Source-Assisted Direction Estimation Inside Buildings

Kamran Sayrafian-Pour
Wireless Communication Technologies Group
National Institute of Standards and Technology
Email: ksayrafian@nist.gov

Dominik Kaspar
Department of Computer Science
Swiss Federal Institute of Technology, Zurich
Email: dokaspar@student.ethz.ch

***Abstract*— Direction estimation inside buildings is a difficult and challenging task due to severe multipath signal propagation. Numerous algorithms and techniques exist that provide high-resolution direction estimation under certain conditions and channel models; however, to our knowledge they all perform poorly at indoor environments. Here, we propose a technique that enables a receiver to achieve greater reliability in estimating source direction through some collaboration with the source. We assume that the receiver and the transmitter are synchronized and they are equipped with circular phased array antennas that have beamforming capability. If the transmitter-receiver pair always steer their main lobes into opposite directions, the spatial spectrum of the received power can be used as a mean for estimating the direction of the transmitting source. In this paper, we investigate the feasibility of this methodology, and show the achieved improvement.**

I. Introduction

Interest in location-aware application has substantially grown over the past decade. RF-based technologies that find the range or direction of mobile sources inside a building are becoming an attractive area of research and development [1]. A significant application of such technologies is in emergency situations where it is important to be able to track the movements of the first responders inside closed environments. More commercial, public safety and military applications are also emerging every day.

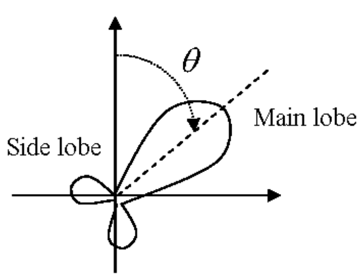


Fig. 1. The response magnitude of a beamformer.

Direction estimation of a mobile source at indoor environments is particularly difficult due to severe multipath and shadowing [2], [5]. An effective approach for estimating the direction of a source is through the use of an array antenna. For example, a beamformer is a spatial filter [3] that operates on the output of the array elements in order to enhance the received signal from a desired direction. This can be viewed as forming a beam in a given direction as pictorially displayed in Fig. 1.

An array antenna with beamforming capability is able to electronically steer the direction of its main lobe toward any desired angle. In particular, a circular array, which has a 360-degree field of view, is an appropriate candidate for two-dimensional direction estimation applications. Sample radiation patterns of such an antenna for various array sizes (i.e. number of elements) are shown in Fig. 2.

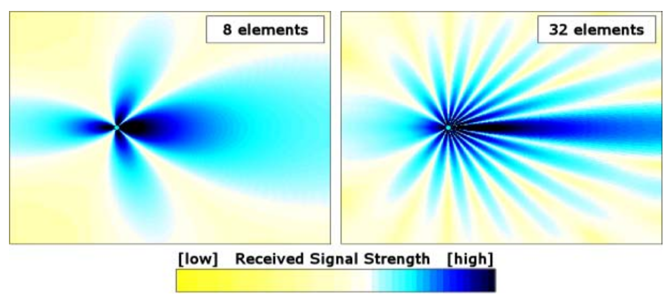


Fig. 2. Beam pattern of a circular array with 8 and 32 elements.

Direction estimation with a beamformer is equivalent to finding the peak of the spatial spectrum measured by the signal processor at the receiver [4], [6]. Under simplified settings, this is equivalent to the direction from which maximum energy is received.

Maximum Likelihood estimators and Subspace methods (e.g. MUSIC, ESPRIT) are among other popular algorithms that are used for source direction estimation. Accuracy, resolution and complexity of these algorithms under simplifying conditions are well documented and their varying performance has been reported [7], [8], [9], [15]. However, at indoor environments where severe multipath and shadowing are among the biggest channel impairments, we can show that the performance of all these different methodologies is quite similar. Figure 3 shows the Cumulative Distribution Function (CDF) of error in direction estimation for the sample building layout shown in Fig. 5. The wall material in this building has a dielectric constant of 15 (i.e. custom wall-type). As observed, sophisticated signal processing algorithms such as Maximum Likelihood and MUSIC do not offer any advantage in performance when compared to a simple beamforming algorithm.

