Distributed Beamforming in Wireless Sensor Networks

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(2009)

wireless communication systems

Sensor networks

wireless LANs

Information processing

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Date 25-08-2009

Final Approval

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A dissertation submitted to the
Department of Computer Science,
International Islamic University, Islamabad
as a partial fulfillment of the requirements
for the award of the degree of
Masters of Science in Computer Science

Declaration

I hereby declare that this thesis, neither as a whole nor as a part thereof has been copied out from any source. It is further declared that No portion of the work presented in this report has been submitted in support of any application for any other degree or qualification of this or any other university or institute of learning.

Shehzad Ashraf Ch

Acknowledgements

This project and all my efforts are fruitful only due to Allah Almighty, the Most Merciful and Beneficent Who gave me strength to complete this task to the best of abilities and knowledge.

I would like to take this opportunity of thanking my supervisor **Mr. Asim Munir**, who gave all his knowledge, guidance and support to boost my confidence and learning. He was always there to solve problems and helped me through this project. I am thankful to him for this.

I would also like to thank my wife who supported me a lot and patiently let me do the task

Last but not the least; I would like to acknowledge **Mr. Syed Husnain Abbas**. Who provided me support with his technical help, without his support and motivation I was not able to do the work. I would like to admit that I owe all my achievements to my truly, sincere and most loving parents, sister, brothers and friends who mean the most to me, and whose prayers have always been a source of determination for me.

Shehzad Ashraf Ch.

Every researcher needs to address "What", "Why" and "How" for every research problem.

Abstract

Sensor network, due to its important properties like low cost, small size and low power consumption, got significant attention in modern communication systems. Power efficiency is the key issue in wireless sensor network. Beamforming shows its advantage to enhance amplitude and decrease noise influence, resulting in high signal to noise ratio (SNR) in communication systems. Beamforming produces N (no. of nodes) gain in received power. Collaborative communication produces N gain in received power. If we combine Beamforming and Collaborative communication constructively, N^2 gain can be achieved.

To see the feasibility of collaborative communication and beamforming, a detailed literature review is conducted and factors that can influence the received power are explored. Literature from the available resources is analyzed and research dimension is defined. Search criterion and strings are defined to retrieve the relevant literature. Research questions are analyzed on the selected studies to find the research gaps in the existing literature.

From the research gaps found future directions are identified. To verify the research results some studies are analyzed mathematically and by simulation. The fundamental study performs carrier synchronization in the absence of fading and noise. We have simulated the existing results and determined the effects for different parameters like Noise, Interference, and Fading etc. We presented a method to reduce phase error in the presence of fading, noise and interference for energy efficient transmission.

Terms Used

Collaborative Communication

In collaborative communication same data is sent by all transmitters (Slave nodes) to the base station. The base station combines the data coherently (in-phase) to form a strong signal. This approach normally termed as distributed beamforming. This includes dealing with sensors of variable parameters and variable distances.

Master Sensor Node

One sensor node from N sensor nodes distributed randomly is treated as Master node possessing the following properties.

1. Master sensor node sends timing signal to all slave sensor nodes to send data to base station.
2. The master node controls the time synchronization (Master sensor node sends a pulse and each slave sensor node starts its transmission).
3. Master sensor node sends the carrier signal (use for modulation) and each slave sensor node use this signal to modulate the signal.
4. Master sensor node sends data to all slave sensor nodes to be transferred to base station.
5. The phase synchronization between master sensor node and slave sensor node is done within the network so that the phase errors at the base station could be reduced.

Carrier Signal

Master sensor node transmits the high frequency signal to all the slave sensor nodes for modulation; this signal is called reference or carrier signal. It is a Sinusoidal wave.

Slave Sensor Node

From N sensor nodes there is one master sensor node and remaining N-1 sensor nodes are called slave sensor nodes. The slave sensor node receives data and carrier signal (for modulation) from Master sensor node. The received data is modulated using carrier signal from master sensor node and transmitted to base station. Each one is called as transmitter.

Base Station

Base station receives the modulated signal sent from all the slave sensor nodes, demodulates it and detects the data sent by sensors.

Phase-Locked Loop

A phase-locked loop or phase lock loop (PLL) is a control system that generates a signal that has a fixed relation to the phase of a "reference" signal. A phase-locked loop circuit responds to both the frequency and the phase of the input signals, automatically raising or lowering the frequency of a controlled oscillator until it is matched to the reference in both frequency and phase. A phase-locked loop is an example of a control system using negative feedback.

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Chapter 1
Introduction

Introduction

Communication has never been so important as it is now a days. Efforts are going on in order to analyse and improve the ways to effectively convey the information.

Wireless communication got significance in past ten decades. Initially digital systems like telegraph were used for wireless communication. Main problem in these systems was multi user interference. Related problems were overcome by continuous-wave (CW) band pass systems. This led to a new technology to broadcast AM, FM radio, and, television signals. ALOHA network at the University of Hawaii [1] provided a breakthrough in the form of packet radio network invention. It provides the simple architecture where the mobile stations communicate with each other without using base station. This idea opened the new basis for Arpanet [2] and brought about change towards the modern Internet. This idea was supported by US government agency (DARPA). The principle of direct communication between nodes is applied to a new type of network called the wireless sensor network (WSN) [3].

1.2. Wireless Sensor Networks

WSN is a sensing, computing and communication infrastructure that allows us to instrument, observe, and respond to phenomena in the natural environment, and in the physical and cyber infrastructure. The sensors can range from small passive micro sensors (e.g, smart dust) to larger scale, controllable weather-sensing platforms. The computation and communication infrastructure of the sensors is radically different from that found in today's Internet-based systems, reflecting the device- and application-driven nature of these systems.

Sensor network is a collection of several sensor nodes. Sensor nodes are low cost, small size and limited power characteristics. But it has limited storage and requires expensive communication operations [1], [2]. In sensor networks a large number of sensors are used to get reliability through redundancy. Due to limited power of sensor node, energy efficient transmission is the key requirement. In fixed array antenna large power gain can be achieved at base station using Cooperative communication, Multi- Hop Routing, Collaborative Communication and Beamforming [3]-[9]. In sensor network the sensor nodes are distributed, Above mentioned techniques required some factors to be addressed. These factors are accurate knowledge of position of sensor nodes, time synchronization, frequency synchronization and phase synchronization among sensor nodes and the base station.

In collaborative communication all sensor nodes transmit same data to the base station [10]. If sent data from all sensor nodes are received by base station at the same time (Time synchronization), all transmitter use the same carrier signal to send the data (Frequency synchronization) and data sent from all transmitters are combined coherently (phase synchronization), a large gain can be achieved [10]. If frequency synchronization and phase synchronization is achieved, the collaborative communication may also be called distributed beamforming. Master slave architecture is proposed in [11] to achieve frequency synchronization. From total N sensor nodes one sensor node is selected as master node that transmits the carrier and time signal to rest of N-1 sensor nodes also called slave nodes. The effect of phase errors due to placement of slave nodes is also analyzed in [11]. In master slave architecture [11] there is one information source that sends information to all the slave nodes, one master node that sends the carrier and timing signal to all the slave nodes and one receiver. Master node is at the equal distance from all the slave nodes [11] that is very difficult to achieve in practical scenario. Master and slave nodes are synchronized with respect to time and frequency to estimate the channel coefficients using reciprocity principle [11]. Result shows that high power gain can be achieved in the presence of displacement errors [11], [12].

1.3. Applications of Wireless sensor networks

The density of instrumentation made it possible to shift to mass produced intelligent sensors and the use of invasive networking technology gives wireless sensor networks a new kind of scope that can be applied to a wide range of uses. These can be commonly differentiated into following categories:

- Monitoring space
- Monitoring things
- Monitoring the interactions of things with each other and the encompassing space

The first category includes environmental and habitat monitoring, precision agriculture, indoor climate control, surveillance, treaty verification, and intelligent alarms. The second includes structural monitoring, eco physiology, condition based equipment maintenance, medical diagnostics, and urban terrain mapping. The most important applications involve monitoring complex interactions, including wildlife habitats, disaster management, emergency response, ubiquitous computing environments, asset tracking, healthcare, and manufacturing process flow.

1.4. Beamforming

Beamforming is the process of trying to concentrate the array to signals coming from only one particular direction. Spatially, it looks like a large dumbbell shaped lobe aimed in the direction of interest although there exists some side lobes. Making a beamformer is to achieve directionality for an omni directional signal. Figure 1.1 is the visualization of a beamformer. It is based on the concept that the best way to not listen in noisy directions, is to just steer all your energy towards listening in only direction of interest. It is an important concept used for array signal processing that can also be used in many sonar systems.

Figure 1.1 : Visualization of a Beamformer

1.4.1. Delay & Sum Beamformers

If there are more than one beamformers then the output of each sensor will be the same, except that each one will be delayed by a different amount. So, if the output of each sensor is delayed appropriately then we add all the outputs together as a result the signal that was propagating through the array will reinforce, while noise will tend to cancel. These beamformers can be implemented by delaying the first sensor output by $n\tau$, where n is the sensor number after the first, and τ is some time. Figure 1.2 is a block diagram of delay and sum beamformer

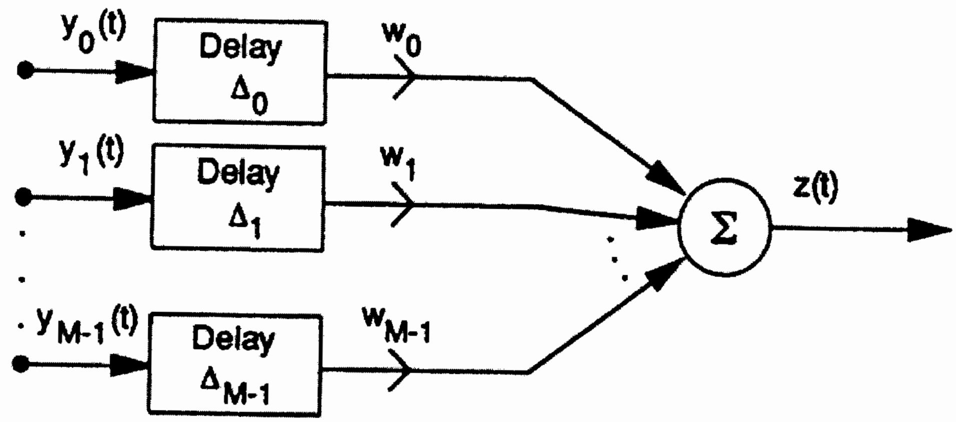

Figure 1.2 : Visualization of Delay & Sum Beam Former

A beamformer is a spatial filter that operates on the output of an array of antenna in order to enhance the amplitude of a coherent wave-front relative to background noise and directional interference [12]. Figure 1.3 [13] shows a curved array of hydrophone sensors (staves). Each sensor (red circle) is located at (x,y) coordinate as shown in Figure 1.3. These sensors are pointing in known directions (blue arrows), and our aim is to form beams that point in chosen directions (green arrows). This pointing direction is called the Maximum Response Angle (MRA) and can be arbitrarily chosen for the generated beams.

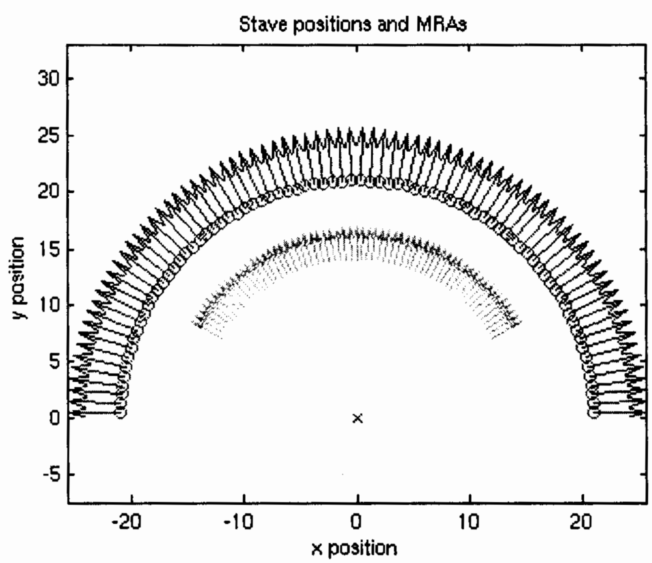

Figure 1.3 : Antenna Array Structure

The response of a given element is plotted on a polar graph [13], where angle is the offset from the MRA, and the radius is the magnitude response (measured in dB) in that direction. Element responses (determined by the 3dB down point) are very wide; in this example the width is about 90 degrees.

