2D INDOOR MAPPING USING IMPULSE RADIOS

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ABSTRACT

This paper presents mapping and positioning algorithms suitable for impulse radio ad-hoc networks operating indoors. By using these algorithms, given the times of arrival (TOAs) of dominant echoes from the surroundings, maps of very simple indoor environments can be successfully reconstructed in relation to communicating radios without any fixed references. Challenges posed by reconstructions of more complex indoor environments are addressed. The algorithms can be extended to map more complex scenarios.

1 INTRODUCTION

The Global Positioning System (GPS), the dominant system offering location information outdoors, suffers a poor indoor performance due to low signal availability, as GPS signals are not designed to penetrate through most construction materials. This has recently made indoor localisation a hot research topic. Many indoor positioning techniques have been developed, most of which rely on pre-deployed references to determine the location of tagged devices [1-5]. This architecture implies that location information is only available in environments where references with known positions have been deployed. However, in many scenarios where location information is very useful, a reference system is not likely to have been previously deployed. For example, when a fire brigade is rescuing people from a smoke-filled building, a fireman needs to know his location in order to find the nearest exit or corridor. Also, a fireman needs to know the position of his colleagues in order to help or get help from them. In this case, there is no time for the fire brigade to deploy a reference system before entering the building. Therefore, an indoor wireless system providing location information without pre-deployed references would be useful.

The fine time resolution [6,7] of impulse radios makes them an ideal candidate for positioning applications indoors. A technique suitable for ad-hoc impulse radio networks to map the surrounding environment and pinpoint themselves in relation to the environment has been proposed [8].

1.1 Proposed technique

As multipath signals from the same transmitter can be treated as originated from images of the transmitter in surrounding walls, by measuring the time differences of arrival (TDOAs) among multipath signals, a receiver can be constrained onto hyperbolae with the transmitter and its images as foci.

If this hyperbolic-alike positioning technique is practical, it addresses the challenge of lack of pre-deployed references by replacing them with the images of transmitters in surrounding walls.

Using images of the transmitter as references addresses another major challenge faced by indoor positioning systems, which is the synchronisation among references, as indoor systems require more accurate synchronisation in order to achieve a smaller positioning error. Images of a transmitter are spontaneously synchronised with the transmitter, i.e. whenever the transmitter transmits a pulse, all its images “transmit” at exactly the same time. This solves the problem of synchronisation among references, which is usually very costly to implement in conventional positioning systems, e.g. the Global Positioning System equips individual satellites with atomic clocks for synchronisation purposes.

Mapping and positioning algorithms have been developed for the proposed technique, by which the positions of radios can be determined in relation to reconstructed environments. The fundamentals of the developed algorithms will be described in section 2.

The calculations are not trivial, but they only need to be updated at a sufficient rate to update the mapping information and track the movements of radio users. This is expected to be well within the capacity of modern processors and therefore can be done by individual users locally. Today’s timer in the receiver of an impulse radio can resolve down to near 10ps time delay [9], which suggests approximately 0.3cm along-the-path spatial resolution.

1.2 Paper outline

This paper is organised as follows: in section 2, the fundamentals of developed 2D mapping and positioning algorithms are presented by using the reconstruction of two very simple indoor scenarios. Based on the algorithms described in section 2, in section 3, the challenges posed by more complex environments in scenario reconstruction are discussed. Conclusions are drawn in section 4.

2 ALGORITHM FUNDAMENTALS

2.1 Single-wall Scenario

Fig. 1 shows a scenario with two impulse radios operating in an environment consisting of a single wall. There are four channels, whose impulse responses (CIRs) are represented by $CIR_{1,1}$, $CIR_{1,2}$, $CIR_{2,1}$ and $CIR_{2,2}$, where the first subscript is the transmitter and the second is the receiver. By reciprocity, $CIR_{1,2}$ is the same as $CIR_{2,1}$. $CIR_{1,1}$ consists of a single echo with a delay corresponding to the round-trip time to the wall and back at the speed of light. From this, we can calculate R_1's distance from the wall, or from its image on the other side of the wall. At pedestrian speeds in indoor environments (~1.5 m/s), the distance to the image cannot change by more than 3cm in 10ms. During this period the radio can transmit up to 200,000 pulses at 20Mpulses/s, so there is plenty of scope for improving the accuracy by averaging.