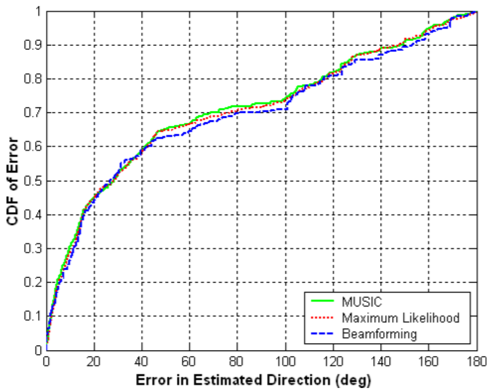


Fig. 3. CDF of the error in estimating the source direction (freq = 2.4 GHz, 8-element circular array antenna at the receiver, 400 random test points for the TX-RX pair).

Another important issue for indoor environments is that the characteristics of the multipath channel are strongly dependent on the layout of the building; and in particular on the construction material of the walls, windows and other existing objects. Fig. 4 displays the performance of a beamformer that is used to estimate the direction of an isotropic radiating source for the sample layout of Fig. 5 and various wall-types.

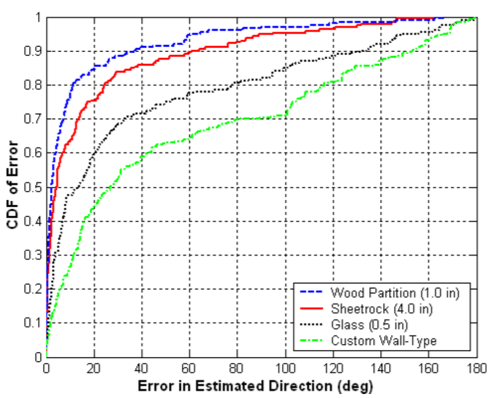


Fig. 4. CDF of error in estimating source direction for various wall materials using a beamforming algorithm (freq = 2.4 GHz, 8-element circular array antenna at the receiver, 400 random test points for the TX-RX pair).

The thesis of this paper is that signal processing techniques alone are not enough to ensure reliable operation of direction estimation inside buildings. Another layer of communication or network-wide collaboration could be exploited to enhance the performance. In what follows, such a technique referred to as Synchronized Rotating Beams (SRB) is proposed. It takes advantage of collaboration between a receiver and a transmitting source in order to increase the reliability and decrease the probability of error associated with the direction estimation at indoor environments. The purpose of this collaboration is to maximize the received energy from the true direction of the source as opposed to other misleading multipath directions.

In Section II, we describe the simulation platform that has been used to evaluate the performance of various direction estimation algorithms. Section III describes the details of the proposed scheme and compares its performance to the simple beamforming algorithm discussed above. A modification to the SRB algorithm is discussed in Section IV and finally concluding remarks are expressed in Section V.

II. Simulation Platform

We have investigated the feasibility and performance of a given direction estimation algorithm by implementing a simulation platform that matches the condition of an indoor environment. The main difficulty in simulating an indoor RF channel is the strong dependence of the received signal on the layout of the building (e.g. multipath channel). In particular, all walls, windows and other objects that affect the propagation of RF waves will directly impact the signal strength and more importantly the directions from which RF signal is received. Empirical, statistical and deterministic models have been used to describe the behavior of such multipath channels [12], [13], [14]. In our study, we have elected to use a sophisticated ray-tracing tool to accurately predict the received signal indoors. Wireless System Engineering (WiSE) is a ray-tracing tool that has been developed and verified by Bell Laboratories [10], [11].

Fig. 5 shows a pictorial sample of the multipath signal for a given building layout and transmitter-receiver location obtained through the ray-tracing tool. We realize that even such models have limitations in their accuracy and are also subject to errors when there are changes in the environment such as furniture moving, or even people walking through the building; however, this approach will give us the opportunity to create a testbed that to the extent possible mimics the conditions of an indoor channel.

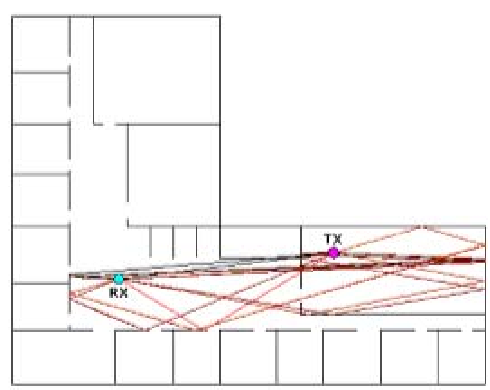


Fig. 5. Sample output of the ray-tracing tool for a given building layout.

