motivation

Technology has reached a point where we rely on our hand held devices in almost everything we do when it comes to information. Whether they are laptops, tablets, or smartphone, they give us access to any kind of content through the Internet or any other content sharing networks. In doing so, the need to interact with your environment, not just virtual environment, but also physical environment, is becoming increasingly important. Inerraction with our physical environment means having information on the availability of services we have in our close proximity and also the ability to interact with devices in the same vicinity. As mentioned in the introduction, GPS remains the main way for outdoor interaction, but when it comes to indoor activities, we have to rely on other emerging technologies. There are a number of indoor navigational and discovery solution available currently, and whether Wi-Fi, Magnetic location service, or NFC, they have their own pros and cons in giving the user a smoother interaction. In our in-depth research, we look in to ultrasound medium as a way to communicate small but valuable information and room discovery system.

Background and Related Work

The need for location based services has many facets of benefits. A system with a feature to recognize its geographical location, users present in that location and the services available to it is appealing in any sense. These services, called LBS (Location Based Services), have been associated with a number of ground breaking applications in recent advancement of mobile computing. From health applications to marketing services, they all depend on the availability of location giving resources. Any given LBS has five basic components (2), this components projected in to our use case, the lecture room Scenario, would be listed as follows.

**The Mobile Device**: The concerned device

**Communication component**: In our scenario, the device needs access to a communication channel to get the information regarding the location and also a channel to get the actual service and content that’s relevant to the location.

**Positioning component**: A system for indentifying the location.

**Service and Application Provider**: A system for giving the service and application based on the computed location.

**Data and content provider**: For providing the actual content based on the indentified service and content.

Of those five components mentioned above, the Communication and the Positioning component are what we are concerned in our work, since the others are more or less independent of the type of LBS we use.

GPS (global positioning services) has been the core service of these advancements when it comes to outdoor usage. But GPS falls short of the accuracy needed when used in indoor applications, and in this section we’ll talk about different categories of indoor LBS, specifically designed to address the shortcoming of GPS.

The basic concept behind the design of any location indentifying system is to exploit the change in the value of network parameters relative to space. The more acute the change in those parameters, the better the accuracy is for the system in identifying its position. And those different systems, which are mentioned shortly, exploit different types of fields in one way or another. Electromagnetic, Magnetic and Acoustic fields are the three main categories of physical fields used in currently available indoor positioning systems. Under the Electromagnetic based systems we have Wi-Fi, Bluetooth and GPS. And the new “indoorAtlas” is categorized under the Magnetic field based systems. And finally we have the sound wave based systems, in which our system is based. In the next section we’ll walk through those different systems by addressing their pros and cons.

GPS

GPS (global positioning system) is a navigational system based on satellites. It is the widely used system from the so called satellite based navigational systems, the other being GLONAS and GALLILIO.

The GPS positioning and timing service for civilians is made up of three components. The satellite, control system and user side. The satellites are orbiting the earth in their numbers, 24 of them in the current constellation. Those 24 satellites continuously send one way positioning and timing signal. The control side monitors and maintains them in their orbits. And finally, the user side in the civilian case, receives the signals from at least four satellites at time and based on the signals received calculates the current position of the receiver.(5)

The civilian case has only one frequency used per satellite and with the current system, preventing signal degradation using techniques like Ionospheric correction (needs a good reference). Unlike the military receivers which are provided a second signal to do the correction, the civilian receivers suffer greatly in the accuracy when used indoors. The signal power from GPS statellites can drop up to 100,000 times when used indoors, and with it the horizontal accuracy drops to hundreds of meters.

Though the great availability of GPS signals can never be doubted, the accuracy, even at its best of 3 meters, is far from the level needed in in-door localization, which is less than 2 meters in the very least. And with all the signal degradation when used in our case scenario, the signals can be unusable. (6)

Wi-Fi

The abundance in the availability of Wi-Fi hot spots is getting high by the day. A recent research has found that there are 150 Wi-Fi hot spots per person in the world, and if you consider developed countries like UK, the number goes down to 11 per person (8). This abundance and the majority of them being available indoors is the prime driving factors in researches of Wi-Fi based indoor navigational systems.

