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Beamforming in Wireless Sensor Networks

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Abstract— Wireless interconnection is now considered a defining feature for sensor networks. The sensors are visualized as miniature battery-driven computing devices; because of energy constraints, all computing, storage/retrieval, and especially communication operations are considered expensive. Scalability and robustness (to sensor failures) are considered essential features for a sensor network. The limitations of sensor devices is that they have small batteries with small amounts of available power; thus limiting the lifespan of the sensors. An attractive solution to making the wireless sensors more energy efficient is to use cooperative beamforming. Implementing cooperative beamforming clearly comes with power and time overhead for the data sharing among the collaborative sensors. Implementing cooperative beamforming is a multi-variable optimization problem. In this paper various beamforming techniques along with a special emphasis on cooperative beamforming in acoustics with the help of Antenna technology is discussed which can save energy over sensosr transmissions.

Index Terms— Beamforming, Sensor Networks, Wireless Sensors, Antenna Technology, Cooperative beamforming, Collaborative sensors, Distributed MIMO.

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1 INTRODUCTION

There is an ever-increasing demand on wireless communication servers to provide voice and high-speed data services. At the same time, to support more users per basestation to reduce overall network costs and make the services affordable to its users. As a result, wireless systems that enable higher data rates and higher capacities are a pressing need. Unfortunately, because the available broadcast spectrum is limited, attempts to increase traffic within a fixed bandwidth create more interference in the system and degrade the signal quality. Beamforming is a ubiquitous technology when it comes to wave propagation. Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception. This is achieved by combining elements in the array in a way where signals at particular angles experience constructive interference and while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity. The improvement compared with an omnidirectional reception/transmission is known as the receive/transmit gain (or loss).

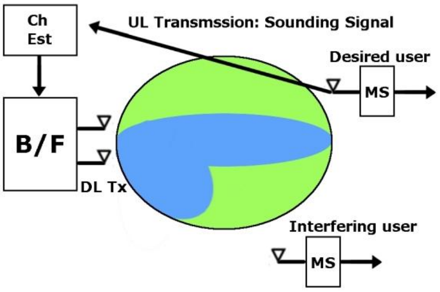

Fig. 1. Beamforming

2 ANTENNA TECHNOLOGY AND BEAMFORMING

Sensor network communication systems suffer from interference problem (intra-cell, inter-cell). Thus, the interference issue is a key factor in designing the system. Many techniques were developed and now used for mitigating the interference problem. These techniques attempt to reduce the interference effects on the performance through increasing SIR and user capacity. Smart antennas are an interference reduction method. With the use of this technology, two types of gain can be achieved, multiplexing gain which leads to higher data rates, and diversity gain which leads to better reliability. Smart antennas are compatible with Multiple Input Multiple Output (MIMO) systems [11]. Smart antenna technology offers a significantly improved solution to reduce interference levels and improve the system capacity. With this technology, each user's signal is transmitted and received by the basestation only in the direction of that particular user. This drastically reduces the overall interference in the system. A smart antenna system, as shown in Figure 2, consists of an array of antennas that together direct different transmission/reception beams toward each user in the system.

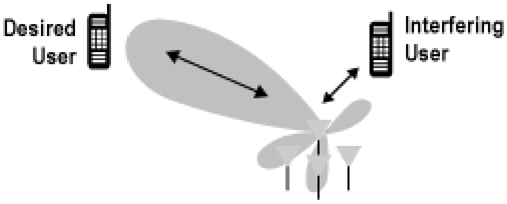

Fig. 2. Smart Antenna System and Beamforming

In beamforming, each user's signal is multiplied with complex weights that adjust the magnitude and phase of the signal to and from each antenna. This causes the out-

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put from the array of antennas to form a transmit/receive beam in the desired direction and minimizes the output in other directions.

Beamforming has found numerous applications in radar, sonar, seismology, wireless communications, radio astronomy, speech etc. Because of the wide range of applications of beamforming, there exist multiple design criteria for beampatterns. They include creating a beampattern that matches a desired beampattern, having a minimum beamwidth for a certain sidelobe level or null steering.