The high-level block diagram of the simulation platform is shown in Fig 6.

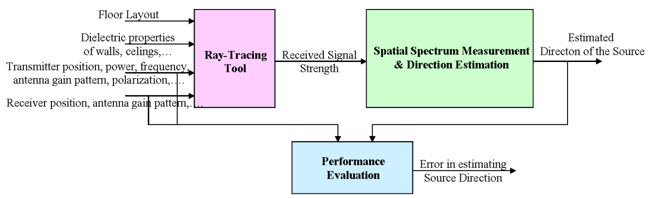


Fig. 6. Block diagram of the simulation platform.

The ray-tracing tool used in our study is capable of providing the complex impulse response of a stationary indoor channel. For our application, it is important to be able to compute an accurate impulse response with high spatial resolution. For example, in the case of a receiver with an array antenna, one would like to be able to predict the received signal at each element of the array that are usually separated by a distance less than the half the wavelength (i.e. 6.25 cm for 2.4 GHz) of the transmitted radio wave.

The received power in a phased array antenna is a function of the azimuth angle where the main lobe is pointing; this in turn is a function of the steering vector that can be applied by a beamforming algorithm [3]. For a given layout, building material, transmitter-receiver location, frequency and array size, the spatial spectrum at the receiver coordinates can be obtained by rotating the main lobe around the receiver using a sequence of appropriate steering vectors. In order to further verify the accuracy of the obtained spatial spectrum, we also conducted a simple experiment to compare sample hardware measurements to the predicted spatial spectrum of the ray-tracing tool (See Appendix for more details).

III. Synchronized Rotating Beams (SRB)

The peak of the estimated spatial spectrum in a beamforming algorithm specifies the direction from which the received RF energy is maximum. If the source antenna pattern is omni-directional, then in severe multipath environments such as indoor, this peak is not necessarily the direction of the source. On the other hand, if the source could somehow focus its transmission energy in the direction of the receiver, then the beamforming algorithm would have a higher chance in estimating the correct direction of the source. This is the basic philosophy in the proposed SRB algorithm.

The following assumptions are considered for a two-dimensional direction estimation problem inside buildings:

- The source is transmitting a narrowband signal.
- The source exists in the far field of the receiver array antenna.
- The receiver and the transmitter are equipped with a phased array antenna with beamforming capability.
- The array antennas at the receiver and transmitter are assumed to be calibrated.
- The transmitting and receiving nodes are able to recognize a reference frame for the azimuth angle (e.g. through the use of an electronic compass).
- The transmitter (i.e. source) can achieve synchronization with the receiver (through some form of communication).
- The main lobe of the antenna pattern of the receiver (or transmitter) can be steered toward any given direction in the two dimensional x-y plane (i.e. circular array elements for a 360-degree field-of-view).

The signal processors at the receiver-transmitter pair cooperate to generate a spatial spectrum at the receiver by going through the following SRB algorithm:

1) Let $\theta = 0$ (e.g. North).
2) The signal processor at the receiver steers the direction of its main lobe toward θ degrees azimuth; at the same time, the signal processor at the transmitter steers the direction of the main lobe of its antenna pattern to $\theta +$ 180 degrees.
3) With the current positions of the main lobes of the receiver and transmitter, the receiver measures the signal strength i.e. $S(\theta)$.
4) $\theta = \theta + stepsize$.
5) if $\theta < 360$ then go to Step 2.
6) if $\theta > 360$ then estimate the source direction to be: $\theta^* = argmax(S(\theta))$.
7) Go to Step 1.

Note that the $stepsize$ is a constant that determines the resolution of the spatial spectrum at the receiver.

The direction of the source is always the direction at which the main lobes of the receiver-transmiter pair are facing each other. At this position, the transmission power is more concentrated in the direction of the receiver; therefore on average, the received power from the true direction of the source should be higher compared to the received power from other multipath directions. This will increase the chance of estimating the correct source direction from the spatial spectrum measured at the receiver. Schematically, this process is shown in Fig. 7.

If the transmitter does not collaborate as specified in Step 3 in the above algorithm (i.e. maintains omni-directional radiation pattern), then we are left with the basic beamforming direction estimation algorithm, which was discussed in Section I.