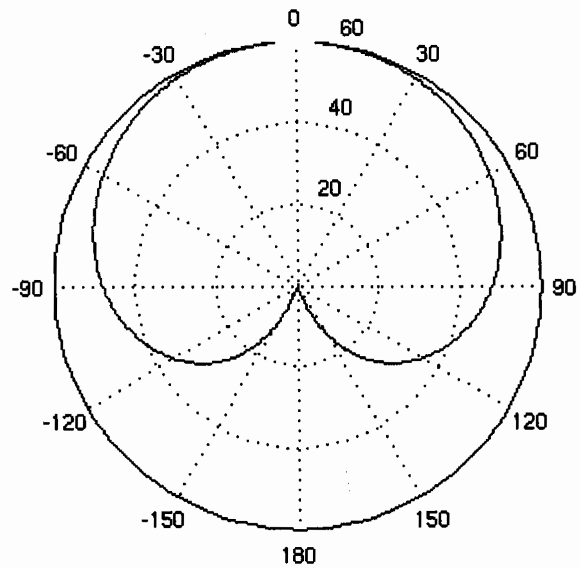

Figure 1.4: Response of Single Antenna

The goal of beamforming is to add multiple signals to achieve a narrower response in a desired direction. Through this, we can determine direction of the beam by hearing its sound [12].

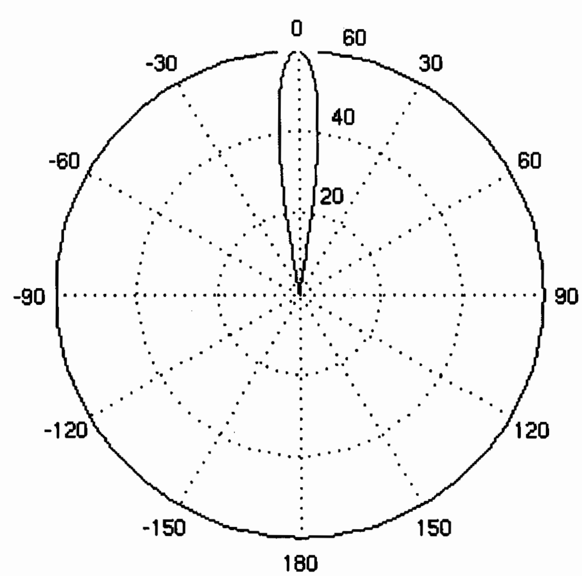

Figure 1.5: Goal of Beamforming

Beamforming is used to increase SNR and cancel the interference. Consider a scenario for hands-free teleconferencing setup shown in Figure 4[14]. The distance between the speaker and the microphones is large. As a consequence, background noise is picked up by the microphones typically resulting in a low signal-to-noise ratio at the microphone outputs. In order to guarantee a high speech transmission quality and intelligibility, the recorded signal has to be enhanced [14].

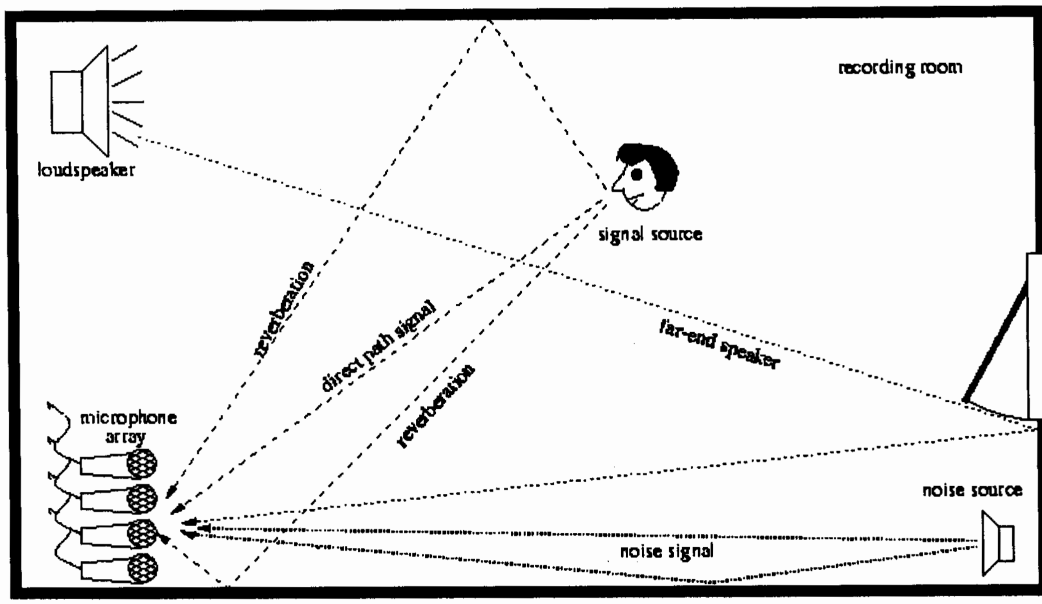

Figure 1.6: Beamforming Example (Typical Recording Room)

The speech signal (desired signal) and background noise overlap in time and frequency domain [why beam]. By using multiple microphones, *i.e.* a microphone array, the different spatial characteristics of speech and noise can be exploited. In this way the undesired signals can be suppressed [14].

Statistical independence of the MIMO spatial channels is well exploited by Space-Time diversity. If receiver channel gain is known to the transmitter, direct transmission from each antenna is possible and minimizes the interference between the MIMO spatial channels [15]. If the geometry of array is known, transmission in desired direction can be achieved. It leads towards the general idea of beam steering in phased array antenna. If there is multi-path fading then the channel gains cannot be determined by known channel geometry. Channel gains can be estimated by sending the known sequence (Training sequence) to receiver. This is a three way hand shaking process where transmitter and receiver transmit the known sequence to each other. It leads towards a feedback mechanism for the receiver to send estimated channel gains to the transmitter. Quantized feedback uses finite number of bits for channel information and can be used to resolve these deficiencies in the feedback channel. Statistical feedback is also useful to overcome these effects by using the fading averages (mean or covariance of the channel) that is known to the transmitter. Partial channel knowledge produces substantial gain from beamforming [16], [17]. Channel estimation technique is proposed in [18] that uses the reciprocity property of electromagnetic channels. In this method forward-link channel is estimated indirectly using measurements on the reverse link and vice-versa. The basic requirement in this method is that both forward and reverse links use same frequency bands. Wideband frequency division duplexed systems [19] are the extension of this concept. Knowledge of geometry of the antenna array is not required in the techniques disused above.

Beamforming, virtual antenna arrays have been the key research areas in past few years [11], [20], [21], [22]. The information regarding the interference from the distributed array is gathered from characterization of the side-lobes of the antenna pattern [22]. The extension of the above work that focuses on the main-lobe instead of side-lobes for interference information is presented in [23]. A synchronization method for coherent communication is presented in [24]. In this method, each transmitter synchronizes with the receiver separately to align its phases. This method is similar to closed-loop synchronization method presented in [20]. The feedback procedure for beam-steering presented in [25]; which is a distributed implementation of a stochastic approximation algorithm. This is a well-known class of mathematical algorithms [26], where a randomized search procedure is used to find the roots of a function that is difficult to characterize analytically [25]. This technique was first used by Robbins-Monro [27] in 1952. This technique has been recognized as a powerful technique with applications in many areas. Stochastic gradient algorithm was recently proposed [28] for downlink beamforming from a cellular Base Station.

The above mentioned studies and facts lay the foundation of our investigation. It is observed that wireless sensor network is gaining popularity rapidly. Due to constraints of wireless sensor network, energy efficiency is the key requirement. It is also observed that beamforming produces high signal to noise ratio and suppresses interference and noise. Moreover, collaborative communication produces large gain in received power. Therefore, the purpose of this literature review is to gather evidence about collaborative beamforming in sensor network.

1.5. Problem Definition

Although sensor networks are advantageous their limiting factor is the low life due to limited power time. Distributed beamforming recovers from these limitations. An analysis is carried out to determine the robustness of beamforming.

This report describes the design and implementation of the beamforming algorithms using existing techniques like Match Filter, Minimum Mean Square Estimation (MMSE), Minimum Variance Distortionless Response (MVDR) and Minimum Power Distortionless Response (MPDR) in addition to designing a digital optimal frequency and phase estimator for beam forming. The performance is verified by performing detailed numerical and simulation analysis.

1.6. Objectives and Methodology

There are many objectives of this research that are achieved:

i) A performance criterion for energy efficient transmission using distributed beam forming in the sensor network is defined

ii) The phase and delay effects in the sensor network and try to optimize the model for these effects are investigated.

iii)The algorithms like Minimum Mean Square Estimation (MMSE), Match Filter, Minimum Variance Distortion less Response (MVDR) and Minimum Power Distortion less Response (MPDR) for performance analysis in the sensor network are implemented.

iv)A digital phase estimator that minimizes the phase error is designed.

v) The detailed simulation and numerical analysis for the phase estimator is performed.

The proposed methodology to achieve these objectives is based upon resources and available literature on the sensor network, beam forming and distributed beam forming in the sensor network.

Chapter 2
Literature Review

2. Literature Review Process

2.1 Motivation & Benefits

A review of prior, relevant literature is an essential feature of any academic project [review]. An effective review creates a firm foundation for advancing knowledge. It facilitates theory development, closes areas where a plethora of research exists, and uncovers areas where research is needed [28].

The theme of this section is to conceptualize research areas and survey and synthesize prior research. It is very useful to provide important input in setting directions for future research. Most research starts with a literature review of some sort. A literature review should be thorough and fair; otherwise it will be of a little scientific value. This is the main rationale for undertaking literature reviews. A literature review synthesises existing work in a manner that is fair and seen to be fair. The search strategy must allow the completeness of the search to be assessed. In particular, researchers performing a systematic review must make every effort to identify and report research that does not support their preferred research hypothesis as well as identifying and reporting research that supports it.[28]

> *"Indeed, one of my major complaints about the research field is that whereas Newton could say,* ***"If I have seen a little farther than others, it is because I have stood on the shoulders of giants,"*** *I am forced to say, "Today we stand on each other's feet." Perhaps the central problem we face in all of research field is how we are to get to the situation where we build on top of the work of others rather than redoing so much of it in a trivially different way. Science is supposed to be cumulative, not almost endless duplication of the same kind of things".*
>
> Richard Hamming 1968 Turning Award Lecture

Objectives of literature review are as follows

- ✓ Formulation of search string to find relevant literature
- ✓ Formulation of the research questions
- ✓ Evidence gathering for existing research

- ✓ Identification of research gaps
- ✓ Identification of future directions

2.2 The Process

To perform literature review following set of activities is performed:

• **Search Criterion Formulation:** In this step the search criterion is identified to find the relevant literature.

• **Formulation of Research Questions:** Important research questions are identified.

• **Defining Selection Criteria:** on the basis of defined terms and their priority the selection criterion is defined.

• **Selection of Relevant Literature:** On the basis of search criterion, found literature is investigated and characterized using of selection criterion.

• **Data Summarization:** Selected data is summarized to analyze.

• **Research Gaps Identification:** On the basis of analysis results the research gaps are identified.

• **Formulation of Future Directions:** On the basis of research gaps the future directions are formulated.

• **Report:** All the steps discussed above are written in well formatted way..

The flowchart in Fig. 2.1 elaborates all set of activities in detail.

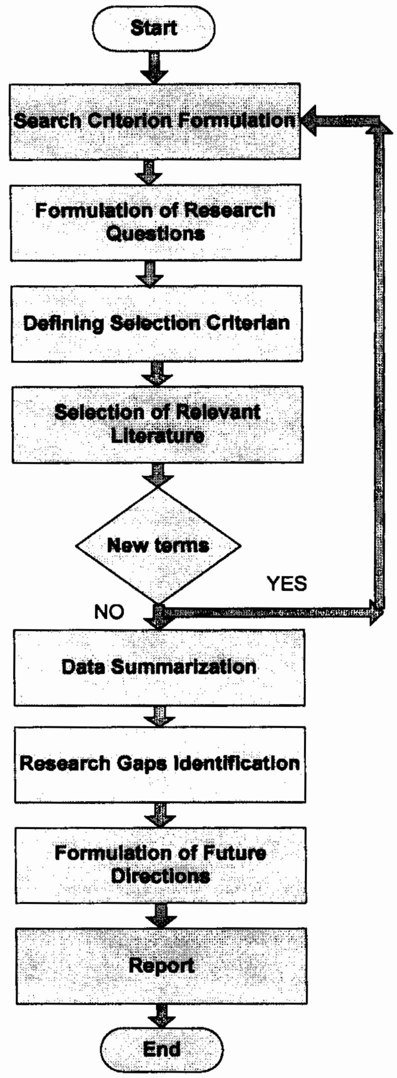

Figure 2.1: Literature Review Process Flow Chart

Identifying the valid research questions is an important component of any literature review [36]. For the formulation of the research questions in this literature review we have used the following terms.

