USRP based OFDM Radar systems for Doorway Detection

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Abstract—**This paper discusses the implementation of open doorway detection in an indoor environment by utilizing the low cost narrow band radar system, i.e. USRP (Universal Software Radio Peripheral) based test bed. OFDM waveform is considered due to its flexibility of subcarrier occupation and ability of re-using the same waveforms as communication signals. We propose power comparison detection method and ranging detection method with the comparison between these two methods. The results show that our proposed method can work well under indoor fading environment. This scenario allows for the development of an autonomous detection robotics in an indoor unknown environment.**

I. INTRODUCTION

With an advent of high-speed digital converters and processors a new application of microwave technology has emerged: software-defined, multi-functional systems. One such new development is re-use of the same waveform for both radar and communications thus providing for simultaneous operations of communication and sensing. An obvious advantage of this approach is much more effective use of spectral resources when both functionalities need to be present. In [1] the authors argue that combining radar and communication systems can allow both environmental sensing and V2X communications to be performed more efficiently. An OFDM system for simultaneous radar and communications operations is proposed in [2] and [3], which shows that the performance is completely independent from the transmitted information. In [4] the authors build a USRP-based (Universal Software Radio Peripheral) test bed for this fusion OFDM system which measures the range of static and moving vehicles simultaneously.

We propose to apply this approach to indoor mapping with communication-like signaling: specifically, in our current work we perform doorway detection with OFDM waveforms in the unknown environment. The low cost software design radio USRP is implemented as the front end while signal is processed in computer [4]. We use the reflection power comparison detection method and ranging detection method to distinguish the difference between wall and doorway. With the dynamic spectrum assignment and fusion properties of OFDM system the utilized signals can be used not only for sensing, but also for broadcasting the mapping information to nearby systems.

In [5, 6] an approach to indoor navigation, detection and room structure mapping was proposed that involved ultra – wideband (UWB) custom-made imaging radar sensor system. In our work we will focus on overcoming challenges that arise from using a much more cost effective solution (USRP). Depending on usage scenario it may be preferable to implement either approach.

In this paper we will outline the following: a).The doorway detection method based on power comparison, which includes the fading effect description and detection method named frequency domain filter with both ideal and experimental data. b). Ranging detection method and relative experiment results, which utilize the similar detection structure of power comparison method. c). Comparison of the merits and drawbacks of these two approaches.

II. SYSTEM CONFIGURATION

In this section we will introduce the basic detection environment and detection scenario. All of our experiment data are collected by using the USRP as the RF front-end while all the signal processing is done in software.

We assume that the USRP is set on a mobile robot, e.g. Pioneer P3-DX [7]. Fig. 1 illustrates a realistic detection environment, where all experimental data used in this work are collected. We assume that there is a doorway in the wall nearest to the platform and the indoor environment is relatively clutter-free (no obstacles and large objects are present in platform's path, while multi-path reflection comes from ceiling and floor only). Then, the doorway detection method is divided into two steps:

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Step 1: A shortest range determination (SRD) is employed, by rotating the robot one cycle (360°) with fixed step size (e.g. 5°) in place, in order to find the direction nearest to the wall, where the reflection power is largest.

Step 2: Once the sensor finds the direction to the wall, the robot will turn to the direction where the side of robot is parallel to the wall. The robot then moves along that direction while the sensor scans the wall. Presence of an opening (doorway) is then realized via signal processing in manner similar to SAR imaging.

Figure 1. Doorway detection environment

III. Power Comparison Detection

A. Fading Effect

In Fig. 2, the example of 'Fading vs Range to the Wall' profile at carrier frequency 2 GHz is shown. As can be seen, fading effect tremendously affects the system as the received power changes dramatically with distance. Based on our experimental results, the received power when facing the doorway should be less than 5 (in normalized system units). It is clear that we cannot distinguish the doorway and the wall e.g. at 76 cm distance (received power facing the wall is also roughly 5) but could do so, e.g. at 74 cm distance (received power facing the wall is roughly 21). To mitigate this effect we propose a solution of using multiple carrier frequencies.