We used the ray-tracing simulation platform discussed in Section 2 to assess the performance of the SRB algorithm. The achieved improvement is shown in Figure 8.

The test scenarios considered for the receiver-transmitter pair can be divided into Line-Of-Sight (LOS) and Non-LOS (NLOS) scenarios. A very interesting observation is that

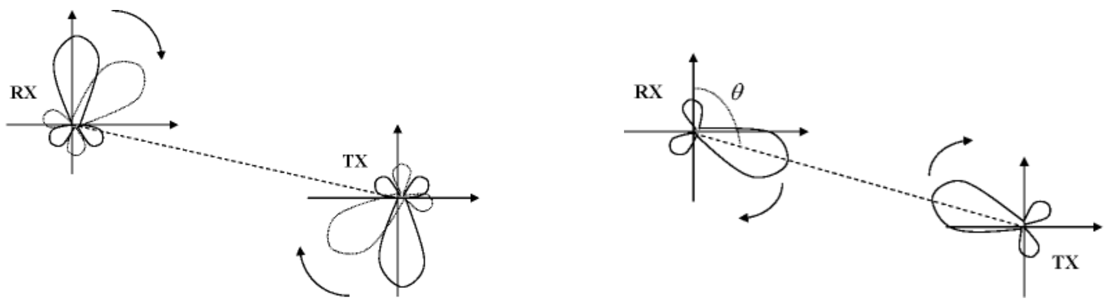
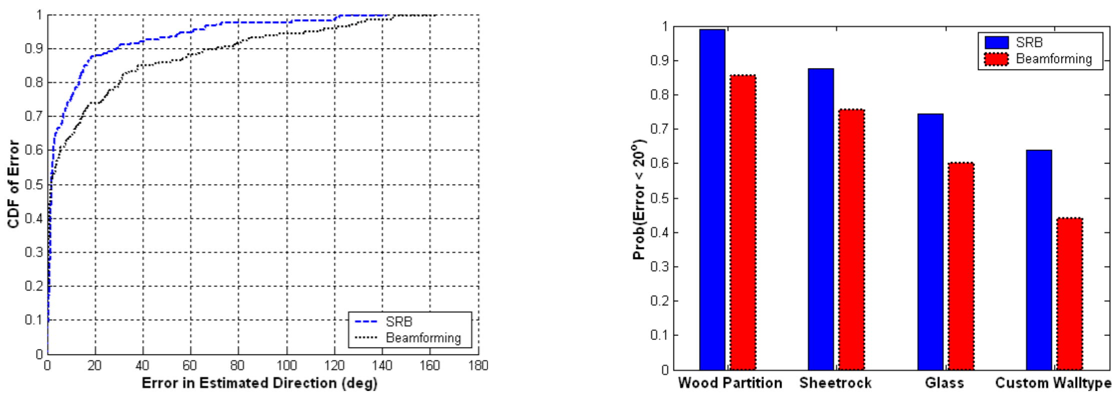


Fig. 7. Generating a spatial spectrum with synchronized rotating beams.



(a) (b)

Fig. 8. Improvement in source direction estimation using SRB (400 random test scenarios, center frequency: 2.4 GHz and 8-element circular array)

the conventional beamforming algorithm could make huge mistakes in estimating the direction even in the LOS cases; however, the SRB exhibits bounded error as seen in Fig. 9.

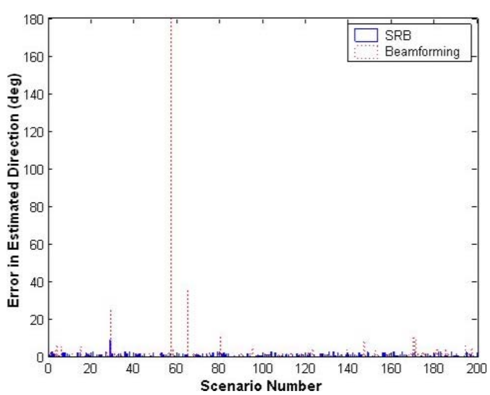


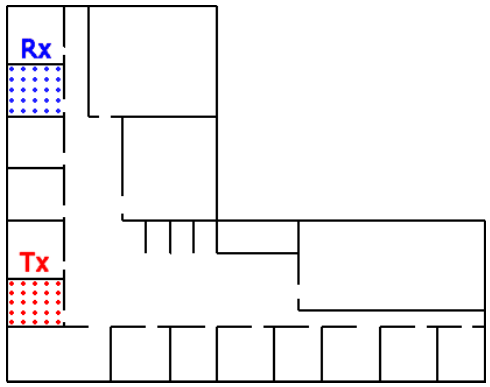
Fig. 9. Error in LOS scenarios.