Table 2.1: Terms

Area of interest	Beamforming and wireless sensor network
Technique	Centralized and Distributed Beamforming
Goal	Energy efficient communication, High signal to noise ratio (SNR)
Environment	Wireless communication in distributed Sensor network

The question identification process was iterative. Below are the research questions that we finalized and investigated.

Research Question 1

Can centralized beamforming technique be used in sensor network, if not what characteristics of the sensor network affect the outcome of centralized beamforming?

Research Question 2

Which models are proposed for beamforming in sensor network instead of centralized beamforming?

Research Question 3

What is the priority and significance of each characteristics of sensor network for beamforming that affects the outcome of beamforming and its effects on outcome?

2.3. Selection of Relevant Literature

Search criterion is applied on different sources to find the relevant literature. The data from different databases, search engines, theses and personal website of authors are collected. Selection criterion is applied to select the relevant literature.

2.3.1 Search Process

Before investigating any thing the important question is "what" to find. To find its answer the following tasks are performed:

1. Terms of the research are defined.
2. Synonyms of key terms are defined.
3. Keywords, alternate terms are defined.
4. Terms are combined using OR and AND operator

Synonyms, OR and AND operator use is shown in tables 2, 3 and 4

Table 2.2: Synonyms Derived from Terms

Basic Term	**Synonyms**
Beamforming in sensor network	Distributed beamforming, collaborative beamforming, feasibility of beamforming
Energy efficient communication in sensor network	Power efficient communication, increase signal to noise ratio
Phase Estimator	Digital Phase Estimator, Analog Phase Estimator

Table 2.3: Combining synonyms using OR operator

(Beamforming in sensor network OR Distributed beamforming OR collaborative beamforming OR feasibility of beamforming)
(Energy efficient communication in sensor network OR Power efficient communication OR increase signal to noise ratio)
(Phase Estimator OR Digital Phase Estimator OR Analog Phase Estimator)

Table 2.4: Combining Different terms using AND operator

(Beamforming in sensor network OR Distributed beamforming OR collaborative beamforming OR feasibility of beamforming) AND (Energy efficient communication in sensor network OR Power efficient communication OR increase signal to noise ratio)
(Beamforming in sensor network OR Distributed beamforming OR collaborative beamforming OR feasibility of beamforming) AND (Phase Estimator OR Digital Phase Estimator OR Analog Phase Estimator)
(Beamforming in sensor network OR Distributed beamforming OR collaborative beamforming OR feasibility of beamforming) AND (Phase Estimator OR Digital Phase Estimator OR Analog Phase Estimator)

2.3.2. Search Sources

The terms defined above are searches in different data sources. Data sources used for search are as follows.

2.3.2.1 Online Databases

1. ACM Digital library
2. CIA - Computer Index Australasia
3. Compendex
4. Computer Database
5. Computing Reviews
6. Derwent Innovations Index
7. Energy Citations Database
8. ENGINE - Australian Engineering Database
9. Gartner Group Intraweb
10. IEEE Xplore
11. Information Technology Case Studies
12. INSPEC
13. ProQuest Computing
14. Scopus
15. SpringerLink
16. Telecommunications
17. Web of Science

2.3.2.2 Online Search Engines

1. Google scholar
2. CiteSeer
3. Agile alliance

2.3.2.3 PhD Dissertation and Thesis

1. ProQuest Dissertations & Thesis
2. International Islamic University Library
3. Auckland University Library

2.3.2.4 Authors Personal Web Pages

1. R. Mudumbai
2. H. V. Poor
3. G. Barriac

4. U. Madhow
5. Alireza Tarighat
6. Ali H. Sayed
7. Gregory Eugene Allen
8. Koen Eneman

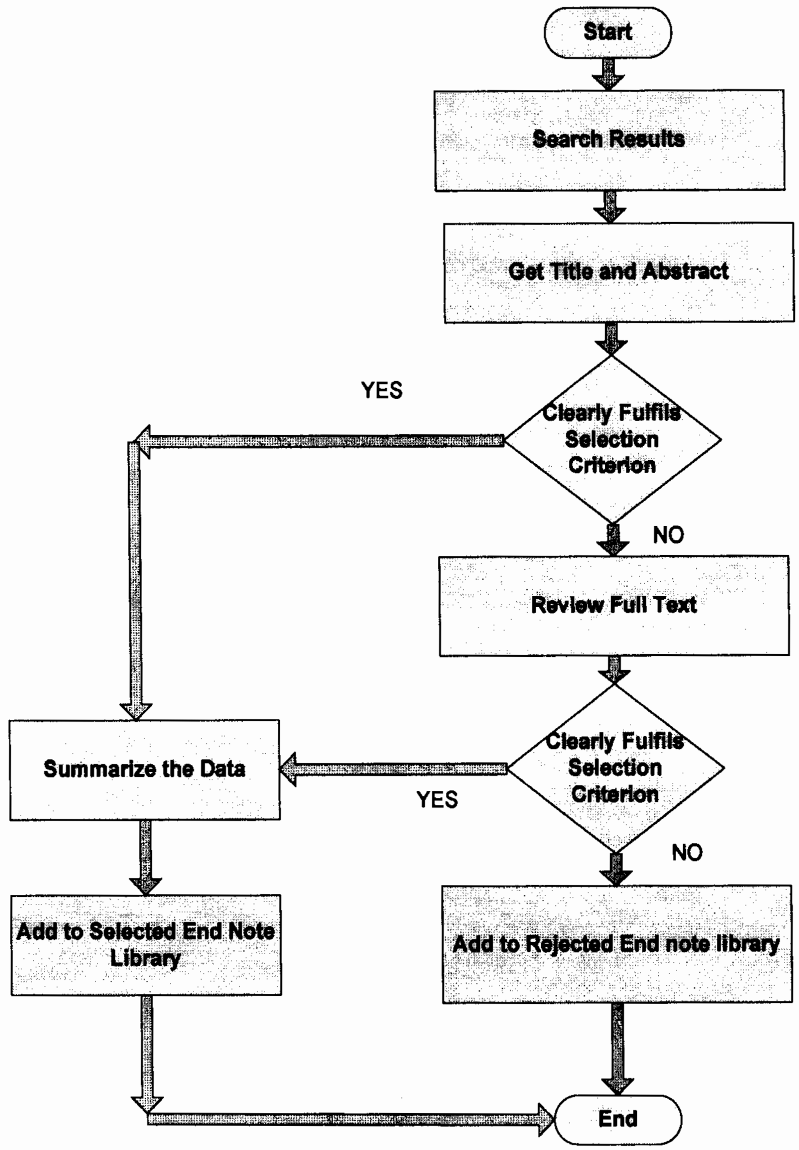

Figure 2.2: Identifying relevant literature flowchart

2.3.3 Search Results

Initially the search string formulated was "***beamforming in sensor network***". This string was searched on above mentioned data sources. Very few results were found, so we modified the search string. The search string that we used was ***("(Beamforming)") AND ("(Sensor Network)")).***

Total 366 results were found, but there were few relevent studies found in multiple data sources. The summary of the total results found, selected papers, non selected papers and paper found in multiple sources is shown in table 5. After evaluation of the results 8 studies were selected and a detailed analysis was performed that is discussed in next section.

Table 2.5: Summary of Search Results

S No.	Database Name	No. of Papers Found	Selected	Not Selected	Duplicated in other sources.
1	ACM Digital library	55	0/55	55/55	6(IEEE), 10(Journal), 20 (Review)
2	Compendex, Geobase, Georef	54	-	-	51(IEEE), 3(ACM)
3	Derwent Innovations Index	4	0/4	4/4	-
4	IEEE Xplore	65	7/65	58/65	-
5	INSPEC	44	-	-	35 (IEEE), 9(ACM)
6	ProQuest Computing	2	-	-	2(IEEE)
7	Scopus	54	0/54	54/54	40(IEEE), 14(ACM)
8	SpringerLink	52	0/9	9/9	2(ACM), 43 Book Ch.
9	Web of Science	11	-	-	5(IEEE), 6(ACM)
10	PhD Dissertation and Theses	10	1/10	9/10	-
11	Author Personal web Page	25	-	-	20(IEEE), 5(ACM)

2.3.4 Selection Criterion

Beamforming in sensor network is our selection criterion. All those studies that discuss beamforming in sensor network fulfil our criterion. Related topics are also studied and categorize as joint references.

2.3.4.1 Selected Studies

After careful investigation, the study selection process short listed the following studies that satisfied the inclusion criteria.

- **S1** → G. Barriac, R. Mudumbai, and U. Madhow, "Distributed beamforming for information transfer in sensor networks," in Proc. 3rd International Symposium on Information Processing in Sensor Networks (IPSN'04), pp. 81–88, Apr. 26–27, 2004.
- **S2** → M. Tummala, C. Chee and P. Vincent, "Distributed beamforming in wireless sensor Networks," Thirty-Ninth Asilomar Conference, pp. 793-797, October 28 - November 1, 2005.
- **S3** → H. Ochiai, P. Mitran, H. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," IEEE Trans. on Signal Process. vol. 53, no. 1053-587X, pp. 4110–4124, 2005
- **S4** → R. Mudumbai, B. Wild, U. Madhow, and K. Ramchandran, "Distributed beamforming using 1 bit feedback: From concept to realization," Proc. of the 44th Allerton Conf. Commun. Control Comput., pp. 1020–1027, Sep. 2006.
- **S5** → R. Mudumbai, J. Hespanha, U. Madhow, and G. Barriac, "Distributed transmit beamforming using feedback control," IEEE Trans. Inf. Theory [Online]. Available: http://www.ece.ucsb.edu/~raghu/research/ pubs.html, submitted for publication.
- **S6** → R. Mudumbai, G. Barriac, and U. Madhow, "On the feasibility of distributed beamforming in wireless networks," IEEE Trans. Wireless Commun., vol. 6, no. 5, pp. 1754-1763, May 2007.
- **S7** → R. Mudumbai, "Energy Efficient Wireless Communication using Distributed Beamforming," PhD thesis, University of California, Santa Barbara, December 2007.
- **S8** → Z. Han and H. V. Poor, "Lifetime improvement in wireless sensor networks via collaborative beamforming and cooperative transmission," Microwaves, Antennas & Propagation, IET, vol. 1, pp. 1103-1110, 2007.

2.3.4.2. Salient Features of Selected Studies

Table 2.6: Salient Features of Selected Studies

Sr. No.	Salient Features
S1	Effects of phase errors are analyzed and one bit feedback control mechanism is used in absence of noise and fading channels.
S2	Adaptive beam steering method is proposed to track a moving target. LMS algorithm is used for adaptive beamforming. Placement error effects are analyzed.
S3	Collaborative beamforming to get N gain in the signal to noise ratio by increasing the directivity of beam pattern. Analysis of effect of phase and localization estimation error in sensor network.
S4	Effects of phase errors are analyzed and one bit feedback control mechanism is used in absence of noise and fading channels.
S5	Effects of phase errors are analyzed and feedback control mechanism is used in absence of noise and fading channels.
S6	Feasibility of beamforming is studied and communication model is proposed to transfer the data to base station in the absence of interference. Analysis of effects of phase errors.
S7	Energy efficient transmission using beamforming is studied and communication model is proposed to transfer the data to base station in the absence of interference. Analysis of effects of phase errors.
S8	Collaborative effect and cooperative communication effect on the life time improvement is studied. A routing protocol is proposed that improve the life time of the network.

2.3.5 Interdependencies of selected studies

In any research area investigation of interdependencies of available studies is the important task. It helps to find the research gaps and leads to the future directions. Selected studies have a lot of inter dependencies on each other. Studies S1, S4, S5, S6 and S7 are presented by the same authors and each of them is the extension of previous studies performed by them, this ended up with the PhD thesis.

The interdependencies of selected studies are summarized in table 2.7.

Table 2.7: Interdependencies of Selected Studies

Sr. No.	Selected Studies on which it depends
S1	None from selected Studies, Authors claim it is the first paper in that it addresses the effects of phase error.
S2	None from selected Studies, it is an implementation of LMS
S3	S1, Special case of Master-Slave Architecture presented in S1
S4	S1
S5	S1 and S4 (Transaction paper with some modification in S4)
S6	S1 (Transaction paper with some modification in S1)
S7	S1, S4, S5 and S6
S8	S3

From selected studies it is clear that fundamental study is S1. Nearly all other studies are based upon the findings of this study.