WLAN based indoor localization techniques use the signal strength of the radio signals as the parameter whose variation with respect to the location of the asset is used in positioning. RSSI (Received Signal Strength Indication), is used in WLAN based localization techniques. According to the survey made by (9), there are two main divisions of RSSI based WLAN techniques, fingerprinting based approach and RF propagation based approach. Fingerprinting approach is based on mapping the network parameters with respect to the area of interest, where as the RF propagation based uses the knowledge of the AP (access points) and trilateration to calculate the position of the asset.

The major advantage of using WLAN based location system is it adds no additional hardware or additional features in the existing APs and mobile devices. The major concern with WLAN based systems is that the calculation is made on the server side, the mobile device only provides the system with the received parameters, and this creates a privacy issue.

Bluetooth

Bluetooth is a radio technology used to exchange data wirelessly over a short distance. Operating in the 2.4 to 2.485 GHz radio spectrum, it can offer connectivity solutions with very low power consumption. (11) Though not specifically built for location solutions, it has a number of advantageous features that makes it attractive in the use of indoor location solutions. The availability of Bluetooth hardware in almost all modern devices, low power consumption and its inexpensive components are the prime advantages (10). Starting from these needed features, a number of solutions are published as referenced in REFERNCE NEEDED.

Unlike GPS and WLAN based systems, Bluetooth based systems are not truly positioning system. They are rather proximity solution, as their solution is based on the proximity of devices to a reference beacon that broadcasts Bluetooth signals.(11) Bluetooth location solution can reach accuracy of Reference needed

Ambient Magnetic

A relatively new comer to indoor localization is the use of static magnetic fields present in buildings. A working and commercially available system is well published as referenced by (12). According to their investigation, any particular building has a unique static magnetic fingerprint that is the result of the interaction between the static magnetic fields of the structures in the building and earths’ magnetic field at that location. This can be fingerprinted and used as a very accurate indoor positioning system.

The working solution side of the investigation requires you to scan your region of interest for the local magnetic field anomalies and upload it to a central server. This magnetic fingerprint can then be referenced anytime a location information is required. In this particular case, the device sends the current magnetic signature and the server replies with the corresponding position based on the floor plan uploaded along with scanned magnetic field signature. The details of the techninicalies are well published in (12)(13)

Ultra Sound

Using Ultrasound or Inaudible acoustic signals as a means of communication or positioning system follows the same basic rules as any radio communication system. But in this case we use propagation of sound waves through vibration of air as the medium of communication. We humans are theoretically sensitive to vibrations of our ear drum in the frequency range of 20Hz to 20Khz.PUT REFERENCE ON SOUND BASICS. But this theoretical range is the ideal case, and in reality varies with age. As given on a chart below, which is borrowed from REFERENCE THE PDF, we can see that in most humans the maximum frequency is 16.5 KHz.

Using inaudible acoustic signals has contrasting pros and cons, and using the advantages as the basis of the features is the aim of any system that employs them. Those advantages can be listed as follows.

**Built in Hardware**: Any modern device has a built in microphone and speaker, with the ability to emit and receive sound waves with a maximum frequency of half the sampling rate. And the sampling rate in most modern devices is at least 44100 Bits/sec. This availability helps the employment of any acoustic based system, with maximum frequency of 22 KHz, without the addition of any hardware.

**Sound Propagation:** The behavior of sound waves when reaching the boundary between air and other materials is different (14). Majority of the energy, depending on the absorption index, is absorbed, reflected or refracted and very small part penetrates. An in-depth list of absorption index of materials is listed in (15). This unique nature of sound waves makes ultrasound systems room accurate up to a large transmission power value. As long as the systems are not transmitting power levels above the healthy limits, we can influence the signal to nose ration without interfering in other ultrasound systems our side the room.