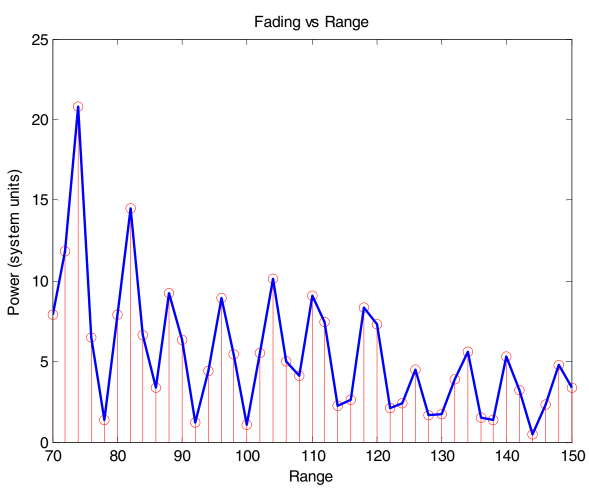


Figure 2. Fading vs range: Oscillatory behavior is due to fading

Fading also affects SRD. As outlined above, SRD is performed to establish the nearest wall location. During SRD USRP transmits and receives roughly 1000 OFDM symbols; mean received power is then calculated and we determine the shortest direction to the wall. Due to the fading effect, this method may not work at certain distances, e.g. as illustrated in Fig. 3. An example of successful performance of SRD is illustrated in Fig. 4. Therefore, multi-frequency SRD should be applied (presented in subsection C).

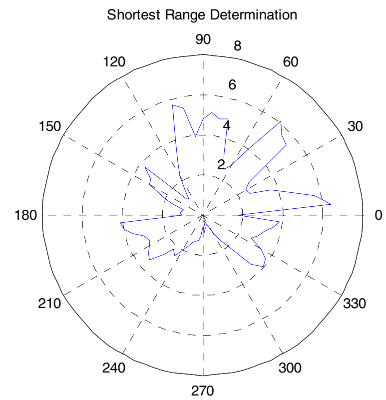


Figure 3. Example of unsuccessful performance of SRD (correct wall direction is at 0°)

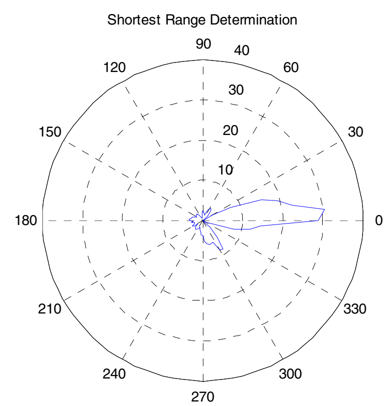


Figure 4. Example of successful performance of SRD (correct wall direction is at 0°)

B. Doorway detection profile with no SRD error

In absence of SRD errors we assume that it is perfectly performed. The robot moves parallel to the wall while the USRP keeps collecting reflected signal data. In our experiment, we compute the received power every 10 cm from 0 cm to 420 cm, whereas the doorway starts from 190 cm and ends at 350 cm. There are two sets of data from our experiment shown in Fig. 5 and Fig. 6. At Range 1 (69.36 cm), it is clear that detection profile at 2 GHz carrier outperforms the one at 1.3 GHz due to power readings at 1.3 GHz being corrupted by fading effect. We collected several sets of data at different carrier frequencies and then chose the best based on our detection algorithm (presented in subsection E) to detect the doorway.

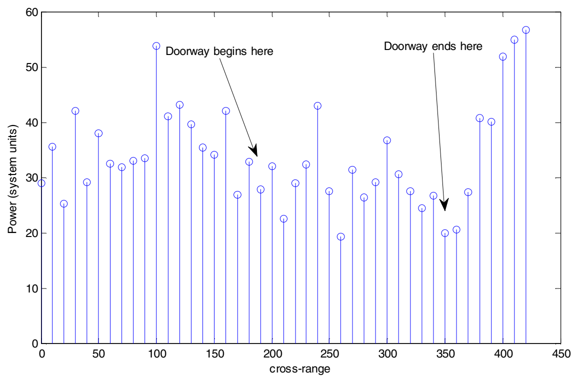


Figure 5. Example of bad doorway detection profile at 69.36cm with 1.3GHz carrier frequency