Another interesting observation was the sensitivity of the simple beamforming algorithm to the exact receiver-transmitter location even though radio propagation environment does not seem to vary much. To elaborate on this point, consider the following scenario where the receiver is located somewhere inside a room as shown in Fig. 10(a). The transmitter is also restricted to be inside a different room so that there is no LOS path to the receiver. While both receiver and transmitter are restricted to be inside separate rooms, multiple test positions can be defined by considering a grid of points inside each room. We have simulated the simple beamforming and SRB for this situation and noticed that the simple beamforming is susceptible to large errors even though the room sizes are small. SRB on the other hand exhibited a bounded error for all receiver-transmitter test positions. Figure 10(b) displays the histogram of the direction estimation error for SRB and simple beamforming.

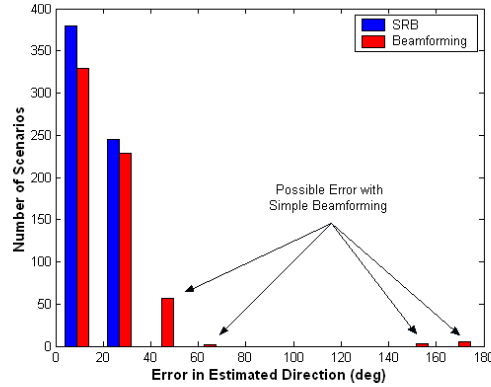
The estimation error in all these experiments depends on the size of the array antenna that is used. Higher number of elements in the array will enable the signal processor to create a sharp main lobe. This will enhance the combined gain of the receiver-transmitter antennas when they are facing each other. And this in turn increases the probability of a peak in the spatial spectrum at that position. The average error for various antenna array sizes has been displayed in Fig. 11.

IV. Analysis of the Error and the Two-Pass SRB Algorithm

Estimation errors using SRB will occur in two categories. Figure 12 demonstrates an example of the first category. In this case, the LOS path (i.e. the dashed blue line) between the receiver and transmitter is blocked by an obstacle such as a wall. The path that actually causes a peak in the measured spatial spectrum at the receiver is shown with a solid red



(a)



(b)

Fig. 10. Error in NLOS scenarios.

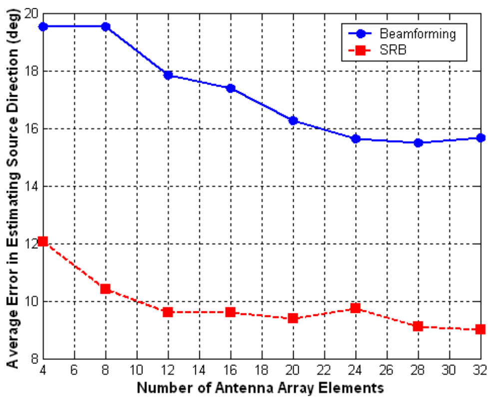


Fig. 11. Average estimation error versus the array size.

line. In addition to the power loss due to the longer path, the two reflections will also attenuate the signal; however, the attenuation caused by the wall that blocks the LOS path is still higher. For example, consider the case where the LOS-blocking wall is metallic. This will cause the SRB to estimate the wrong direction for the source. Simulation results for typical wall types and office layouts have shown that the number of cases that fall into this category is very small. Also, we have noticed that changing the carrier frequency and increasing the array size might help in further reducing the number of such events.

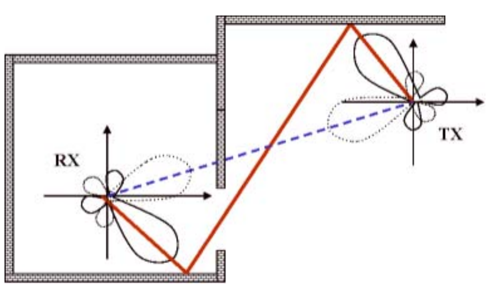


Fig. 12. Direction estimation error using SRB.

The second category that could cause error in direction estimation is shown in Figure 13.