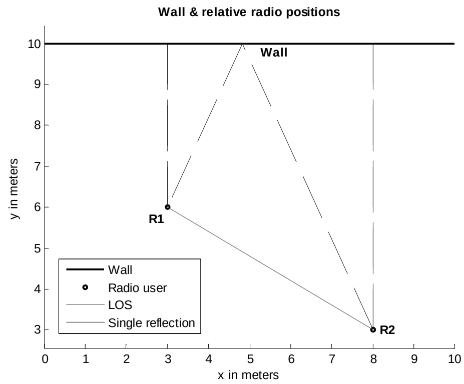

Fig. 1. Two radios communicate in a 1-wall environment

$CIR_{1,2}$ consists of two pulses, one by the line-of-sight (LOS) and the other by reflection from the wall. We cannot measure the time of flight (TOF) of the pulse at the receiver because we do not know when it was transmitted, but we can measure the time difference between the arrivals of the two pulses. This places R_2 on a hyperbola, whose foci are R_1 and its image in the wall, as shown in Fig. 2. The wall is represented by the straight line perpendicular to the line joining the foci, and half way between them.

$CIR_{2,2}$ consists of a single echo with a delay corresponding to the round-trip time from R_2 to the wall and back at the speed of light. From this we can calculate R_2's distance from the wall. This is shown in Fig. 2 by the straight line parallel to the wall, a fixed distance away from it. Where this line cuts the hyperbola is the position of R_2, relative to R_1 and the wall. Clearly there is a mirror-image ambiguity as the line cuts the hyperbola in two places, leading to two possible relative positions.

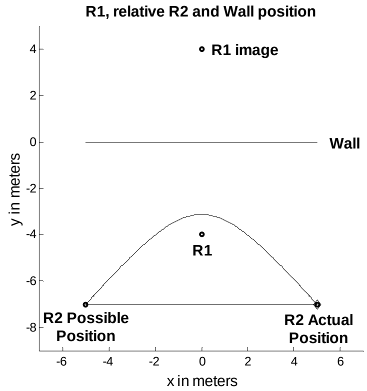

Fig. 2. Possible positions of R2 derived in relation to R1 and its image

2.2 Orientation Ambiguity

There is a further angular uncertainty, as we have no fixed frame of reference, so the wall could have any orientation between ± π relative to compass north. This uncertainty can be resolved by waiting until one of the radios moves, and then repeating the position calculation. We can now use the direction of motion as the reference direction, and display the wall and the other radio relative to a "track" showing the new and old positions of the moving radio, as shown in Fig. 3. The mirror-image ambiguity still remains at this stage, however.

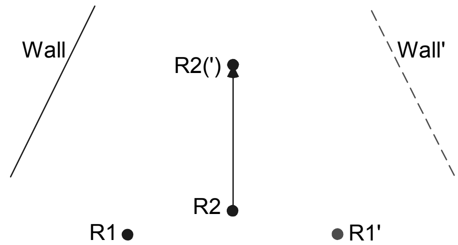

Fig. 3. Orientation ambiguity is resolved when user R2 has moved to R2('), while the mirror-image ambiguity remains

2.3 Two-wall Scenario

In the two-wall scenario shown in Fig. 4, the angle between the walls has been set slightly less than $\pi/2$ to clarify the effects of double reflections. $CIR_{1,1}$ contains three echoes. The first two are single reflections, one from each of the walls. The last one is the double reflection from both walls "around the corner". At this point, the system does not know that this is a double reflection, so we set up three separate coordinate systems, one for each echo, with a focal length corresponding to each of the three round-trip delays, where the focal length is the distances from the radio user to its images in the possible wall.

$CIR_{1,2}$ contains four pulses, one by the LOS, two by single reflections from the two walls, and one by double reflection "around the corner". Again, the system does not know that this is a double reflection, so we may create up to three hyperbolae on each of the three coordinate systems, i.e. up to nine hyperbolae in total. In the example of Fig. 5, only two hyperbolae are shown for the shortest focal length because one of the $CIR_{1,2}$ path length differences is greater than this focal length, so the third hyperbola is not "real".