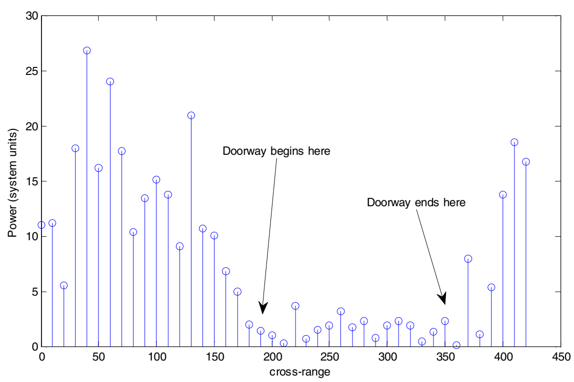


Figure 6. Example of good doorway detection profile at 69.36cm with 2GHz carrier frequency

C. *Doorway detection profile with SRD error*

SRD can have errors due to finite step in angular movement even if the shortest range direction is quite distinguishable. To illustrate this, Fig. 7 shows the doorway profile at 2 GHz with a 5° SRD directional error. This causes unwanted fading as well. Intuitively we could possibly treat the largest deep valley as the doorway position. It is confirmed in next subsection that our proposed detection algorithm follows our guess and performs with acceptable detection results. Surprisingly, the SRD errors conversely help to mitigate the fading effect because they present different range to the wall at different cross-ranges, which we could treat as range diversity.

D. *Detection algorithm for power comparison*

In Fig. 8(a), red trace is the ideal simulated normalized doorway detection profile, where the power facing the wall is all 1 and the power facing the doorway is all 0. We then simulated a low-pass version of the reflected signal's power based on this structure; it is shown in blue. This is due to our conclusion that higher frequency components of the reflected power profile contain irrelevant information of the doorway and should be removed from the profile. Therefore, we propose a frequency domain filter algorithm to detect the doorway in the following steps:

Step 1: We decide whether there is a doorway based upon the value in the nearest sample around DC frequency point of the spectrum of obtained reflected power profile. If this value is larger than N (multiple of the mean of power outside the DC point), we decide there is a doorway, and vice versa. Experimentally, we established optimal N for our scenarios to be 3-4.

Step 2: Once it has been established that the doorway exists based on step 1, we keep the M samples nearest to DC frequency (where M is 3-4 based on empirical data) and set the rest of samples (including the DC point) to zero and perform conversion back to time/space domain.

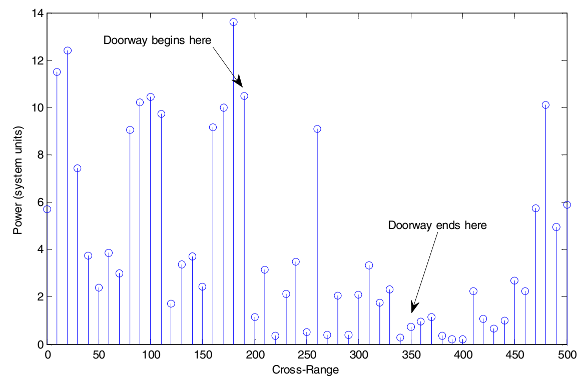
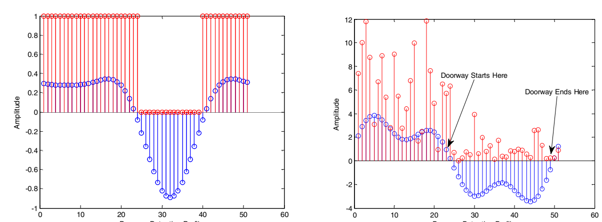


Figure 7. Example of doorway detection profile at 2 GHz with 5° SRD error



(a) (b)

Figure 8. Ideal case(a) and Experimental data(b) with proposed FD detection algorithm (red line is original data, blue line is processed data)