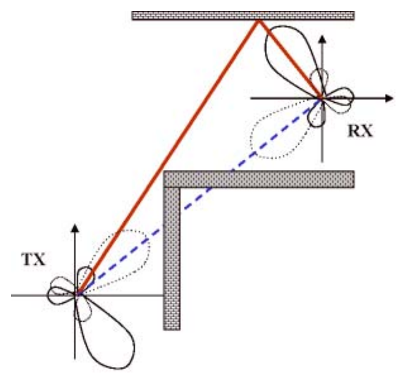


Fig. 13. Direction estimation error using SRB.

This case occurs when there is an obstacle with large attenuation between the receiver and the transmitter. The obstacle basically eliminates the combined gain associated with the directional antenna patterns of the receiver and the transmitter. In this scenario, the peak in the spatial spectrum occurs for a path that most likely goes through the side-lobe of the receiver (or the transmitter) antenna. A good approach to alleviate some of these situations is to use various side-lobe suppression techniques [16]. Details of such signal processing algorithms are beyond the scope of this paper; however, we can measure the ultimate gain in performance that can be achieved by such techniques if we assume an ideal array antenna with perfect beam pattern (i.e. no side-lobes) as shown in Fig. 14.

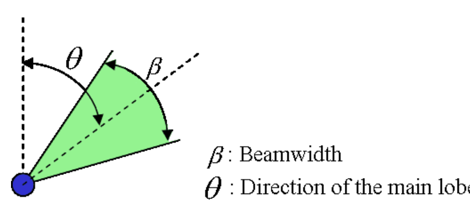


Fig. 14. An ideal antenna pattern.

Using the SRB algorithm with such an ideal antenna, we investigated the improvement in system performance. The result is shown in Figure 15.

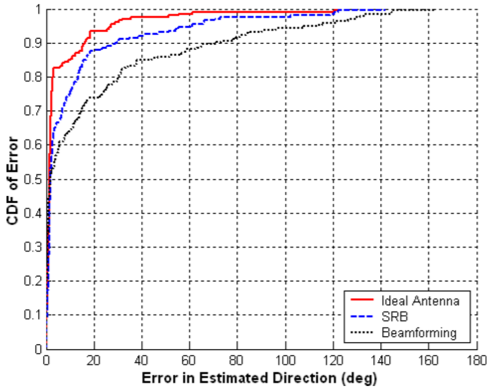


Fig. 15. Improvement in estimation error using an ideal antenna.

The SRB algorithm described in the previous section can be complemented by adding a 2nd pass to generate a 2nd spatial spectrum (i.e. $S_2(\theta)$). This procedure which is outlined below can detect some of the error cases described in Fig. 13.

First Pass:

1) Let θ = 0 (e.g. North).
2) The signal processor at the receiver steers the direction of its main lobe toward θ degrees azimuth; at the same time, the signal processor at the transmitter steers the direction of the main lobe of its antenna pattern to $\theta +$ 180 degrees.
3) With the current positions of the main lobes of the receiver and transmitter, the receiver measures the signal strength i.e. $S(\theta)$.
4) $\theta = \theta + step - size$.
5) if $\theta < 360$ then go to Step 2 of the first pass.
6) if $\theta > 360$ then let 1st-Estimate of the source direction to be: $\theta^* = argmax(S(\theta))$.

Second Pass:

1) Set and maintain the main lobe of the receiver at θ^* and continue measuring the received signal strength i.e. $S_2(\theta)$; the transmitter continues the same procedure as in the first pass.
2) Set the 2nd-Estimate of the source direction to be: $\theta^{**} = argmax(S_2(\theta))$.
3) If $\theta^{**} = \theta^*$ then let the final estimate of the source-direction to be θ^*; else declare θ^* to be "Less Reliable"
4) Go to Step 1 of the first pass.

The second pass in the above algorithm can increase the reliability of the direction estimate obtained in the first pass. Figure 16 displays the CDF of the estimation error for all test cases that have satisfied the second pass.

Performance improvement of the 2-pass method can be explained by considering Fig. 13. When the transmitter main lobe in the 2nd pass is steered toward the direction of the red solid line (where the receiver experienced the peak in the spatial signature of the 1st pass), a new higher peak in the 2nd spatial spectrum (i.e. $S2(\theta)$ is observed that is located in the different direction than the first peak. This could signify a potential unreliable estimate.