2.4. Detailed Summary of Selected Studies

The studies selected in section 5 are examined in detail. We perform mathematical analysis of all the selected studies. It is clear in section 5 that the fundamental study is S1. Detailed mathematical and simulated analysis of S1 is performed and a simulator is implemented in SIMULINK to compare the analytical and simulation result.

S1 → G. Barriac, R. Mudumbai, and U. Madhow, "Distributed beamforming for information transfer in sensor networks," in Proc. 3rd International Symposium on Information Processing in Sensor Networks (IPSN'04), pp. 81–88, Apr. 26–27, 2004.

Energy efficient transmission is the key issue in sensor network. Distributed beamforming technique is established for energy efficient communication in sensor network. Same data is transmitted using multiple sensor nodes in such a way that received signal energy is the cumulative result of all received signals. This can be achieved if the base station is synchronized (Phase and delay) with the sensor nodes (used to transmit information). There are two ways to do this: One way is that each sensor node is synchronized to the base station, but is costly and takes more time for convergence. Another way is that all sensor nodes are synchronized to each other and use the same signal for modulation. The latter model is discussed in this study and results shows that data can be transmitted in an energy efficient way. Master-Slave architecture is proposed in this study where master node transmits the carrier and data signal to the entire slave nodes for frequency synchronization. Physical model is shown in Figure 7.

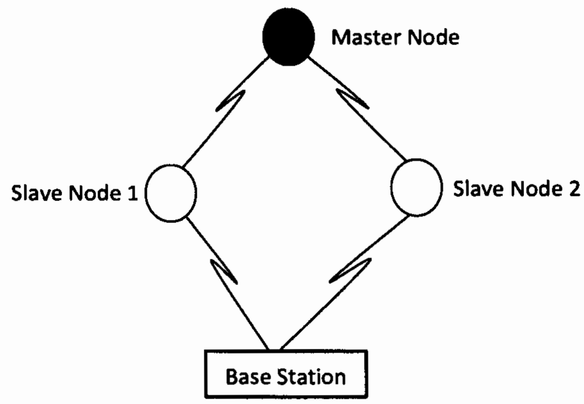

Figure 2.3: Physical Structure

Goals of this study are as follows:

1. Transmit data from information source to receiver using sensors.
2. Maximize the received power.
3. Appropriate calculation of weights is required to produce beamforming.
4. Phase synchronization is done at the transmitter side instead of receiver side to reduce cost and convergence time.

Assumptions considered in this study are as follows:

1. Slave nodes and master node know the position of each other.
2. Slave node can adjust the frequency, phase and time delays.
3. Channel coefficients $w_i^{\wedge}$, $w_i^{`}$ and w_i^H are zero mean and i.i.d (Statistically identical and independent) random variables.
4. There is no Noise and Interference in channel.
5. Channel is known to all the Nodes and receiver.

The results of this study are shown in Figure 8 and Figure 9.

Figure 2.4 shows that unit received power reduces slightly as the number of sensors are increased and unit received power reduces as phase error increases.

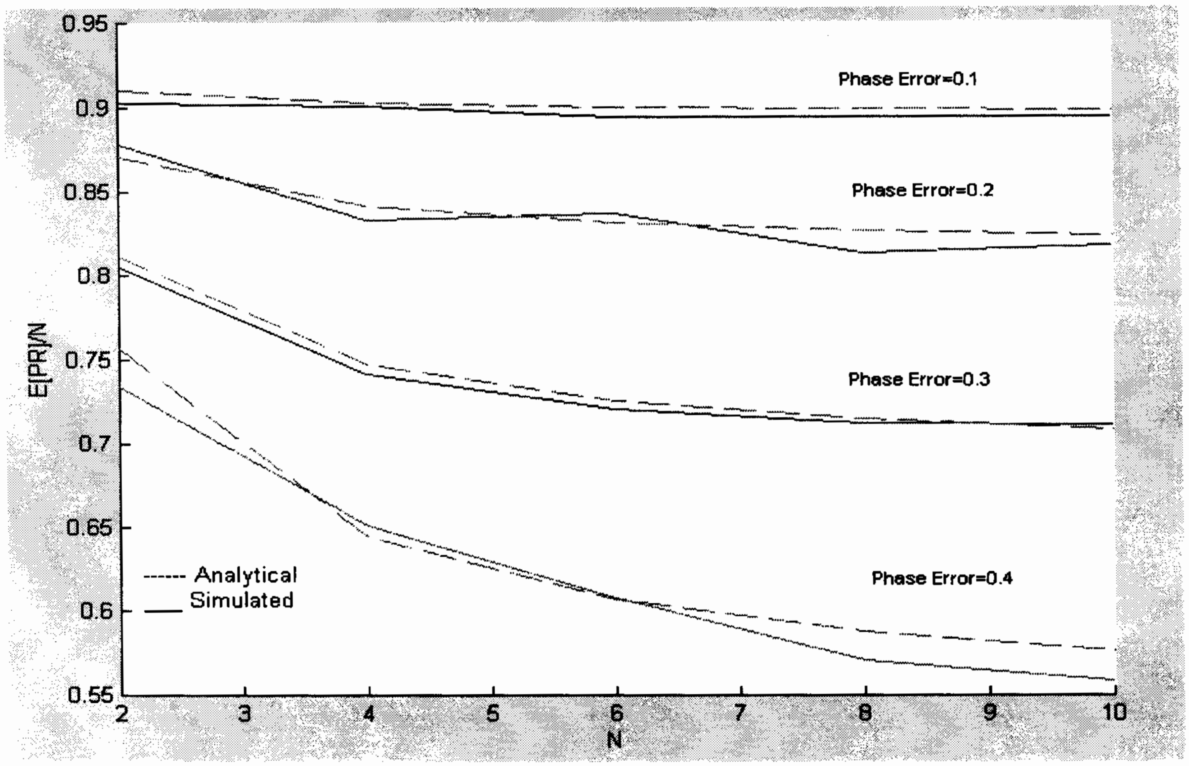

Figure 2.4: Simulated and Analytical Results OR unit Received power for phase errors 0.1, 0.2, 0.3, and 0.4

Figure 2.4 shows the unit received power and Figure 2.5 shows the total received power by the transmitter for different values of the phase error. Figure 2.5 shows that received power increases as the number of sensors are increased and received power reduces as phase error increases.

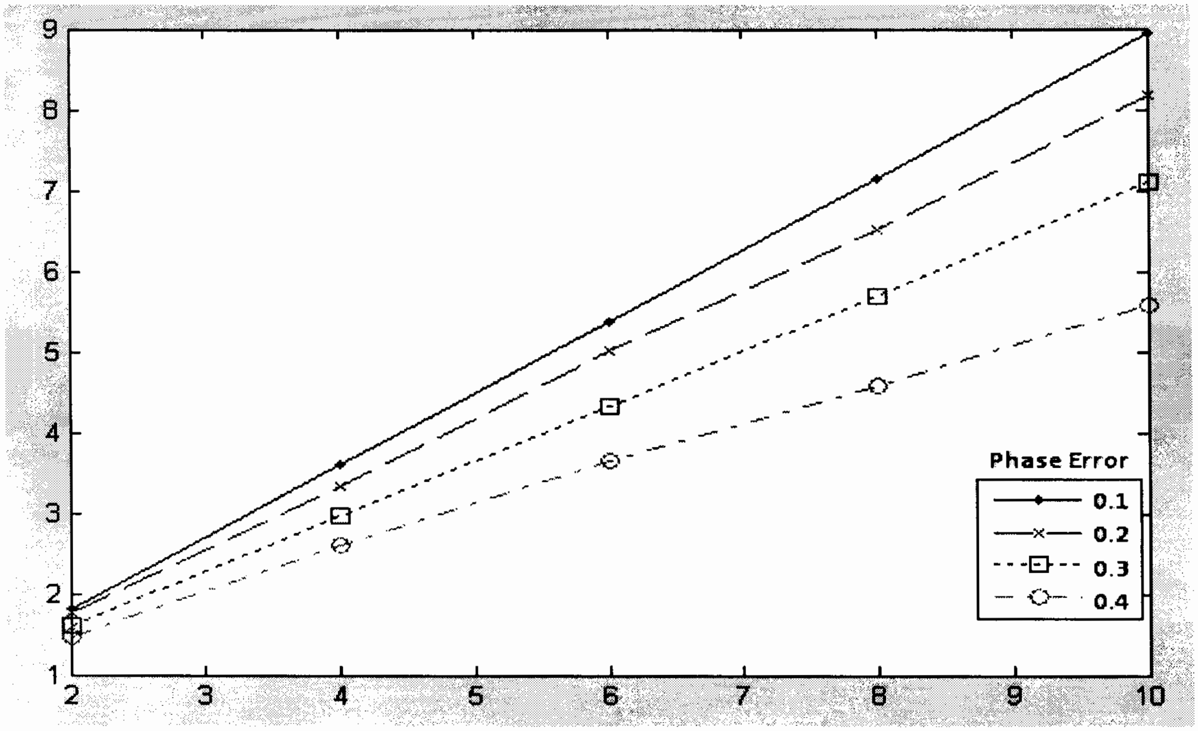

Figure 2.5: Simulated Results for average received power for phase errors 0.1, 0.2, 0.3 and 0.4

Claims of S1

The claims of the this study is given below

1. Distributed beamforming is possible.
2. Collaborative communication is achieved that results N (No. of slave sensors) gain in received power.
3. Phase errors play an important role for collaborative beamforming.

Future Work mentioned in study S1

1. Design of Phase estimator to reduce the phase errors.
2. Use of source coding and sensor net organization.
3. Implement the algorithms like Minimum Mean Square Estimation (MMSE), Minimum Variance Distortionless Response (MVDR) and Minimum Power Distortionless Response (MPDR) to compensate effects of interference sources.

S2 → M. Tummala, C. Chee and P. Vincent, "Distributed beamforming in wireless sensor Networks," Thirty-Ninth Asilomar Conference, pp. 793-797, October 28 - November 1, 2005.

An adaptive distributed beamforming approach for sensor networks is presented in this study, wherein sensor nodes coordinate their transmissions to form a distributed antenna array that directs a beam toward an airborne relay (Unamanned Aerial Vehicle). Least mean square (LMS) algorithm is used for adaptive algorithm. Simulated results show that the antenna main lobe remains stable in the presence of position errors and sensor failures, and thus can be steered in an adaptive manner as a UAV flies past. Physical system is shown in Figure 2.6.

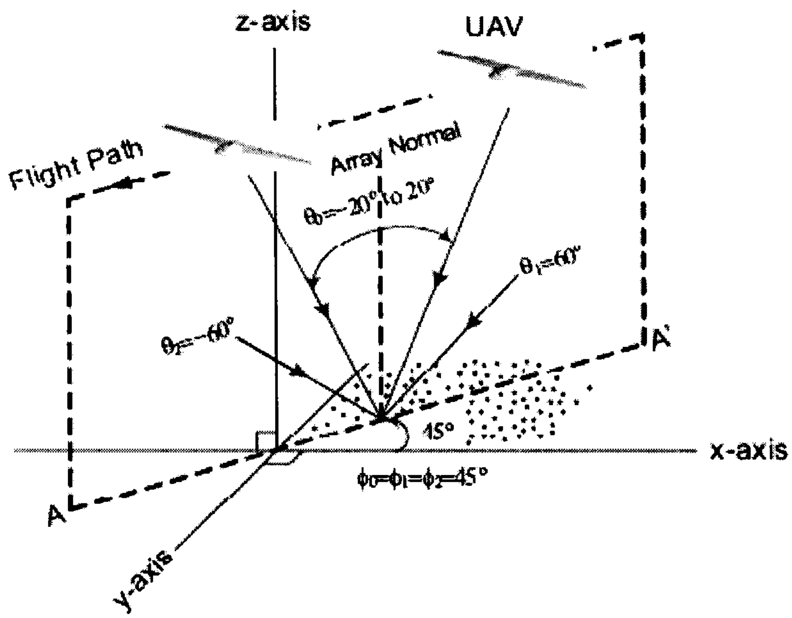

Figure 2.6: Physical System

Goals of this study are as follows:

1. Tracking of moving object.
2. Analysis of effects of the sensor node density, position errors and sensor node failures on the beam generated by a distributed sensor array.
3. Analysis of effects of position errors and sensor node failures on the maximum average power gain.

Assumptions considered in this study are as follows:

1. The desired modulating signal s(t) sent by the UAV is known to the sensor cluster array and is the same as the reference signal r(t) used for the LMS algorithm.
2. Each cluster head node has perfect knowledge of its own position and the position of the secondary nodes within the sensor cluster prior to beamforming.
3. The AOA of the desired signal is known to the sensor cluster.
4. There is perfect frequency, phase and data synchronization among the sensor nodes within the cluster and between the UAV and the sensor cluster.
5. There is perfect coordination among the cluster head node and the secondary nodes within a sensor cluster for beamforming.
6. All sensor nodes are modelled as isotropic antenna elements and mutual-coupling between sensor nodes are not considered.