The solution to these different beampattern designs is almost as numerous as the number of applications of beamforming [12]. Some examples are:

- Minimum Variance Distortionless Response beamforming
- Statistical Eigen beamforming
- Beamspace beamforming
- Frost beamforming
- Generalized Sidelobe Cancellers

2.1 Switched and Adaptive Beamforming

Beamformers can be classified as either data independent or statistically optimum, depending on how the weights are chosen. The weighs in a data independent beamformer do no depend on the array data and are chosen to present a specified response for all signal / intereference scenarios. The weights in a statistically optimum beamformer are chosen based on the statistics of the array data to optimize the array response. In general, the statistically optimum beamformer places nulls in the directions of interesting sources in an attempt to maximize the signal to noise ratio at the beamformer output. Data independent beamformer design techniques are often used in statistically optimum beamforming. The statistics of the array data are not usually known and may change over time so adaptive algorithms are typically employed to determine the weights.

If the complex weights are selected from a library of weights that form beams in specific, predetermined directions, the process is called switched beamforming. Here, the basestation basically switches between the different beams based on the received signal strength measurements. On the other hand, if the weights are computed and adaptively updated in real time, the process is called adaptive beamforming. Through adaptive beamforming, the basestation can form narrower beams towards the desired user and nulls towards interfering users, considerably improving the signal-to-interference-plus-noise ratio.

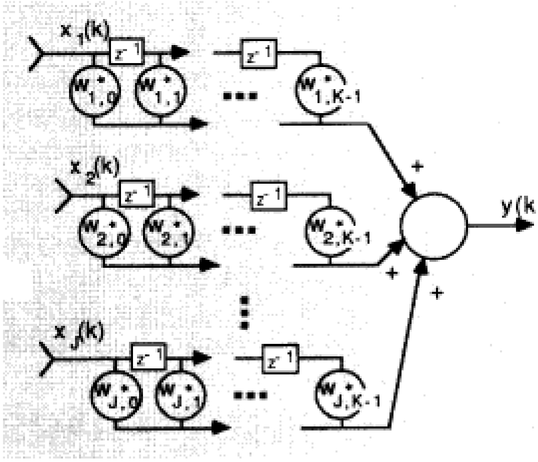

Fig. 3. Common broadband beamformer

2.2 Acoustic Beamforming

Finding out the exact source of a sound is a tough challenge for any acoustics engineer. A number of methods, based on microphone arrays are into practice. In general, the methods fall into three categories: near-field acoustic holography, acoustic beamforming, and inverse methods[4,5]. Depending on the test object, the nature of the sound and the actual environment, engineers will have to select one method or the other.
These are two important criteria to assess the validity of sound source localization methods:

- **Spatial resolution** is the ability to separate two sound sources. This is usually expressed in centimeters. It represents the closest distance between two sources, where they still appear to separately and do not merge into a single source. The lower the spatial resolution, the better the source localization.

- **Dynamic range** expresses sound level differences in dB between real sound sources and their surrounding mathematical artifacts inherent to the sound source localization techniques. The higher the dynamic range, the better the source localization.

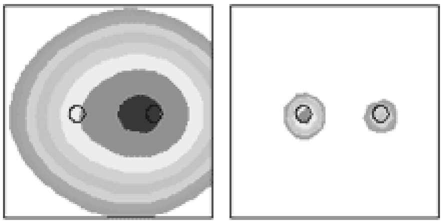

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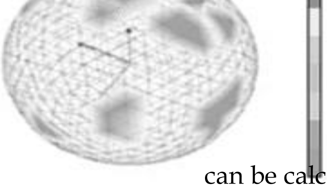
Fig. 4. Spatial Resolution



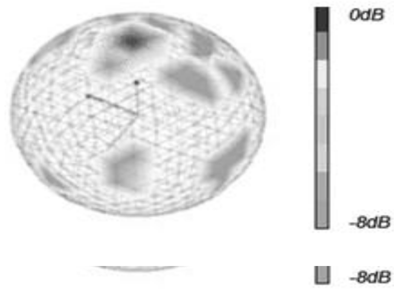


Fig. 5. Dynamic range

Acoustic beamforming is a technique where the microphone array is placed in the far field. As a rule of thumb, the far field is defined as being further away from the source than the array dimensions or diameter. The area between near field and far field remains a grey zone. In the near field, sound waves behave like circular or spherical waves whereas, in the far field, they become planar waves.