**Cheap Hardware:** In beacon based system, high frequency audio hardware can easily be cheaply assembled.

Ultrasound based solutions suffer from disadvantages that origin from their nature. Some of the major disadvantages are listed below.

**Bandwidth Limitation:** As seen in the chart above, the audible range for most adults ends at about 16.5 and for the young, the range even ends higher than. Being on the safe side, we only have a usable frequency range between 18KHz and 22.5KHz, assuming a conservative sampling rate of 44100 bits/sec in which almost all devices will have. With a bandwidth of 4.5KHz, the potential connection speed is limited, we’ll talk more about the theoretical background on this in the coming sections.

Another issue that affects the bandwidth is the built in ant-aliasing filter that exists in any audio assembly. Anti-aliasing filter is used to prevent frequencies above the Nyquist frequency from passing(16), so that aliasing in the lower frequencies is prevented. A typical frequency response of a microphone can be shown in the following pic. Borrowed from (Reference name), the graph shows the signal being heavily attenuated above 20KHz. Depending on the device, the exact usable range may vary, but generally frequencies above 20.5 KHz are highly attenuated and difficult to use in the signaling.

Image needed here

**Reverberations issues:**  Another problem that arises from the nature of sound waves is the reverberation factor in a closed room. The delayed dampening of the previously transmitted sound waves creates interference in the current transmitted signal. This asks for a tradeoff between the precious error rate and bit rate. With the aim of reducing the reverberation effects, we can add silent intervals between, but doing that will also decrease the bit rate . We’ll talk more about out design choices and their theoretical investigation in the upcoming sections.

**Health issues:** The question of health risks is a two faced issues, unlike the risks coming from electromagnetic waves in radio communication as mentioned in (17) acoustic communication is a clean system. On the other hand, the fact that the signal is inaudible mounts health risks for the users in high power transmission. Even though we can alter the signal to noise ration freely, unlike radio communication, it needs a responsible system that keeps the power levels below risk levels.

**Localization and Communication Using Inaudible Acoustic Signals**

**Acoustic Signals**

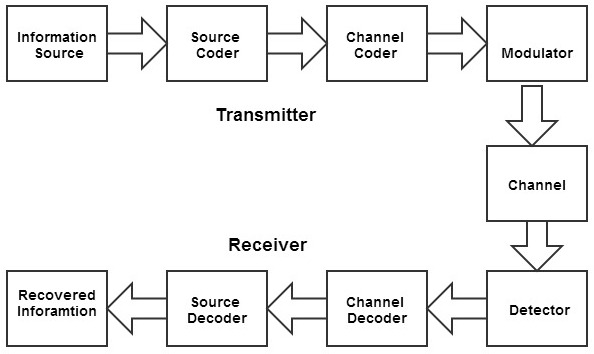
Sound waves propagate through matter by vibrating it. We humans are created to receive an air propagated acoustic signal, but sound waves actually travel in different speeds through different materials. In air, sound waves travel at a speed of …… We are able to perceive sound waves from 20 Hz to 20Khz, theoretically. But in reality the sensitivity of human ear decreases with age and higher frequencies are rarely audible in adult human ear. A good chart, inspired by (3), gives a good hint in to audibility of acoustic signals with age.

Just like Electromagnetic waves, sound waves also exhibit reflection, reverberation, refraction and absorption. As referenced in (15), sound waves exhibit higher reflection and refraction indices than other physical waves. And this is what makes acoustic signals attractive for applications that need to be restricted in a physical barrier, just like in our lecture room scenario. With this unique nature of acoustic signals, our signals would be restricted regardless of the power of transmission we use, and they are effectively room accurate in the very least.