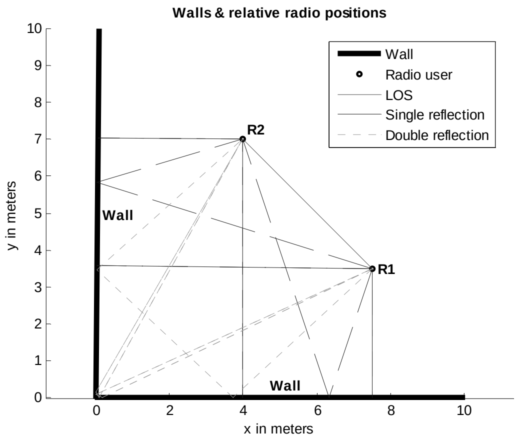

Fig. 4. Two radios communicate in a 2-wall environment

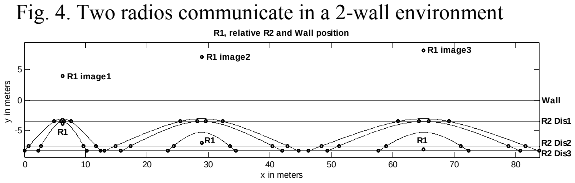

Fig. 5. Locus of R2 as hyperbolae in three separate coordinate systems

$CIR_{2,2}$ contains three echoes, two single reflections and one "around the corner" double reflection. Again, the system does not know that there are only two walls and not three, so we set up three lines cutting the hyperbolae at up to 54 positions, i.e. up to 27 pairs of mirror images.

Now the distance between the two radios is the distance from the focus to the point where the line cuts the hyperbola, and this can only take a single value. Using this knowledge we can eliminate most of the possible false scenarios. Initially, we consider the two shortest focal lengths, as these are the most likely to represent single reflections. Each of these offers up to nine possible distances between the radios, but in general only one value will appear in both sets. By placing the two foci together, and rotating one coordinate system until the second radio's positions match, we can generate four possible geometries of the surroundings, resulting from the two hyperbola cutting points in each coordinate system. The four geometries form two mirror-image pairs. Leaving the mirror-image ambiguity, two of the four geometries are shown in Fig. 6.

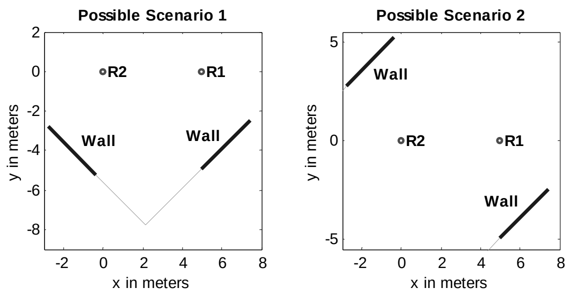

Fig. 6. Generated possible geometries of the surroundings

We now reconstruct the CIRs that would be expected from the two candidate geometries to check whether they predict double reflections that match the remaining echoes in the actual measured CIRs. If one of them does, we can identify the third focal length and coordinate system as a double reflection and eliminate it from further consideration, at the same time eliminating the other candidate geometry.

The rotational uncertainty and mirror-image ambiguity remain, and must be resolved as in the one-wall case, but the two-wall case is now essentially solved.

2.4 Necessity of different types of pulses

Based on the discussions of developed algorithms in sections 2.1, 2.2 and 2.3, it can be concluded that the LOS signal is crucial, as it acts as the time reference in inter-radio channels. If the LOS is blocked, the time references in inter-radio channels will be lost. This will require other algorithms based on the assumption that the LOS is blocked. However, as radios are moving and transmitting up to millions of echoes per second, even though the LOS signal could be blocked, it is always possible to get it back sometime later. Though radio users do not know whether the LOS signal is blocked or not, it is very likely that, with the LOS signal blocked, there is no sensible scenario reconstructed. Even if there is a sensible geometry reconstructed by chance, as radios move, they will find that the reconstructed surrounding environment varies, which should not happen.

Single reflections are essential to reconstruct the wall reflecting it. If a single reflection is blocked or its amplitude is below the sensitivity of the receiver, the wall reflecting it will be absent from the reconstructed scenarios. Again, as radio users move, e.g. toward the wall reflecting it, it is always possible to get the single reflection back.

If a double reflection is blocked or its amplitude is below the sensitivity of the receiver, it should not affect scenario reconstructions, as there are always other double reflections to check whether the times of arrival (TOAs) of echoes expected from reconstructed scenarios fit the measurements or not.