The results of this study are shown in Figure 2.7 and Figure 2.8.

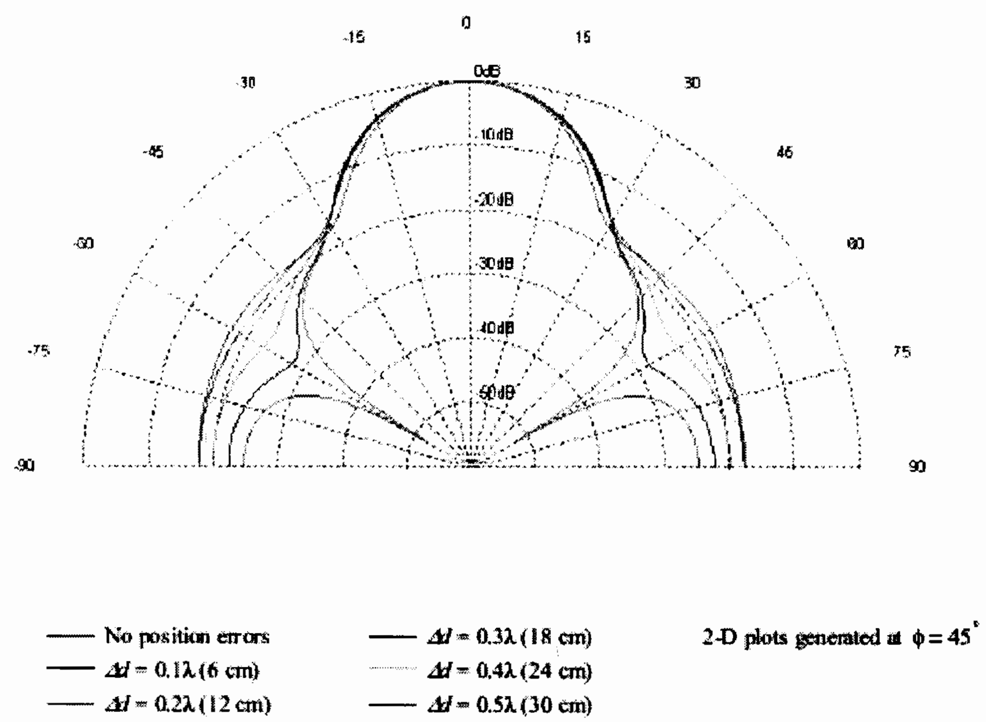

Figure 2.7: Polar plot of average power gain of the beams generated by the 7X7 sensor cluster in the presence of position errors.

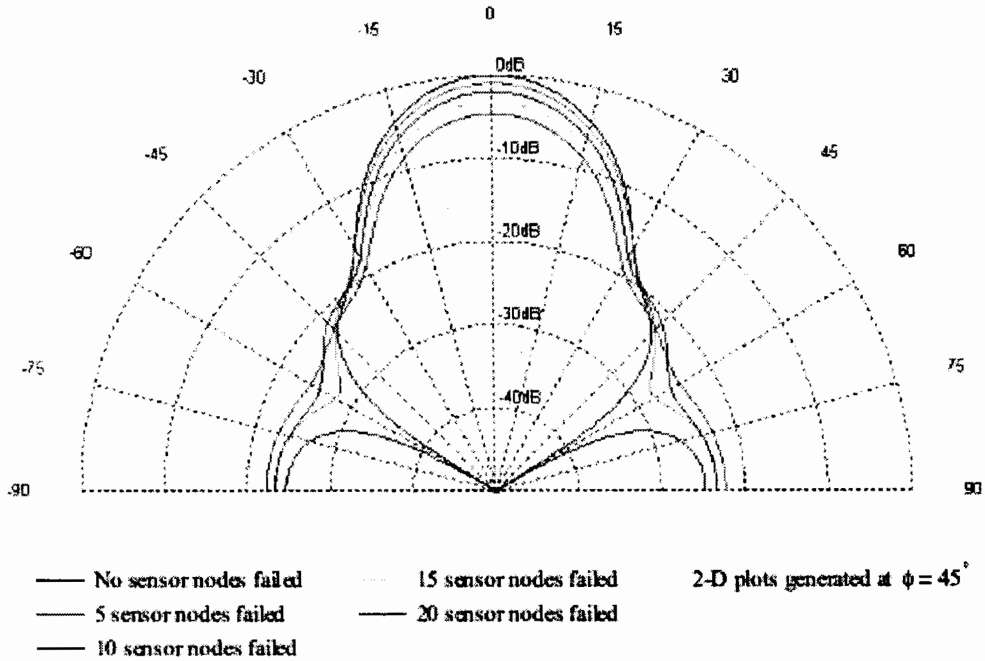

Figure 2.8: Polar plot of average power gain of the beams generated by the 7X7 sensor cluster as the number of sensor node failures increase from five to twenty

Claims of S2

The claims of the this study is given below

1. The shape of the main lobe remained relatively unchanged when the density changed.
2. In the presence of position errors and sensor node failures the shape of the main lobe remained relatively unchanged.

Future Work mentioned in study S2

Future directions are not mentioned in this study.

S3 → H. Ochiai, P. Mitran, H. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," IEEE Trans. on Signal Process. vol. 53, no. 1053-587X, pp. 4110–4124, 2005

In this study performance of collaborative beamforming is analyzed using the theory of random arrays. The statistical average and distribution of the beam-pattern of randomly generated phased arrays is derived in the framework of wireless ad hoc sensor networks. Each sensor node is assumed to be composed of a single isotropic antenna and the nodes in the cluster collaboratively transmit the signal such that the signal in the target direction is coherently added in the far field region. It is shown that with sensor nodes uniformly distributed over a disk, the directivity can approach, provided that the nodes are located sparsely enough. The distribution of the maximum side-lobe peak is also studied. With the application to ad-hoc networks, two scenarios (closed-loop and open-loop) are considered. Associated with these scenarios, the effects of phase jitter and location estimation errors on the average beam-pattern are also analyzed. Physical system is shown in Figure 2.9.

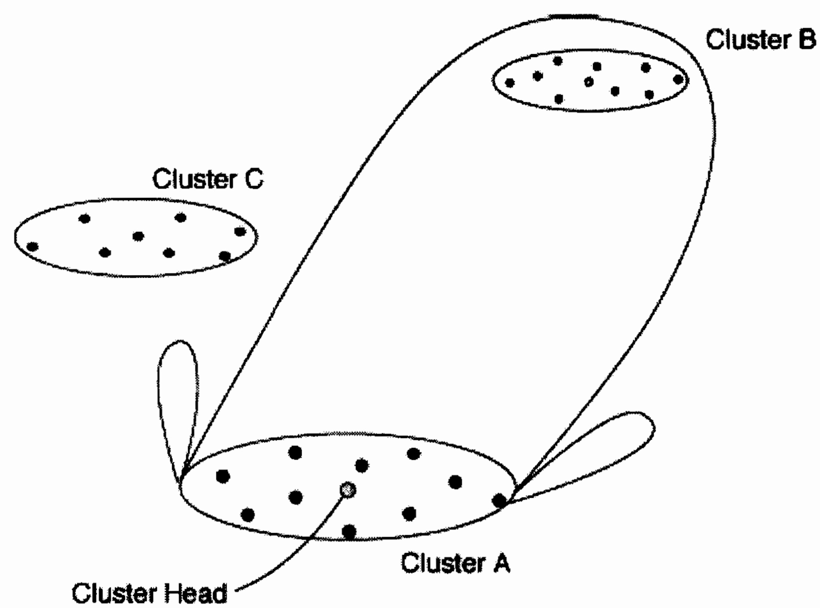

Figure 2.9: Physical Model

Goals of this study are as follows:

1. Achievement of Directivity gain.
2. Analysis of Distribution of main-lobe and side-lobs of beam-pattern.
3. Analysis of effects of frequency offset and phase jitter on beam pattern.

Assumptions considered in this study are as follows:

1. The location of each node is chosen randomly, following a uniform distribution within a disk of radius.
2. Each node is composed of a single ideal isotropic antenna.
3. All the sensor nodes transmit identical energies, also having identical path, so the underlying model falls within the framework of phased arrays.

4. There is no reflection or scattering of the signal and there is no multi path fading or shadowing.
5. To avoid mutual coupling effects among the antennas of different sensor, the sensor nodes are sufficiently separated.
6. All the nodes are perfectly synchronized so that no frequency offset or phase jitter occurs.

The results of this study are shown in Figures 2.10, 2.11 and 2.12.

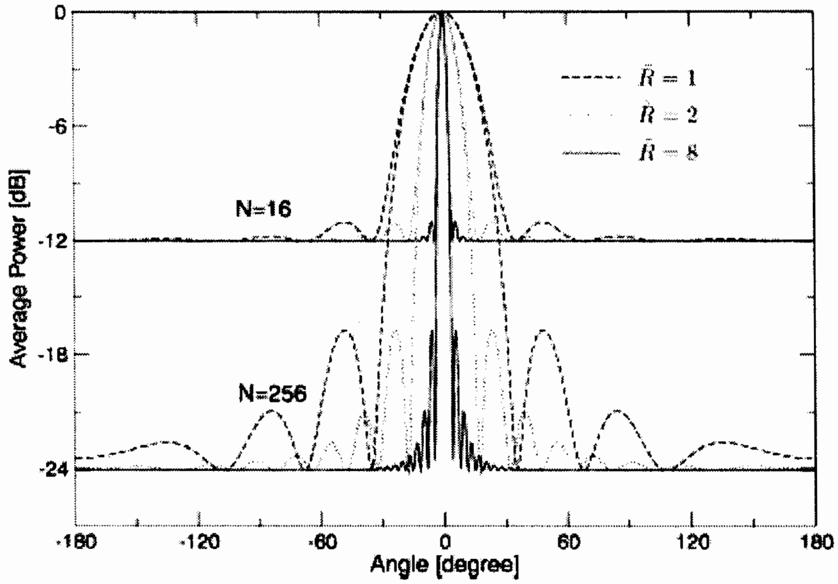

Figure 2.10: Average beam-pattern with different R and N = 16, 256

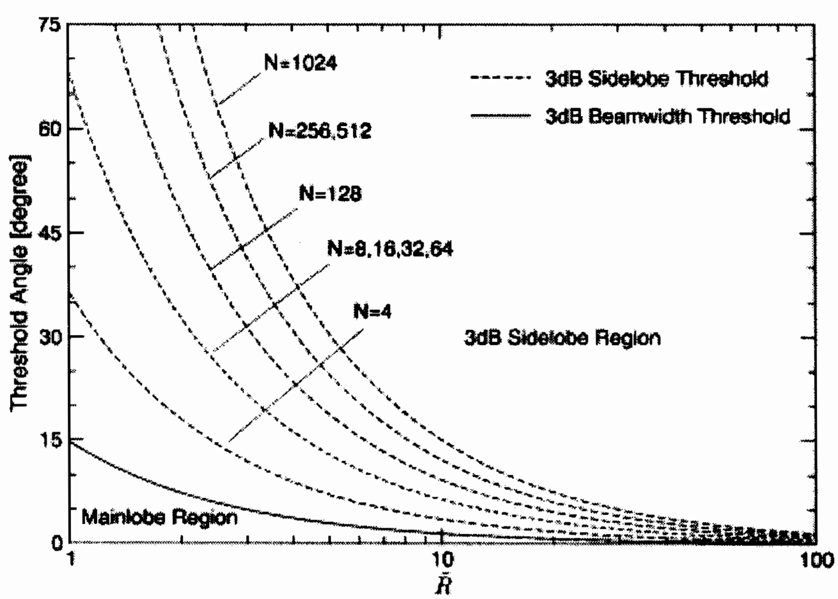

Figure 2.11: Threshold of 3-dB beam-width and 3-dB side-lobe region with respect to R and number of nodes N

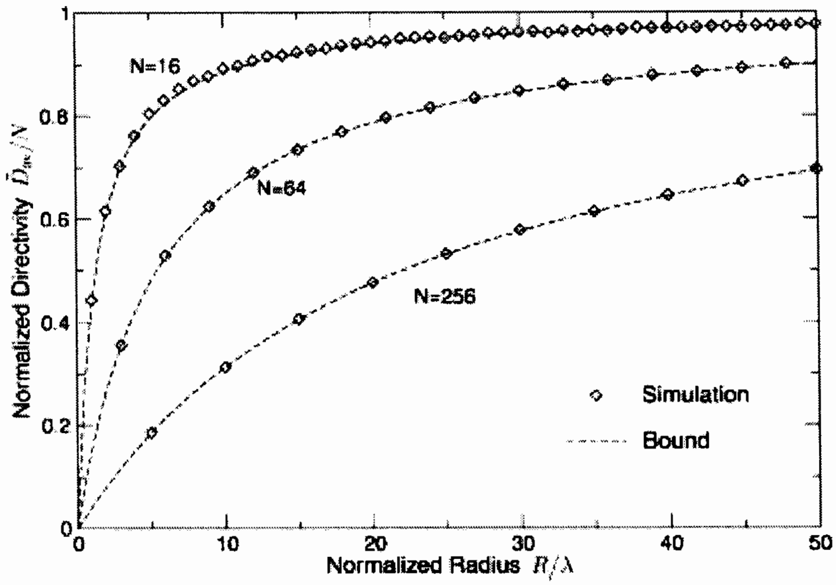

Figure 2.12: Relationship between directivity D/N and normalized radius R

Claims of S3

The claims of the this study is given below

1. Under ideal channel and system assumptions, directivity of order can be achieved asymptotically with sensor nodes, as long as the sensor nodes are located sparsely enough.
2. Nodes randomly distributed over a large disk, a nice beam-pattern with narrow main-lobe and average side-lobes as low as plus some margin for maximum side-lobe peaks can be formed.