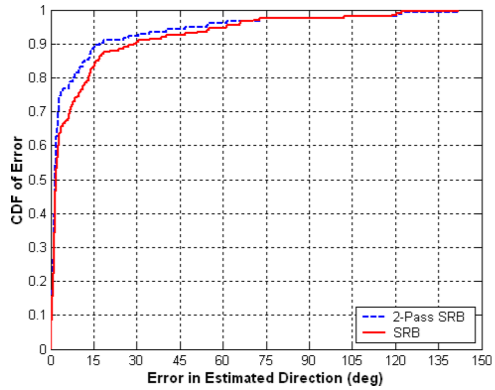


Fig. 16. Reliability of source direction estimation using a 2-Pass SRB algorithm.

V. Conclusion

The underlying philosophy in this paper is that the direction information can be extracted more reliably from the spatial spectrum of the received signal if both transmitter and receiver can focus their radiation (or reception) antenna pattern toward each other. Therefore, by taking advantage of communication between a transmitter-receiver pair, we have proposed to establish synchronized beamforming algorithms at these two nodes in order to create the appropriate positions for the main lobes. Following this strategy, improvements of up to 40% in the reliability of the estimated direction was observed.

We have used the same array sizes for the receiver and the transmitter in our simulations. It is conceivable that in practice the receiver is a stationary node placed strategically inside (or outside) of the building. In that case, the receiver could be more sophisticated and use bigger array antennas compared to the mobile source.

Although throughout this paper the source has been considered to be stationary, it is expected that the mobility of the source can also be used to improve the accuracy of the estimation process by considering the fact that the direction of a slow moving source can only exhibit small changes in a short period of time. In this way, if knowledge of the starting direction of a mobile source is available, then by running the SRB algorithm in a tracking mode, some of the erroneous estimates can be identified and replaced by better approximate values from the prior history of the results. Further studies are required to assess the effectiveness of this approach.

Finally, we have only considered the direction estimation problem associated with a single transmitter and receiver. For multiple transmitting sources, a multi-access scheme should be in place to enable the receiver to separate the signals received from different sources. With multiple receivers on the other hand, a direction-based localization scheme can be implemented based on our proposed scheme. The accuracy of this localization system will be investigated in a future publication.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Dr. Kate Remley, Mike McKinley and Marc Rutschlin from the Electromagnetics Division of the National Institute of Standards and Technology, Boulder Colorado for providing the measurement results of the rotating directional antenna.

APPENDIX

In order to justify the use of the ray-tracing tool for performance analyses of the SRB algorithm, verification of the accuracy of the simulated spatial spectrum with real measurements was necessary. Therefore, a simple experiment (see Fig. 17) was set up that involved a directional antenna located on a rotating platform (Details of the hardware experiment have been omitted for brevity). The spatial spectrum was generated by taking the measurement of the received power when the azimuth angle of the directional antenna was pointing at 0, 10, 20, ..., 350 degrees.

Fig. 18 demonstrates the comparison made between the measured spatial spectrum and the ray-tracing estimate. The measured spectrum corresponds to a single physical coordinate; and therefore, exhibits the effects of multipath fading. By averaging the sample spatial spectrums corresponding to a few nearly collocated positions, a closer match to the smoothed outcome of the ray-tracing tool was observed. Averaging four such measurement samples provided good match in the experiment (see Fig. 19). The authors hope to implement a prototype of the proposed scheme in the near future to further validate the conclusions achieved with the ray-tracing simulation platform.

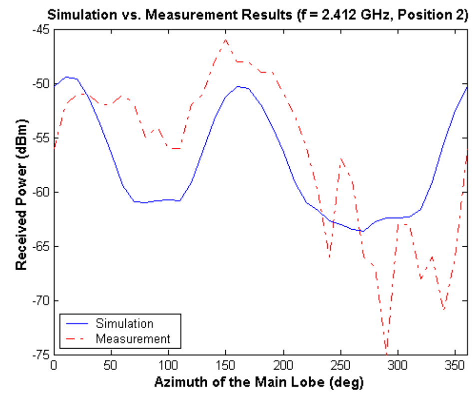


Fig. 18. Comparison of the measured spatial spectrum with the ray-tracing estimate.