Fig. 8(b) is an example of frequency domain filter algorithm based on experiment data. We firstly confirm that the value in step 1 is larger than 4, i.e. N=4. Then, we set the DC component to zero and keep the nearest 6 points (M =3) while discarding the rest. Finally, we apply IDFT to transfer filtered signal from frequency domain data back to time domain. The result is marked in the blue line in Fig. 8(b), which shows acceptable performance if we consider the negative part to be doorway, which means the threshold is 0. In order to improve performance, we focus on a metric of minimizing the errors of detecting the middle point of doorway. The square error of middle point detection is defined as follows:

$$\Psi = \frac{1}{M}\sum_{m=1}^{M}\left(MID_{True} - MID_{Detect}\right)^2 \tag{1}$$

where M is the successful detection number and $\mathrm{MID}_{\mathrm{True}}$ is the true middle point of the doorway while $\mathrm{MID}_{\mathrm{Detect}}$ is the detection middle point of the doorway. By minimizing this cost function with all the experiment data, we find the best threshold is 0.4.

E. Detection algorithm results

In Table 1, we show the doorway middle point detect error results for all experimental data for different ranges and carrier frequencies. The true middle positions of doorway for non-SRD errors and SRD-errors are 270 cm and 355 cm respectively. In this detection results, we set N=4, M=3 and threshold is 0.4. It is clear that the algorithm doesn't work well e.g. at 310 cm distance due to overwhelming fading and low signal to noise ratio (SNR) making the doorway completely masked. Furthermore, we couldn't detect the doorway at 69 cm with 1.3 GHz carrier frequency and at 310 cm with 2 GHz carrier frequency. With a given carrier frequency, there are some ambiguous ranges that we couldn't detect the doorway successfully. Therefore, multi-frequency detection is necessary.

Carrier Frequency	Range	SRD Error	Trial1	Trial2	Trial3	Trial4	Trial5
1.3G	69cm	0°	N.A.	N.A.	N.A.	N.A.	N.A.
2G	69cm	0°	5cm	-5cm	0cm	0cm	5cm
1.3G	126cm	0°	35cm	20cm	25cm	25cm	20cm
2G	126cm	0°	5cm	N.A.	20cm	5cm	10cm
1.3G	310cm	0°	0cm	-5cm	N.A.	N.A.	N.A.
2G	310cm	0°	N.A.	N.A.	N.A.	N.A.	N.A.
2G	N.A.	5°	-25cm	-15cm	-20cm	-15cm	-15cm
2G	N.A.	10°	5cm	15cm	15cm	10cm	10cm

Table 1 FD Detection Algorithm Results for Experiment Data

IV. RANGING DOORWAY DETECTION

In the section we propose an alternative doorway detection method via ranging. We perform ranging detection by using the same OFDM symbol discussed above. For USRP setup, we use only one USRP as the transceiver due to the need of synchronization. In the experiment, we transmit 20 frames OFDM symbols with 10 MHz bandwidth at 2 GHz carrier frequency. Then we utilize 25 MHz symbol rate to oversample the received signal in the same USRP and then oversample the received 25 MHz data to 100 MHz in software by repeating each symbol 4 times and filtering 100 Hz data. Therefore, the range resolution is 1.5 meters.

A. Doorway detection algorithm for ranging

Based on our emperical experience, while the USRP faces the wall, the range values are usually stable in one value or oscillate between two nearby values. For example, in Fig. 9 most range values oscilate between 0 cm and 150 cm while the range values are stable at 150 cm in Fig. 10. We assume that the doorway length is always smaller than the wall length. Thus our detection algorithm is:

Step1: We find the 1 or 2 most frequent range values e.g. 0 cm and 150 cm in Fig. 9 or 150 cm in Fig. 10. Then we subtract the value of this (or mean of these two) most frequent value and take the absolute value. If the number of most frequent value is 1, we directly come to step 2. If the number of most frequent values is 2, we subtract 75 cm from the absolute value in order to compensate for the difference of these two most frequent values.

Step 2: Now we consider the number of 0 as the wall while the rest non-zero values present the doorway location. If there are two groups (if two non-zero values are within 50 cm, we consider them belonging to the same group) of non-zero value which are divided by 50 cm cross-range, then we consider the group with more non-zero values as the doorway, e.g. in Fig. 11 the non-zero values group which range from 60 cm to 120 cm is discarded because another non-zero value group from 200 cm to 440 cm has more elements.