**Acoustic communication**

Numerous works has been done to replicate data communication using acoustic signals as carriers. As referenced in (17, 3), these systems are build for specifically data communication. Though with limited bit rate, they have shown that as in radio, acoustic signals can also be used to reliably communicate data.

Acoustic communication follows the same principles as any digital wireless communication. The basic communication building blocks, as depicted in the following figure, apply for acoustic signals as well.



The above block diagram from the basics of digital communication is self explanatory, but to see the components through the perspectives of acoustic communication, we’ll go through them briefly.

**Information Source**: The information, for example the lecture ID, to be transmitted.

**Source Coder**: Forms bit sequence from the information input.

**Channel Coder**: Encodes the bit sequence for error correction purpose depending on the channel characteristics.

**Modulator**: Transforms sequence in to analog waveform suitable for transmission. In our case the wave forms would be ultrasound acoustic signals. And the hardware would be speakers instead of transmission antennas

At the receiving end, the reciprocals of the above process take place. The receiving hardware would be microphones instead of antennas. As we investigate in the coming sections, design decisions, the choice of the modulation and demodulation will be based on the characteristics of sound waves.

**Transmission**

The transmission end consists of three main parts in Source Coder, Channel Coder and Modulator. The choice of channel coder and source coding components are independent of the type of carrier signal we are using, but the choice of the modulation technique, as the interface between the transmitter and the channel, must satisfy the characteristics of sound waves.

Any type of modulation technique put the symbol sequence in to the parameters of the carrier signal. In acoustic carrier signal, we have three types of parameters that we can vary. These are the amplitude, phase and the frequency of the sound waves. Based on those variations, there are four major types of modulation techniques (23).

*ASK (Amplitude Shift Keying)*: Uses the amplitude as a varying parameter.

*PSK (Phase Shift Keying)*: Uses the phase as the varying parameter.

*FSK (Frequency Shift Keying)*: Uses the frequency of the carrier signal as the varying parameter.

*QAM (Quadrature Amplitude Modulation)*: Uses a mix of amplitude and phase.

Communication models that use modifications of ASK (24) and PSK (REFERENCE) have been demonstrated. And an in-depth comparison of different techniques applied to wireless Ultrasound communication is well documented in (25). Depending on the environment parameters, these different techniques have pros and cons. Unlike some of those relatively new works, a seasoned application of Ultrasound in wireless communication is used in undersea communication of submarines and ships, and FSK is the chosen techniques in those systems. Since RF signals attenuate heavily, undersea application of wireless Ultrasound has been the main stay for a long time. As referenced in (), the use of FSK is simple and robust, and we’ll go a little deeper on the FSK as projected in wireless Ultrasound.

**FSK**

FSK is a modulation technique in which the variation in frequencies is used to represent the digital data (26). In its simplest format, two frequencies are used to represent 0s and 1s, this format is called BFSK (Binary Frequency Shift Keying). A specific version of BFSK which is used for audio modulation is called AFSK (Audio Frequency Shift Keying). Other variations are possible by increasing the number of discrete frequencies used in the modulation, these are called in general MFSK (Multiple Frequency Shift Keying). MFSK can be MFSK4 for 4 different frequencies, which means each frequency can represent 4 different symbols, and in turn each symbol can represent 2 bits each (00, 01, 10, 11). Another highly used type of MFSK is MFSK16, again with 16 symbols and 4 bits in each symbol. M can be any be 2 the power of any number.

As it is well investigated in (27), increasing M is a balancing act between the bandwidth efficiency and the error performance. As we increase M, for the same bit rate, we have more time T for transmitting a particular tone, and with that the duration of signal transmission at a constant frequency is increased. This boosts the robustness of the system at the expense of overall bandwidth efficiency. In our application we are more interested in the robustness of the system, since it’s we are only looking to communicate light information with an average bit rate.