Future Work mentioned in study S3

1. Applicability of beamforming when the destination or nodes in the cluster are in rapid motion or the channel suffers severe multi-path fading.
2. Development of specific algorithms for frequency offset correction of each node and phase error or location estimation error.
3. Development of efficient protocols for sharing the transmit information and calibration information among nodes.

S4 → R. Mudumbai, B. Wild, U. Madhow, and K. Ramchandran, "Distributed beamforming using 1 bit feedback: From concept to realization," Proc. of the 44th Allerton Conf. Commun. Control Comput., pp. 1020–1027, Sep. 2006.

In this study theoretical and experimental result for a distributed beamforming system based on a simple 1- bit feedback algorithm is presented. The algorithm is based on an iterative procedure that synchronizes multiple transmitters to cooperatively send a common message signal coherently to a receiver, using only a single bit of feedback in each timeslot. Under this scheme, the transmitters make independent, random phase adjustments every timeslot, and retain only those phase adjustments that increase the SNR at the receiver. The design of an experimental prototype to implement the beamforming algorithm, measurement data that shows the SNR gains from beamforming is also presented in this study. Analysis of the convergence behaviour of the procedure mathematically using a statistical approach is also performed in this study. It is shown that the mathematical model gives accurate predictions for the convergence rate in static and time-varying channels, and uses the analysis to demonstrate the scalability of the algorithm. Physical system is shown in Figure 2.13.

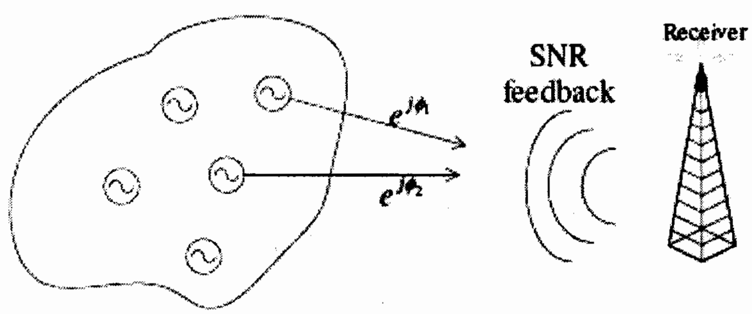

Figure 2.13: Physical Model

Goals of this study are as follows:

1. Transmit data from information source to receiver using sensors.
2. Maximize the received power.
3. Study convergence of feed-back control algorithm.
4. Perform phase synchronization at the transmitter side using 1-bit feedback from receiver.

Assumptions considered in this study are as follows:

1. All nodes know the position of each other.
2. There is no frequency offset.
3. Channel coefficients $w_i^{\wedge}$, $w_i^{`}$ and w_i^H are zero mean and i.i.d (Statistically identical and independent) random variables.
4. There is no Interference in channel.
5. Channel is known to all the Nodes and receiver.

The results of this study are shown in Figure 2.14 and Figure 2.15.

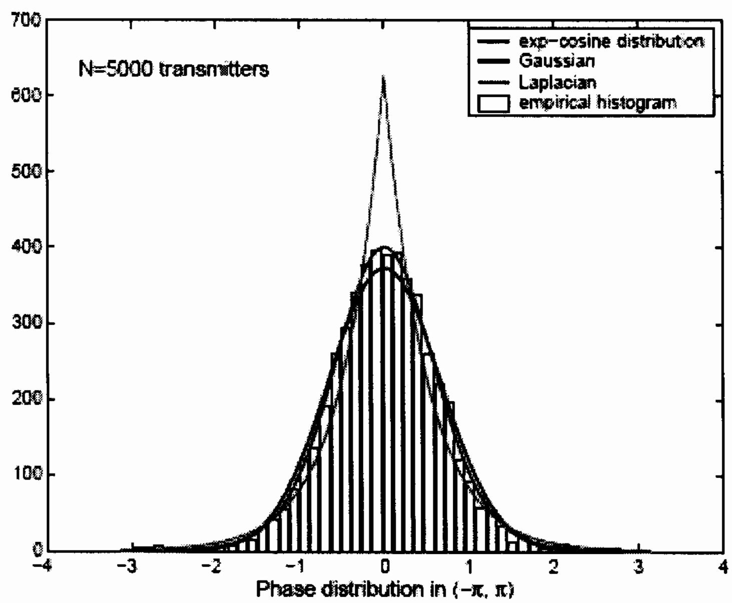

Figure 2.14: Histogram of empirically observed phase angles compared with analytically computed distributions

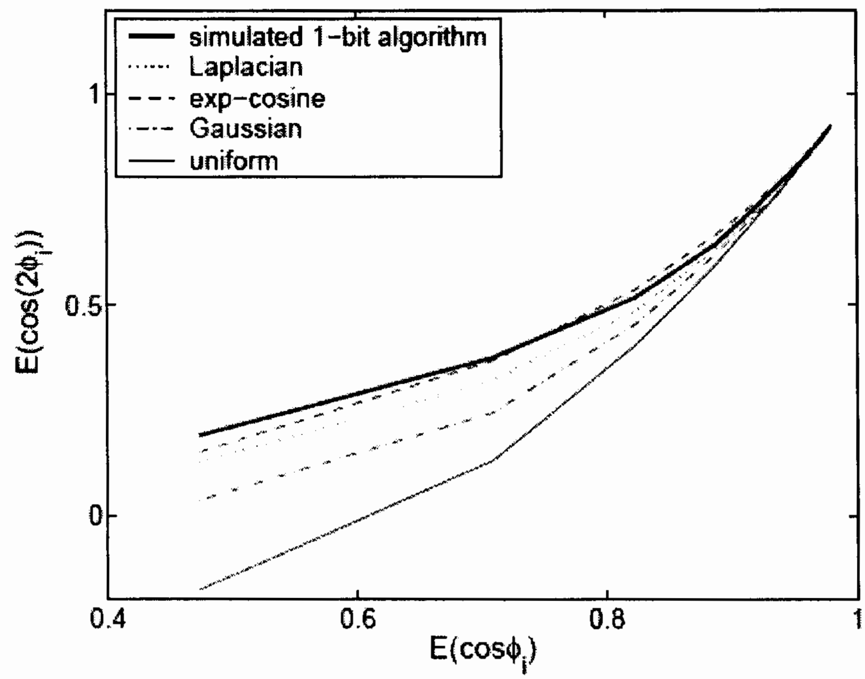

Figure 2.15: Comparison of E[cos(2φ_i)]from empirically observed phase angles with analytically computed distributions

Claims of S4

The claims of the this study is given below

1. Collaborative communication is achieved that results N (No. of slave sensors) gain in received power.
2. Large SNR gains are achievable under practical conditions using distributed beamforming.
3. Reduction in phase error using 1-bit feed back control.

Future Work mentioned in study S4

1. Design of better Phase estimator to reduce the phase errors.
2. Measuring and optimizing the algorithm for tracking time-varying channels.
3. Design of algorithm to reduce interference effects.

S5 → R. Mudumbai, J. Hespanha, U. Madhow, and G. Barriac, "Distributed transmit beamforming using feedback control," IEEE Trans. Inf. Theory [Online]. Available: http://www.ece.ucsb.edu/~raghu/research/ pubs.html, submitted for publication.

This study is the modified version of S4. S4 was published in conference proceedings. With few modifications in analysis part of S4, this study is submitted for review in Transaction. System model, Goals, assumptions and results of this study are similar to S4.

Claims of S5

Same as S4.

Future Work mentioned in study S5

Same as S5.

S6 → R. Mudumbai, G. Barriac, and U. Madhow, "On the feasibility of distributed beamforming in wireless networks," IEEE Trans. Wireless Commun., vol. 6, no. 5, pp. 1754-1763, May 2007.

This study is the modified version of S1. S1 was published in conference proceedings. With few modifications in analysis part of s1, this study is published in Transaction. System model, Goals, assumptions and results of this study are similar to S1.

Claims of S6

Same as S1.

Future Work mentioned in study S6

Same as S1.

S7 → R. Mudumbai, "Energy Efficient Wireless Communication using Distributed Beamforming," PhD thesis, UNIVERSITY OF CALIFORNIA, Santa Barbara, December 2007.

This study is the combined version of studies S1, S4, S5 and S6. S1 and S4 were published in conference proceedings. With few modifications in analysis part of s1 and S4 the studies S5 and S6 were published in Transaction. All these studies ended up with a PhD thesis.

This study discusses the use of distributed beamforming to improve the energy efficiency and transmission range of wireless networks. Under distributed beamforming, a number of wireless transmitters collaboratively transmit a common message signal in such way that their individual transmissions combine coherently (i.e. in phase) at the intended receiver. In essence, a set of distributed wireless nodes organize themselves as a virtual antenna array. As in beamforming from a conventional antenna array, highly directional transmissions can be achieved using a virtual array, and therefore substantial SNR gains can be realized compared to a network in which each node transmits independently to the receiver. Distributed beamforming arises naturally from information theoretic analyses of multi-user channels and is an essential ingredient of capacity-achieving coding strategies in several cases. However these analyses are based on baseband models of the channel and as such involve some implicit assumptions. The two most important such assumptions are (1) synchronized carrier signals, and (2) known phase relationship between the transmitters. The main contribution of this study is a detailed analysis of the feasibility of these assumptions, and a design for a practical wireless system based on distributed beamforming that explicitly addresses these issues. This design is based on a simple iterative procedure for beam-steering using receiver feedback. Carrier synchronization is achieved by using phase locked-loops to lock all the transmitters to a common reference signal broadcast by a designated master transmitter. It is shown that the SNR gains from beamforming are sensitive to the choice of PLL parameters, and examine this dependence in detail.

The feedback procedure for beam-steering works as follows: each transmitter independently makes a small random adjustment to its phase in each iteration, while the receiver broadcasts one bit of feedback, indicating whether the signal to noise ratio is better or worse after the adjustment. The transmitters keep the 'good' phase adjustments and discard the 'bad' ones, thus implementing a distributed ascent algorithm. It is also shown that, for a broad class of distributions for the random phase adjustments, this procedure leads to asymptotic phase coherence with probability one. A simple analytical model, borrowing ideas from statistical mechanics, is used to characterize the progress of the algorithm, and to provide guidance on parameter choices.

Claims of S7

1. Beamforming is possible in sensor network.
2. Collaborative communication produce N gain in received power and collaborative beamforming produce N2 gain in Signal to Noise ratio (SNR).
3. Problem of carrier synchronization was central to its implementation, and presented a solution based on master-slave architecture.
4. A feedback algorithm is presented that allows a simple practical implementation and analyzed its properties by theory and simulations.

Future Work mentioned in study S7

1. Design of Digital phase estimator that is robust to time variant system.
2. Feed back control system can be designed that works on multiple bits feedback from receiver for better improvement.
3. PLL in master slave architecture also produces phase error. Design of digital system for carrier synchronization.
4. Multi-hop routing algorithms can be designed.
5. Coding techniques can be implemented.

S8 → Z. Han and H. V. Poor, "Lifetime improvement in wireless sensor networks via collaborative beamforming and cooperative transmission," Microwaves, Antennas & Propagation, IET, vol. 1, pp. 1103-1110, 2007.