B. Doorway detection via ranging with no SRD error

Perfect SRD performance is assumed in this section. In our experiment, the detection is also performed in the same way as described in power comparison detection method. We discuss these profiles by two parts as follows:

Part 1 - Facing the Wall:

Fig. 9 illustrates the ranging doorway detection profile at Range 1 (69.36 cm), where the range value oscillates between 0 cm and 150 cm when facing the wall. This is due to the fact that 69.36 cm is very close to one of the ambiguous range, i.e. 75 cm, where the sensor couldn't decide whether it is 0 cm or 150 cm. However, the ranging profile facing the wall in Range 2 (126 cm) is quite preferable, which is shown in Fig. 10. The range values are very stable to 150 cm because 126 cm is quite close to 150 cm.

Part 2 – Facing the Doorway:

Range values fluctuate due to the complex indoor environment. For example, the reflected path directly from the transmit antenna may dominate where the range value is 0 cm. Also the reflection power from the ceiling or floor may be dominant where the range value is approximately 150 cm.

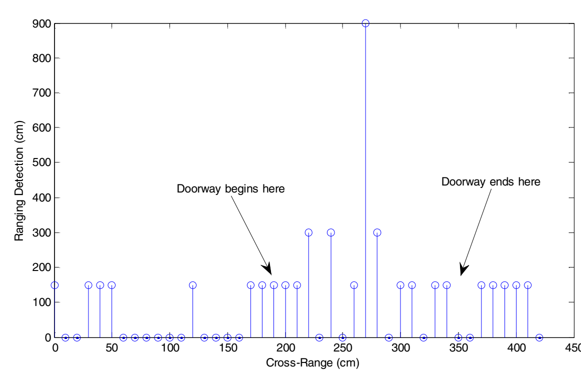


Figure 9. Example of ranging doorway detection profile at 69.36 cm with 2 GHz carrier frequency

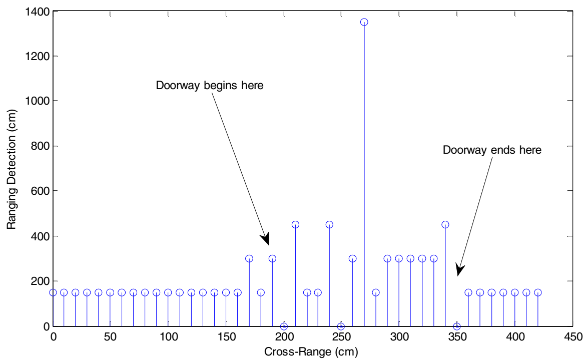


Figure 10. Example of ranging doorway detection profile at 126 cm with 2 GHz Carrier Frequency

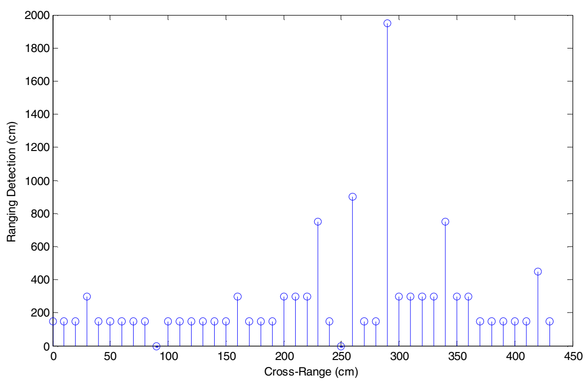


Figure 11. Example of ranging doorway detection profile with 10° SRD error at 2 GHz carrier frequency

C. *Doorway detection with SRD error*

In this subsection, the doorway detection profile with SRD error is discussed. Fig. 11 shows an example of ranging detection profile with 10° SRD error. It is clear that the detection range profile fluctuates more than with zero SRD errors. We propose a simple algorithm to mitigate this.