With the above set up, we can have robust half duplex systems. But to have a full duplex system, which is sometimes required to have asynchronous communication, we need to use frequencies which are orthogonal to each other. As shown in (28), the orthogonality is achieved by balancing between the duration time and the frequency spacing between the tones. As shown in the work, as the frequency spacing is decreased, you need to increase the time duration of each tone in order to maintain the orthogonality. This is formulated as given below…(Formula from 28)

**Detection**

The task of MFSK demodulation is to detect the existence of a particular frequency in the received signal. FSK demodulators are broadly divided in to two types, FM detectors and filter type demodulators (29). Filter type demodulators are both optimum and easier to implement in software, which we are interested in. Filter type demodulators can again be divided in to two based on their requirement of the phase information, coherent and non-coherent. Non-coherent demodulators do not require the phase information (30) , and due to the effect of the reverberations and speed of sound, getting accurate phase information is difficult and complex. With these in mind, we focus in to two types of non-coherent demodulators. Quadrature receiver and FFT detector.

Quadrature receiver requires no phase information to detect the existence of a particular set of frequencies in a given received signal. This is implemented by using a set of in-phase correllators for each tone and a second set of correlators for the quadrature (90 degrees out of phase). By low passing and square adding each correlator with its corresponding quadrature part, the received frequency can be detected without the need for the received phase information. To have a clear distinction between consecutive frequencies, as described in the previous section, they must be orthogonally separated. This set up is depicted in the diagram below (Quadrature receiver digram needed).

MFSK detector using FFT is a matched filter receiver in principle, with no phase information requirement (31). Depending on the energy levels of the frequency bin in the FFT output, we can decide if our frequencies of interest are present or not. Using FFT as a detection component requires us to consider two aspects of it, frequency resolution and computational complexity.

The frequency resolution of a particular FFT setup is the difference in the frequencies they represent between two consecutive bins (Reference required). Having very narrow difference is not always a good solution, since it requires more samples to achieve it. And depending on the sample rate, as the number of samples increase, the more time it takes to process each FFT round. And on the other hand, if we decrease the number of samples to achieve a better processing speed, we won’t use the narrow bandwidth we have efficiently. This balancing act requires us to find the optimum number of samples which results in a tolerable frequency resolution and processing delay.

The other concern of using FFT detector is the computational cost it carries, especially when used in a non native level. The most widely used implementation of fft is the decimation time radix-2 (32). The computational cost of this particular implementation is nlogn and It requires the number of samples to be a 2 to the power of N. As a consequence this restriction we are avoiding optimum number of samples between these values.

**Localization using Acoustic signals**

As mentioned earlier, localization solutions using ultrasound are actually proximity solutions. They give the location of the assets based on its proximity .There are a number of literatures and investigations which demonstrated different localization solutions that use Ultrasound signals (18-22). Some of the systems, like (18), are purely ultrasound based, and the others work side by side with other medium like Radio Frequency (RF).

In (20), a team of indoor positioning researchers from Dublin Institute of Technology demonstrated the use of pure Ultrasound technology for positioning and managed to achieve accuracy of 10 centimeters. This system uses Time Difference of Arrival (TODA) trilateration on the signals coming from different ultrasound beacons to compute the accurate location

In other systems, like (18), the solution is based on a mix of RF and Ultrasound signals. In this system, developed as PhD dissertation at Massachusetts Institute of Technology, called Cricket, the solution provides space, position and orientation solution using a mix of RF and Ultrasound signals. Other commercially available solutions, like the shopping promotion system Shopkick and Shopnow, use a mix of Bluetooth and Ultrasound to provide a proximity solution.

As mentioned in the above sections, there are a number of Ultrasound based indoor localization solutions and it’s an ongoing hot topic as there is no standard industry leader in this area. The trend of mixing Ultrasound and other signaling, or a mix of any different type of carriers has a strong side, since different type signals have different qualities that can complement each other when used together.

**Design Decisions and Assumptions**

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