Collaborative Beamforming (CB) and Cooperative Transmission (CT) have recently emerged as the communication techniques that can make effective use of collaborative/cooperative nodes to create a virtual multiple input/multiple output system. Extending the lifetime of a network that is composed of battery operated nodes is the key issue in the design and operation of wireless sensor networks. The lifetime of proximity nodes to use CB/CT in reduction of the load is considered for forwarding to only nodes having critical battery life. CB/CT plays its role in improving the signal strength at a far away destination using energy in nearby nodes is evaluated. The performance is improved by this technique when analysed for a special 2D disc case. From the analysis and the simulation results, it is seen that the proposed method can reduce the payloads of energy-depleting nodes by about 90% in the special case network considered and improve the lifetimes of general networks by about 10%, compared with existing techniques. System model is shown in figure 2.16.

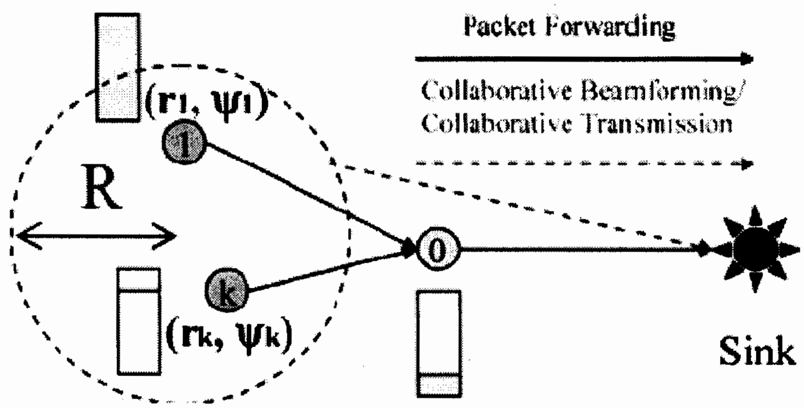

Figure 2.16: System Model

Goals of this study are as follows:

1. Life improvement of the sensor network.
2. Analysis of effects of collaborative beamforming and cooperative communication on design of routing protocol.

Assumptions considered in this study are as follows:

1. Position of the sensors is known.
2. There is perfect frequency, phase and data synchronization among the sensor nodes.

The results of this study are shown in Figure 2.17.

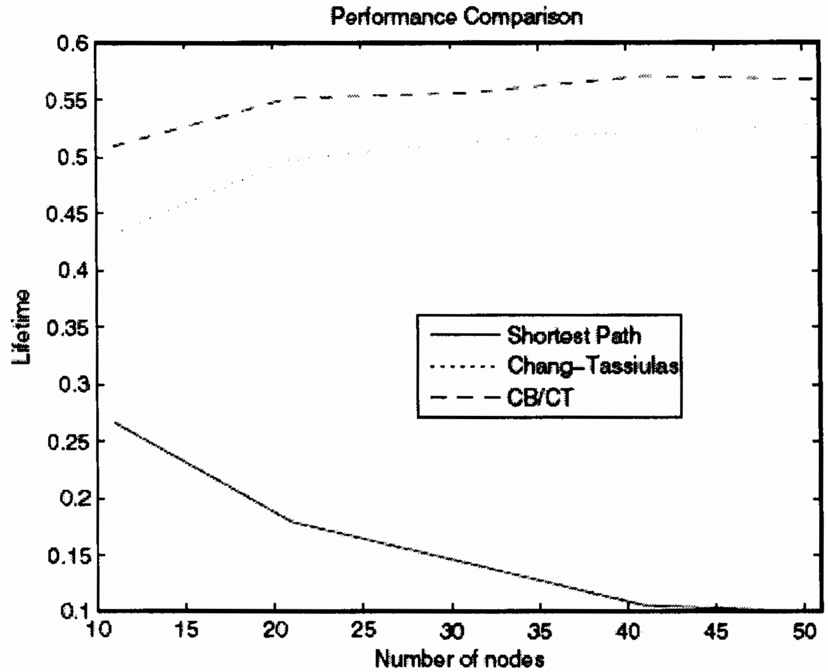

Figure 2.17: Life time improvement comparison

Claims of S2

The claims of the this study is given below

1. Effect of collaborative communication and cooperative transmission is analyzed.
2. Proposed algorithms can reduce the payloads of energy-depleting nodes by about 90% in a 2D disc case and increase lifetimes about 10% in general networks, compared with existing scheme techniques.

Future Work mentioned in study S2

No future work is mentioned in the study.

2.5. Analysis of Selected Studies

In this section selected studies are analyzed and our findings are tabulated and summarized and each question was assessed individually against the findings. Tabulated results are also useful to identify current research gaps.

2.5.1 Research Question 1

It states that "Can centralized beamforming technique be used in sensor network, if not what characteristics of the sensor network affect the outcome of centralized beamforming?"

This question comprises two parts. The first relates to the feasibility of centralized beamforming in sensor network. The second part depends upon the answer of first part. The second part investigates the characteristics of the sensor network due top which centralized beamforming can not be applied.

In relevance to this question few studies discussed the requirements of centralized beamforming and characteristics of sensor network. It is shown that centralized beamforming cannot be applied in sensor network. The reason for this is that key requirements for centralized beamforming are frequency, time and phase synchronization. In fixed array of antenna geometry is fixed and single controller is used to transmit the carrier signal. So at the design time position of antenna element and controller is known to each other 100% accurately. It provides the frequency, time and phase synchronization. But in sensor networks, sensor nodes are randomly distributed and position of sensors need to be known accurately [ref modumbi, throkh].

Table 2.9 shows the data synthesized from each study regarding feasibility of beamforming and characteristics of the sensor network affect the outcome of centralized beamforming.

Table 2.9: Models and Techniques used by Small and Medium Web Development Organizations

Sr. No.	Feasibility of centralized beamforming	Factors that affect the outcome of centralized beamforming
S1	No	• Knowledge of position of sensors nodes. • Frequency, phase and delay synchronization.

		• Channel estimation
S2	No	• Knowledge of position of sensors nodes. • Angle of arrival of desired signal • Angle of arrival of interference signal • Frequency, phase and data synchronization
S3	No	• Knowledge of position of sensors nodes. • Frequency, phase and data synchronization. • Path losses, Reflection and scattering
S4	No	• Knowledge of position of sensors nodes. • Frequency, phase and delay synchronization. • Channel estimation
S5	No	• Knowledge of position of sensors nodes. • Frequency, phase and delay synchronization. • Channel estimation
S6	No	• Knowledge of position of sensors nodes. • Frequency, phase and delay synchronization. • Channel estimation
S7	No	• Knowledge of position of sensors nodes. • Frequency, phase and delay synchronization. • Channel estimation
S8	No	• Knowledge of position of sensors nodes. • Frequency, phase and delay synchronization.

2.5.2 Research Question 2

It states that "Which models are proposed for beamforming in sensor network instead of centralized beamforming?"

This question investigates the proposed model for beamforming in sensor network and which factors that affect the outcome of centralized beamforming are addressed in proposed model.

Table 11: Success & Measures of Success of Different Models and Techniques found useful for Small and Medium Web Development Organizations

Sr. No.	Alternate Model	Addressed Factors that affect the outcome of centralized beamforming
S1	Master Slave Architecture is proposed.	• Frequency, time synchronization. • Channel estimation
S2	No model but used adaptive method using LMS by different assumptions.	• None
S3	Characterization of the side-lobes of the antenna pattern gives information about the interference from the distributed array, and directivity is enhanced to get high SNR.	• Path losses, Reflection and scattering
S4	1 bit feed back control from receiver.	• Frequency, time synchronization. • Channel estimation
S5	Feed back control from receiver.	• Frequency, time synchronization. • Channel estimation
S6	Master slave architecture using single transceiver at	• Frequency, time synchronization. • Channel estimation

	slave node.	
S7	Master slave architecture with feed back control.	• Frequency, time synchronization. • Channel estimation
S8	Routing algorithm for life time improvement	• Path loss

2.5.3 Research Question 3

It states that "What is the priority of each characteristics of sensor network for beamforming that affects the outcome of beamforming and its effects on outcome?"

In relevance to this question the influence of parameters are studied and they are prioritized. The prioritization scale is designed to represent the importance of these factors. This prioritization scale with its description is described below.

1. Very critical

   The outcome of model highly depends upon this factor. Substantial degradation accurse if this factor is not addressed.

2. Important

   The outcome of model depends upon this factor. Degradation accurse if this factor is not addressed.

3. Fair

   The outcome of model partially depends upon this factor. Some degradation accurse if this factor is not addressed.

Sr. No.	**Priority of factors**		**Effects on outcome**
	Factor	**Priority**	
S1	Knowledge of position of	Very critical	• Degradation

	sensors nodes.		in received power at receiver • Low SNR
	Frequency, Phase and delay synchronization.	Very critical	
	Channel estimation	Important/Fair	
S2	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Angle of arrival of desired signal	Fair	
	Angle of arrival of interference signal	Fair	
	Frequency, Phase and data synchronization	Very critical	
S3	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Frequency, Phase and data synchronization.	Very critical	
	Path losses, Reflection and scattering	Important/Fair	
S4	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Frequency, Phase and delay synchronization.	Very critical	
	Channel estimation	Important/Fair	
S5	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Frequency, Phase and delay synchronization.	Very critical	
	Channel estimation		
S6	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Frequency, Phase and delay synchronization.	Very critical	
	Channel estimation	Important/Fair	

S7	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Frequency, Phase and delay synchronization.	Very critical	
	Channel estimation	Important/Fair	
S8	Knowledge of position of sensors nodes.	Very critical	• Degradation in received power at receiver • Low SNR
	Frequency, Phase and delay synchronization.	Very critical	

2.6. Research Gaps

The research area is relatively new, therefore the gaps identified are very wide and consequently represent a large research potential.

Energy efficiency is the key requirement in wireless sensor network. Different ways can be used for efficient energy transmission. Multi-Hop algorithms, collaborative communication, cooperative communication, Beamforming and routing algorithm can be used for this purpose. It is evident from the existing literature that the beamforming is possible in sensor network. To get large beamforming gain few important factors need to be considered. From existing literature it is also clear that to get large beamforming gain following factors are very critical.

1. Accurate knowledge of the position of the sensor nodes
2. Time Synchronization
3. Frequency Synchronization
4. Phase Synchronization
5. Channel Estimation

It is also evident that if we combine collaborative communication and beamforming then each of these produce N (No of sensor nodes) gain in received power. If we combine both of these then N^2 gain in received power can be achieved, if and only if the factors discussed above are addressed properly.

From all studies discussed in previous section it is clear that frequency and phase synchronization are the key factors for large gain in received power. S1, S6 and S7 presented Master-Slave architecture for carrier (Frequency) synchronization. Time synchronization is also done in some of studies. Position knowledge is related to localization techniques. From literature survey and the future work mentioned in these studies, it is clear that sophisticated design of phase estimator can improve received power gain. With this complex channel there is degradation in the performance of phase estimator. So this phase estimator should be robust to the channel state. Carrier synchronization can also be performed in addition to phase estimator to get large gains in received power. Coding techniques can also be used to improve the performance and to avoid the interference.

The outcomes of above research gaps would enable the energy efficient communication and improve the life time of the network. Data can be sent over long distances by with the same power using collaborative beamforming.

2.7. Conclusion

From the surveyed literature, it is concluded that distributed beamforming in the sensor network is viable. It is also concluded that phase errors play an important role in distributed beamforming in the sensor network for information transfer. It is observed that the phase error produces significant reduction in received power. The main aim of this research is to develop a digital phase estimator that produces accurate phase information. The accurate phase information will increase the received power at the base station. The results will be analyzed analytically and by simulation. We will also design and simulate other algorithms to analyze the effects of phase error in distributed beamforming.

Chapter 3
Proposed Solution

3. Proposed Solution

A modified master slave architecture is proposed in which master node can be one of any node in the network. Master node transmits the timing signal, carrier signal and data to all the slave nodes. The position of master node and slave nodes are known to each other prior to starting communication. The distance between the master node and slave nodes can be different in a practical scenario. This architecture achieves time, frequency and phase synchronization among the slave nodes and the base station for collaborative communication is also called distributed beamforming. This Collaborative communication gives N gain in the received power, where N is the number of slave nodes. Initially noise and fading in the channel are not considered and ignored. Mathematical and simulated analysis of proposed model is performed and the results are compared. It is shown that analytical and simulated results are compatible and high gain in received power is achieved in presence of displacement errors. It is also concluded that with the carrier frequency of 1GHz, the placement error of 5cm produces 60^0 phase error. 65% of the power gain is achieved in the presence of 60^0 phase error.