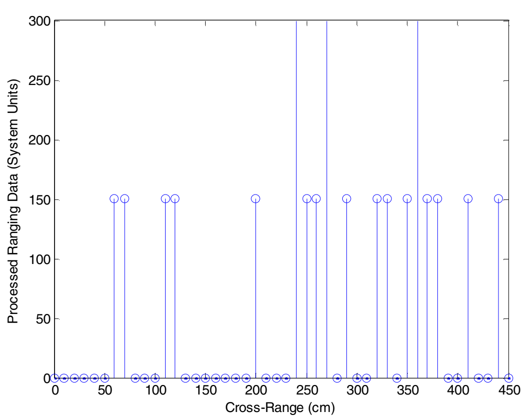


Figure 12. Example of processed ranging data starting from 69.36 cm with 2 GHz Carrier Frequency and 5° SRD Error

In Table 2, we present the ranging detection results based on our detection algorithm. The results demonstrate that our algorithm based on ranging detection is acceptable. Furthermore, based on our empirical experience, we conclude that the very large range value (e.g. 900 cm in Fig. 9) denote that the position is definitely within the doorway. Making full use of this information enables us to improve our system performance.

Carrier Frequency	Range	SRD Error	Trial1	Trial2	Trial3	Trial4	Trial5
2G	69cm	0°	-10cm	20cm	-15cm	-5cm	20cm
2G	126cm	0°	-10cm	10cm	0cm	10cm	30cm
2G	310cm	0°	0cm	-20cm	-20cm	0cm	15cm
2G	Start from 69cm	5°	40cm	10cm	50cm	40cm	-35cm
2G	Start from 126cm	10°	10cm	10cm	10cm	-15cm	10cm

Table 2 Doorway detection algorithm results for experiment data (based on ranging)

V. COMPARISON OF POWER AND RANGE DOORWAY DETECTION METHODS

Power detection method is seen as having better doorway middle point detection accuracy while we mitigate the fading effect by multi-frequency method. However, its detection rate depends on properly determined comparison threshold. Furthermore, fading effect critically degrades the system performance, which can be mitigated by using several carrier frequencies.

Ranging detection method exhibits worse doorway middle point detection accuracy. However, it promises to give a doorway detection result every time within a reasonable range. Besides, fading effect will only degrade our system performance slightly due to the limitation of ranging resolution. Also, the detection performance strongly depends on the initial range to the wall due to ranging ambiguity.

Detection Method	Power Comparison	Ranging
Detection Accuracy	Better	Worse
Detection Promise	No	Yes
Influence of Fading Effect (Ambiguous Range)	Severe	Slight
SRD Error	Range Diversity	Range Dependent
Signal Independent	No	Yes

Table 3 Comparison of power and ranging methods

VI. CONCLUSION

In this paper, we proposed two doorway detection methods, i.e. power comparison detection and ranging detection, to address indoor sensing with low cost narrow-band software design radio USRP, which could be easily implemented in an unmanned ground vehicle for autonomous doorway navigation in an environment with low visibility. A suitable detection scenario is proposed and experiment results are presented, which exhibit detection performance with sub-meter accuracy. This study can be used as an initial step in development of an inexpensive, multi-functional sensor for search-and-rescue missions where optical sensing is less preferred to radar (e.g. in fog, night time, dust, etc).

REFERENCES

[1] Sturm, C., & Wiesbeck, W. (2011). Waveform Design and Signal Processing Aspects for Fusion of Wireless Communications and

Radar Sensing. *Proceedings of the IEEE*, *99*(7), 1236–1259. doi:10.1109/JPROC.2011.2131110

[2] Sturm, C., Pancera, E., Zwick, T., & Wiesbeck, W. (2009). A Novel Approach to OFDM Radar Processing, (3), 9–12.

[3] Sturm, C., Zwick, T., & Wiesbeck, W. (2009). An OFDM System Concept for Joint Radar and Communications Operations. *VTC Spring 2009 - IEEE 69th Vehicular Technology Conference*, (4), 1–5. doi:10.1109/VETECS.2009.5073387

[4] Braun, M., Marcus, M., Fuhr, M., & Jondral, F. K. (n.d.). A USRP-based Testbed for OFDM-based Radar and Communication Systems.

[5] B. Jameson, D. Garmatyuk, and Y. Morton. "Cognitive radar for indoor positioning with a software-defined UWB OFDM system," in *Proc. 2012 IEEE Radar Conf.*, Atlanta, GA, May 2012.

[6] B. Jameson, D. Garmatyuk, et al. "Reconnaissance using adaptive multi-carrier radar," in *Proc. 2013 IEEE Radar Conf.*, Ottawa, ON, May 2013.

[7] http://www.mobilerobots.com/ResearchRobots/PioneerP3DX.aspx