2.5 Mirror-Image Ambiguity

The mirror-image ambiguity can be resolved when either of the radios is detected to have moved twice in different directions. By repeating the mapping process at a certain frequency that allows radio users to make detectable movements, the path of the moving radio can be represented as a "track" in relation to the surroundings. Now if the moving radio has turned left, the correct "track" will also have turned left, whereas the "track" of the mirror image will have turned right, and vice versa. If the radio user knows which way he/she has turned, the ambiguity can be resolved. If the radios are carried by robots and their control circuits can tell which way they have turned, the mirror-image ambiguity will also be resolved. Human users may also be expected to know which way they have turned, given a longer period of time. If the system is used to track radio tags without this intelligence, some other means of measuring rotation may be needed, e.g. accelerometers.

3 CHALLENGES POSED BY MORE WALLS

Being able to reconstruct two walls, which are typical substructures of indoor geometries, the feasibility to reconstruct environments comprising more walls based on the algorithms developed for two impulse radios was investigated. The basic idea is to use the TOAs of the LOS, single reflections and some double reflections to reconstruct two-wall substructures as parts of the complete geometry first, then combining them into a single map. However, it is necessary to address a challenge posed by more walls beforehand, i.e. to identify the LOS, single reflections and double reflections from a large number of non-dominant pulses such as higher-order reflections.

3.1 Selecting out dominant pulses by suitable thresholding

It has been found in indoor multipath measurements at a range of frequencies [10,11] that received echoes comprise a small number of dominant echoes from large flat surfaces like walls, interspersed with noise-like scattering from smaller objects across the entire range of delays. We found the same phenomenon from indoor channel measurements at Ultra Wideband (UWB) bandwidth, which ranges from 3.1GHz to 10.6 GHz, according to FCC rules part 15.517(b) [12]. Some indoor channel measurement results are discussed in section 3.2 of this paper.

It can be expected that, by suitable thresholding in receivers, only dominant pulses including the LOS, single reflections and most double reflections are detected. The TOAs of these dominant pulses can then be used to map the major features of the environment. This reduces the cost of receivers by making it possible for them to be insensitive to amplitude or phase.

3.2 Indoor channel measurements

Measurements have been carried out in order to find out whether, in UWB bandwidth, received echoes comprise a small number of dominant echoes from large flat surfaces like walls, interspersed with noise-like scattering from smaller objects. The other purpose of the measurements is to prove the assumption that, by suitable thresholding on receivers, dominant pulses including the LOS, single reflections and most double reflections can be filtered out from non-dominant ones. We are also attempting to reconstruct real scenarios from measured data and to compare the results with software simulations.

3.2.1 Indoor channel measurement setup

The measurement was carried out in an office environment with a channel sounder [13] operating in the frequency band from 3.5GHz to 10.5GHz. The floor plan of the measurement environment is shown in Fig. 7. A mobile transmitting antenna (Tx) and a fixed receiving antenna (Rx) were used. These antennas were 1.81m above the floor. Their positions were measured using a laser. The transmitting antenna was moved by a person during the measurements. In this experiment, the transmitting antenna approaches the four surrounding walls individually, as shown in Fig. 8, to make it easier to identify the single reflections from individual walls using the measured data.