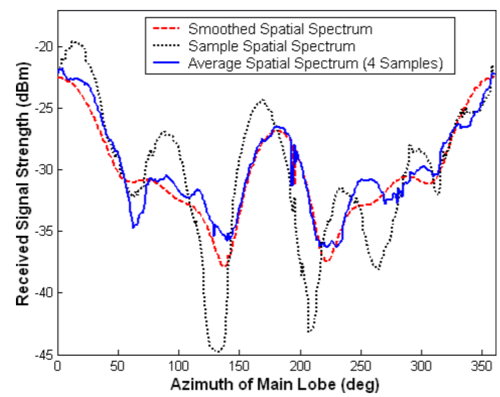


Fig. 19. Comparison of the smoothed spatial spectrum with the sample average.

REFERENCES

[1] J. Hightower and G. Borriello, *Location Systems for Ubiquitous Computing*, IEEE Computer magazine, August 2001.
[2] H. Hashemi, *The Indoor Radio Propagation Channel*, Proceedings of the IEEE, Vol. 81, No. 7, July 1993.
[3] P. Stoica and R. Moses, *Introduction to Spectral Analysis*, Prentice-Hall, Inc. 1997.
[4] R. A. Mucci, *A Comparison of Efficient Beamforming Algorithms.* IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. ASSP-32, no. 3, 548-558, June 1984.
[5] G. Yang, K. Pahlavan and J.F. Lee, *A 3D Propagation Model with Polarization Characteristics in Indoor Radio Channel*, IEEE, 1993.
[6] T. Shan and T. Kailath, *Adaptive Beamforming for Coherent Signals and Interference*, IEEE Transactions on Acoustic, Speech, and Signal Processing, Vol. ASSP-33, No. 3, June 1985.
[7] B.D. Rao and K.V.S. Hari, *Effects of spatial smoothing on the performance of MUSIC and the minimum-norm method*, IEEE Proceedings, Vol. 137, Pt. F, No. 6, December 1990.
[8] G. Morrison and M. Fattouche, *Super-Resolution Modeling of the Indoor Propagation Channel*, IEEE Trans. on Vehicular Technology, Vol. 27, No. 2, pp. 649-657, May 1998.
[9] T. Shan, M. Wax, T. Kailath, *On Spatial Smoothing for Direction-of-Arrival Estimation of Coherent Signals*, IEEE Transaction on Acoustic, Speech, and Signal Processing, Vol. ASSP-33, No. 4, August 1985
[10] S. J. Fortune, D. M. Gay, B. W. Kernighan, O. Landron, R. A. Valenzuela and M. H. Wright, *WISE design of indoor wireless systems: practical computation and optimization*, IEEE Computational Science and Engineering, Vol. 2, Issue: 1, Pages: 58 - 68, Spring 1995.
[11] R. A. Valenzuela, O. Landron, D. L. Jacobs, *Estimating Local Mean Signal Strength of Indoor Multipath Propagation*, IEEE Transactions on Vehicular Technology, Vol. 46, No.1, Feb. 1997.
[12] Q. H. Spencer, B. D. Jeffs, M. A. Jensen, A. L. Swindlehurst, *Modeling the statistical time and angle of arrival characteristics of an indoor multipath channel*, IEEE Journal on Selected Areas in Communications, Vol. 18, Issue: 3, Pages: 347 - 360, March 2000.
[13] R. B. Ertel, P. Cardieri, K. W. Sowerby, T. S. Rappaport, J. H. Reed, *Overview of spatial channel models for antenna array communication systems*, IEEE Personal Communications, Vol. 5, Issue: 1, Pages: 10 - 22, Feb. 1998.
[14] R. Moses, T. Soderstrom, J. Sorelius, *Effects of Multipath-Induced Angular Spread on Direction of Arrival Estimators in Array Signal Processing*, Technical Report, Uppsala University, Feb 1995.
[15] D. Astely, B. Ottersten, *The Effects of Local Scattering on Direction of Arrival Estimation with MUSIC*, IEEE Trans. Signal Processing, Vol. 47, No. 12, Dec. 1999.
[16] A. Appelbaum, L. Kaplan, *Sidelobe suppression considerations in the design of an electronically steered IFF antenna*, IEEE Transactions on

Fig. 17. Hardware experiment to validate the spatial spectrum generated by the ray-tracing tool.

Antennas and Propagation, Volume 24, Issue 4, Pages: 425 - 432, July 1976.