Numerous microphone configurations are possible in acoustic beamforming arrays. In general, the configuration is usually a trade-off between dynamic range and source localization accuracy. To get the best of both worlds, it is preferred to select a circular array with a pseudo-random microphone distribution.

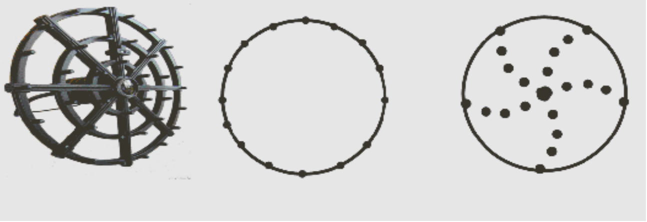


Fig. 6. Array configurations: full pseudo random (left), ring only (mid), spiral (right)

The ring array in middle of figure 2 provides good results when the exact distance to the source is not known, but dynamic range is low. Also, spiral-shaped arrays on the right result in lower dynamic range, compared to arrays that have more microphones distributed over the entire area of the array. More important, arrays without uniform microphone distribution will not have enough dynamic range when used in the near field.

The acoustic beamforming technique was first developed for submarines and environmental applications. In the far field, sound waves hitting the array are planar waves. Under these conditions, it is possible to propagate the measured sound field directly to the test object. All microphone signals measured by the acoustic beamforming array are added together, taking into account the delay corresponding to the propagation distance. The pressure can be calculated at any point in front of the array, allowing propagation to any kind of surface. Acoustic beamforming is sometimes called "sum and delay" since it considers the relative delay of sound waves reaching different microphone positions. Acoustic beamforming requires that all data is measured simultaneously.

2.2.1Advantages and disadvantages of acoustic beamforming

Acoustic beamforming has the following advantages:

- Propagation does not relate to the size of the measurement array. The test object can be larger than the array. Since all data is measured simultaneously, results can be viewed almost instantly after data acquisition.

  Because of the relatively fast acquisition and analysis speed, acoustic beamforming lets engineers evaluate several configurations in a limited amount of time.

This flexibility has some negative aspects:

- The spatial resolution is proportional to the wavelength:

  $$spatial\ resolution = \frac{d}{D}\lambda$$

  Where d is the distance between the source and array, D the array diameter, and λ the wavelength. In an ideal situation, when the antenna is at a distance D to the source, the resolution is equal to the wavelength. If the array is placed farther from the structure, the resolution becomes worse. Acoustic beamforming, in general, is only usable at frequencies above 1000Hz.

- Acoustic beamforming can not be used to calculate sound power. Proper source ranking cannot be done with this technique.

2.2.2 How can the disadvantages be overcome

The main disadvantage is that acoustic beamforming does not perform well in the low frequency range. This can be improved by using a dedicated acoustic beamforming technique called *near-field focalization*.

Near-field focalization is a beamforming technique that uses measurements in the near field, whereas classical acoustic beamforming is measured in the far field. In the near field, the sound waves no longer arrive at the microphone as planar waves, but as spherical waves. The original beamforming back propagation is reformulated to deal with these waves. Near-field focalization improves that spatial resolution to 0.44 .

2.2.3 How can acoustic beamforming and near-field acoustic holography be combined?

While acoustic beamforming provides the best results when using an array with a pseudo-random microphone distribution, near-field acoustic holography (NAH) requires a rectangular array with evenly spaced microphones - both horizontally and vertically. Horizontal and vertical spacing can be different. NAH can not be performed with an acoustic beamforming array as (1) it is not rectangular and (2) it has a pseudo-random microphone distribution.

To overcome this, the problem is rewritten as an inverse method. The transfer function in this formulation includes both propagative and so-called evanescent wave functions, and needs an optimal and stable principle component analysis-based regularization which includes evanescent wave filtering. The method is called irregular near-field acoustic holography or irregular-NAH.