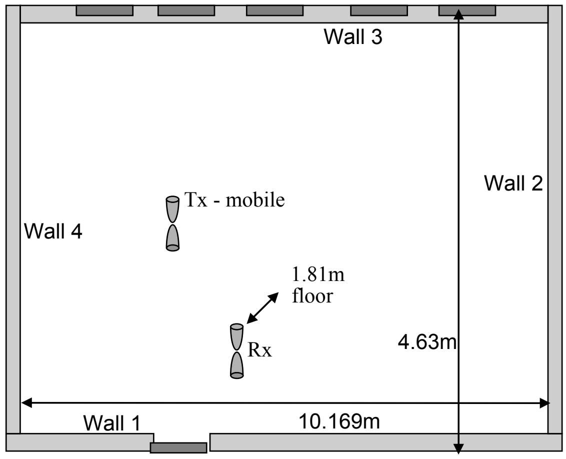

Fig. 7. The measurement scenario

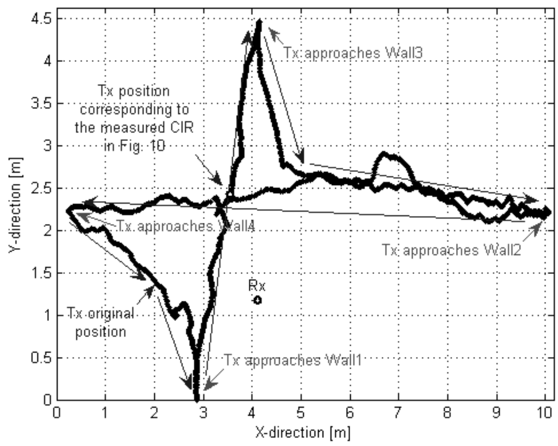

Fig. 8. Movement track of the transmitting antenna Tx

3.2.2 The results

CIRs measured by Rx are shown in Fig. 9. These comprise 1899 samples taken with a constant time interval. The vertical axis represents the TOAs of received impulses in relation to the time of transmission, while the horizontal axis shows the index of the measurement samples. Thus, in Fig. 9, each vertical line represents a measured CIR. An example of a measured CIR is shown in Fig. 10.

As the transmitting antenna Tx approaches a wall, the TOFs of the LOS signal and the single reflection from the wall received by the receivers becomes similar. Knowing this, we can easily identify the correspondences between dominant echoes in a measured CIR and the surrounding walls, e.g. the single reflections from Wall 1, 2, 3 and 4 are indicated individually in Fig. 10. Fig. 10 also shows a sample thresholding, by which dominant pulses including the LOS, single reflections and most double reflections can be selected out from non-dominant ones. The method to find a suitable threshold is described in [14].

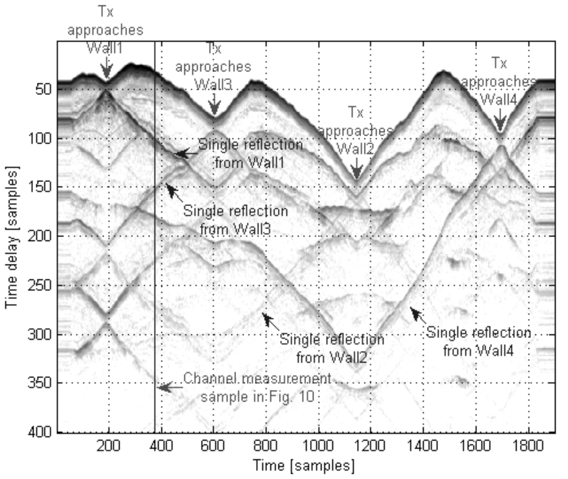

Fig. 9. Data measured by receiving antenna Rx

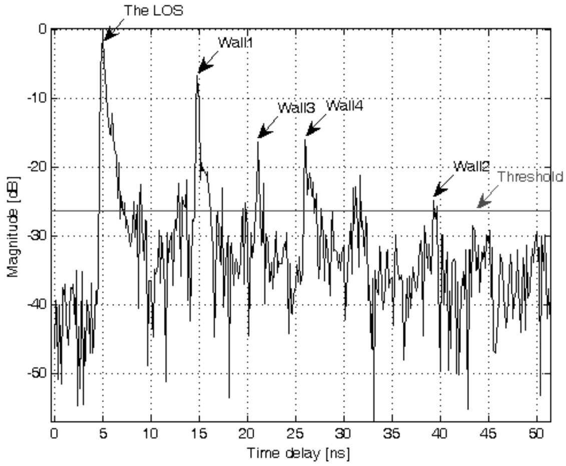

Fig. 10. A measured channel impulse response

3.3 More Walls and More Radios

Being able to select out dominant echoes from channels by suitable thresholding, where there are more than two walls, the technique is essentially the same, with multiple iterations. There will clearly be more echoes, more potential focal lengths, hyperbolae and inter-radio distances. We start by taking the two shortest focal lengths, checking whether these predict double reflections from the nearest two walls in the CIRs, and eliminating any focal lengths corresponding to these double reflections. The process is then repeated for the first and third shortest focal lengths to eliminate echoes corresponding to double reflections from the first and third nearest walls, and so on, until we have the minimum set of walls that account for all or most of the measured echoes in the CIRs.

Where there are more than two radios, each pair may have a different sub-set of the structures in a complex environment "in view". They will therefore be able to exchange partial maps to build up a more complete picture of a complex environment.

4 CONCLUSION

This paper presents mapping and positioning algorithms suitable for impulse radio ad-hoc networks operating in multipath environments. Given the TOAs of dominant echoes selected out in receivers by suitable thresholding, maps of very simple indoor environments can be successfully reconstructed in relation to communicating radios without any fixed references. Mirror-image ambiguity can be resolved by tracking the motion of any radio user. The algorithms can be extended to solve more complex scenarios.

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