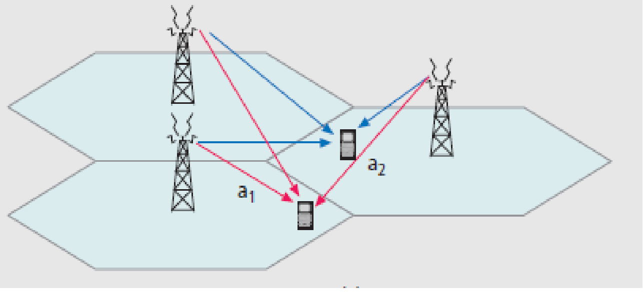


Fig. 7. COMP (cooperative MIMO)

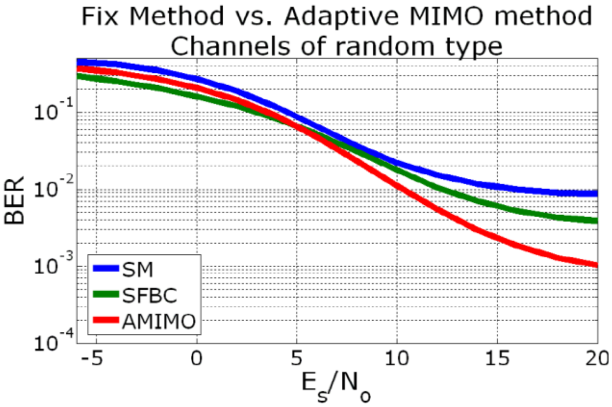


Fig. 8. Fixed Vs. Adaptive MIMO

2.3 Cooperative MIMO

Multiple-input multiple-output (MIMO) is an advanced technology that can effectively exploit the spatial domain of mobile fading channels to bring significant performance improvements to wireless communication systems. Conventional MIMO systems, known as point-to-point MIMO or collocated MIMO, require both the transmitter and receiver of a communication link to be equipped with multiple antennas. In practice, however, many wireless devices may not be able to support multiple antennas due to size, cost, and/or hardware limitations. Cooperative MIMO [14], also known as virtual or distributed MIMO, aims to utilize distributed antennas on multiple radio devices to achieve some benefits similar to those provided by conventional MIMO systems.

The basic idea of cooperative MIMO is to group multiple devices into virtual antenna arrays (VAAs) to emulate MIMO communications. A cooperative MIMO transmission involves multiple point-to-point radio links, including links within a VAA and links between possibly different VAAs. For relay-based cooperative MIMO communications, there are three main cooperative strategies: amplify-and-forward, decode-and forward, and compress-and-forward techniques.

Previous theoretical studies have revealed the pros and cons of cooperative MIMO compared to point-to-point MIMO systems [1]. The disadvantages of cooperative MIMO come from the increased system complexity and the large signaling overhead required for supporting device cooperation. The advantages of cooperative MIMO, on the other hand, are due to its capability to improve the capacity, cell edge throughput, coverage, and group mobility of a wireless network in a cost-effective manner. These advantages hinge on the usage of distributed antennas, which can increase the system capacity by decorrelating the MIMO channels and allow the system to exploit the benefits of macro-diversity in addition to micro-diversity. In many practical applications, such as cellular mobile and wireless ad hoc networks, the advantages of deploying cooperative MIMO technology usually outweigh the disadvantages [13].

3. CONCLUSION

As a general rule, near-field techniques should be preferred for sound source localization. They provide the best results in terms of dynamic range and spatial resolution. There are situations where a near-field technique is not applicable: (1) it is not possible to measure in the near field, (2) the array size becomes too big, or (3) it is not possible to measure in patches due to rapidly changing operational conditions. In these cases, an acoustic beamforming solution will be chosen.

Acoustic beamforming with near-field focalization is a good alternative, providing results with good spatial resolution and dynamic range, depending on the frequency range. It uses an array with pseudo-random distributed microphones. Acoustic beamforming obtains analysis results in a single shot wide-angle measurement, making it an ideal tool for troubleshooting, as it offers a quick preview with improved spatial resolution using near field focalization, but also for in-depth root cause analysis, when using the irregular-NAH technique.

Distributed transmit beamforming is a form of cooperative communication in which two or more information sources simultaneously transmit a common message and control the phase of their transmissions so that the signals constructively combine at an intended destination. Depending on the design objectives and constraints, the power gains of distributed beamforming can be translated into dramatic increases in range, rate, or energy efficiency. Distributed beamforming may also provide benefits in terms of security and interference reduction since less transmit power is scattered in unintended directions. Key challenges in realizing these benefits, however, include coordinating the sources for information sharing and timing synchronization and, most crucially, distributed carrier synchronization so that the transmissions combine constructively at the destination.

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