3.1. Network Structure

In fixed array antenna structure there is a common network node (controller) that controls the frequency, phase and time synchronization as shown in Figure 1 (a). The distance between the antennas are fixed and accurately known to the network node (central controller). In this case the data sent from each antenna is modulated by common carrier, and sent at the same time, so frequency and time synchronization can be achieved. As the accurate position of antenna is known there is no displacement error or phase error. That achieves phase synchronization. In this case collaborative communication (centralized beamforming) can be applied for information transfer. But in distributed sensor network the accurate position of the sensor nodes cannot be known accurately. There is no central node that performs time and frequency synchronization. To perform collaborative transmission frequency, time and phase synchronization needs to be achieved. To achieve frequency and time synchronization master-slave architecture is proposed [11]. The distributed sensor network structure of N=3 nodes and one base station is shown in Figure 3.1(b).

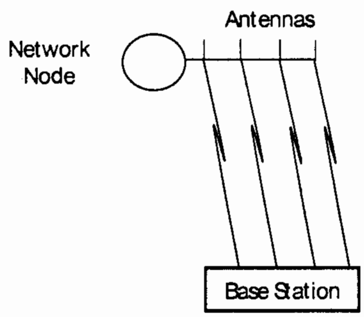

Figure 3.1 (a): Fixed Antenna Array

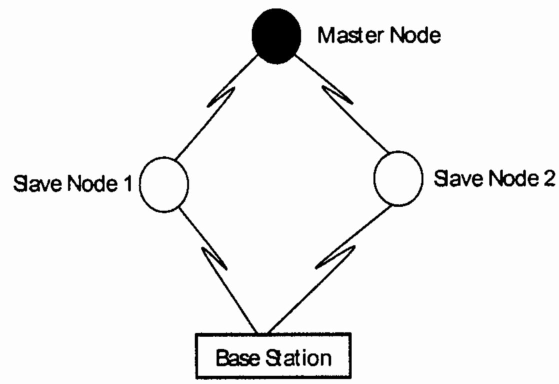

Figure 3.1 (b): Distributed Sensor Network

In this model we have one master node, two slave nodes and one base station. Master node transmits the timing signal, carrier signal and data to both slave nodes (Slave Node 1 and Slave Node 2). This process is performed in two steps. In first step master node transmits the reference signal to both slave nodes. Slave nodes estimate the channel coefficients and adjust their phase and lock themselves with the reference signal sent by master node. In second step master node transmits the data to both slave nodes. Slave nodes modulate the data using carrier signal with some random phase adjustment. This phase adjustment is made by slave nodes on the basis of known distance between master and slave nodes to minimize phase error at base station. Communication between slave nodes and base station is also a two step communication process. In first step a known sequence is sent by slave node to the base station, base station estimates the channel coefficients and the estimated channel coefficients are retuned back to the slave node. In the second step Slave nodes transmit the modulated signal to the base station. Base station receives the modulated signal, demodulates it and detects the data.

3.1.1 Goals

Main goals of the model are:

1. Transmit data from information source to receiver using sensors.
2. Maximize the received power.
3. Appropriate calculation of weights is required to produce beamforming.
4. Phase synchronization is done at the transmitter side instead of receiver side to reduce cost and convergence time.

3.1.2 Assumptions

Following assumptions are considered:

1. Slave nodes and master node know the position of each other.
2. Slave node can adjust the frequency, phase and time delays.
3. Channel coefficients h_{i1}, h_{i2}, h_{i1}^H and h_{i2}^H are zero mean and i.i.d (Statistically identical and independent) random variables.
4. There is no Noise and Interference in channel.
5. Channel parameters are known to all the Nodes and receiver.

3.2 Communication System Model

Communication System model is a six step communication process shown in figure 3.2.

In step 1 channel coefficients h_{i1} are estimated according to master node and slave node at slave node where i =1 to N.

In step 2 estimated channel coefficients h_{i1} computed by slave node in step 1 are sent back to master node and master node updates channel coefficients h_{i1}.

In step 3 channel coefficients h_{i2} between slave node and base station are estimated by base station.

In step 4 estimated channel coefficients h_{i2} by base station in step 3 are sent back to slave node and slave node updates channel coefficients h_{i2}.

In step 5 data is sent from master node to slave nodes. In step 6 slave node transfers the data to base station.

In step 1 master node transmits a modulated known sequence $s(t)$ to the slave node. Received signal $s(t)cos(2\pi f_0 t)$ that is transmitted by the master node becomes $s(t)cos(2\pi f_0 t+\Theta(i))$, (where $\Theta(i)$ is the phase) for i^{th} sensor, where i=1 to N. The phase change is due to the distance between master node and slave nodes. $\Theta(i)= \Theta_0 + \Theta_e(i)$, where Θ_0 is the nominal phase due to nominal distance and $\Theta_e(i)$is the phase error due to the placement error. The slave node's PLL locks itself with this carrier. Output of the PLL is given by:

$$z_i(t) = s(t)\cos(2\pi f_0 t + \Theta_0 + \Theta_e(i) + \Theta_{pll}(i))$$

Where f_0 is the carrier frequency, Θ_0 is the nominal phase, $\Theta_e(i)$ is phase due to displacement error and $\Theta_{pll}(i)$ is the phase changed by PLL and random signal. Slave node demodulates the data received from master node and estimates the channel coefficients h_{i1}.

In step 2 estimated channel coefficients h_{i1} by slave node are modulated and sent back to Master Node. Master node demodulates the channel coefficients h_{i1} and updates its coefficients h_{i1}. These updated coefficients are used in step 5 for communication between master node and the slave node.

In step 3 slave node transmits a modulated known sequence to the base station. Base station multiplies it with the $cos(2\pi f_0 t+ \Theta_0)$, demodulates the modulated signal and estimates the channel coefficients h_{i2}.

In step 4 estimated channel coefficients h_{i2} are modulated by base station and sent back to slave node. Slave node demodulates the channel coefficients and updates its coefficients h_{i2}. These updated coefficients are used in step 6 for communication between slave node and the base station.

In step 5 master node transmits an modulated encoded sequence $q(t)$ to the slave node. Slave node passes it through Phase Lock Loop (PLL) to adjust frequency and phase.

In step 6 slave node multiply the received data from master node with the channel coefficients and transmit it to the base station.

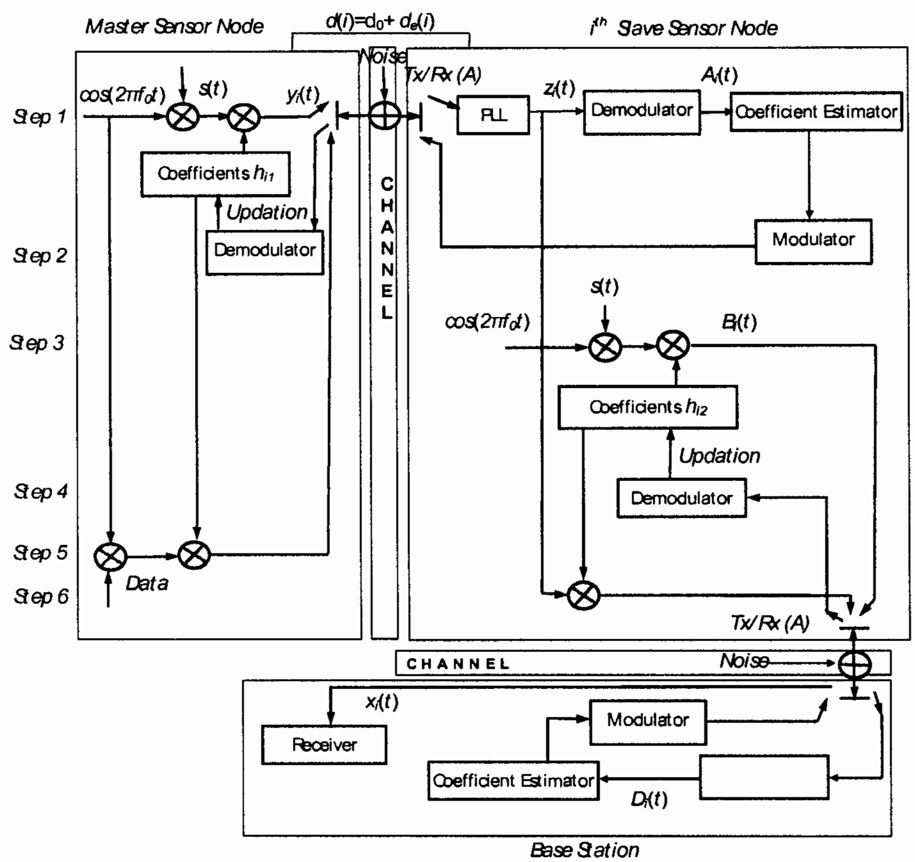

Figure 3.2 : Communication System Model

3.3. Block Diagram Base Station

Block diagram of base station is shown in Figure 3. Base station receive the sum of signals from all sensor nodes $r(t)$. Received signal $r(t)$ is demodulated by base station, passed through low pass filter, integrated and then power is calculated.

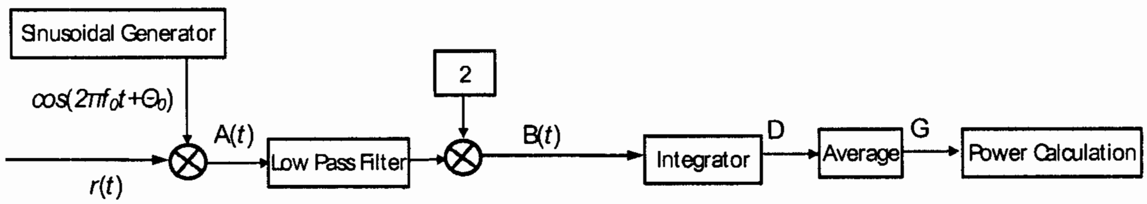

Figure 3.2 : Block Diagram of Base Station

3.4. Mathematical Model

Let N slave nodes make a network to transfer the information from master node to the base station. Let $q(t)$ is the information data transmitted by the master node to all the sensors. The distance between master and sensors can be different. The positions of the master node and slave nodes are known to each other. But the distance between master node and the slave nodes can not be estimated accurately. It results in displacement error and these displacement errors are translated into phase error.

Let d_0 is the nominal distance between master node and the slave node. Let f_0 is the carrier frequency, and assuming line of sight, the phase produced due to distance d_0 can be written as $\Theta_0 = 2\pi f_0 \, d_0/c$, where c is the velocity of light. Let $d_e(i)$ be the displacement error between master node and the slave node then the phase error due to displacement error is given by $\Theta_e(i) = 2\pi f_0 \, d_e(i)/c$. Let $cos(2\pi f_0 t)$ be the carrier or reference signal transmitted by the master node to all the slaves.

Slave node i receives $q(t-\tau_e(i))$, i=1 to N and $\tau_e(i)$ is the delay between master node and slave node and carrier signal is changed to $\cos(2\pi f_0 t+\Theta_0+ \Theta_e(i))$ where Θ_0 is the nominal phase and $\Theta_e(i)$ is the phase error between master sensor and slave sensor due to placement error.

Slave sensor calculates the distance from master sensor and produces the nominal phase Θ_0 and adds a random signal to reduce the phase error and produce reference signal.

Output of the PLL system can be written as

$$z_i(t) = q(t - \tau_e(i))\cos(2\pi f_0 t + \Theta_0 + \Theta_e(i) + \Theta_{pll}(i))$$

Where f_0 is the carrier frequency, Θ_0 is the nominal phase, $\Theta_e(i)$ is phase due to displacement error and $\Theta_{pll}(i)$ is the phase changed by PLL and random signal.

Communication between master node and base station is three steps communication. In first step channel coefficients between master node and slave node are estimated, At start channel coefficients are 1, i.e. h_{i1}=1 where i represents the slave node and i=1 to N.

Received signal by slave node is given by

$$y_i(t) = h_{i1} h_{i1}{}^H s(t - \tau_e(i))\cos(2\pi f_0 t + \Theta_0 + \Theta_e(i)) \quad (1)$$

PLL lock itself with the carrier frequency and phase and produces a signal the output of the PLL is given by

$$z_i(t) = h_{i1} h_{i1}{}^H s(t - \tau_e(i))\cos(2\pi f_0 t + \Theta_0 + \Theta_e(i) + \Theta_{PLL}(i)) \quad (2)$$

Demodulator demodulates the signal by multiplying it with the carrier, passing it through low pass filter and multiplying it by 2.

Out put after multiplying with the carrier is given by

$$z_i(t) = h_{i1} h_{i1}{}^H s(t - \tau_e(i))\cos(2\pi f_0 t + \Theta_0 + \Theta_e(i))\cos(2\pi f_0 t + \Theta_0 + \Theta_e(i) + \Theta_{PLL}(i)) \quad (3)$$

The above equation can also be written as

$$z_i(t) = h_{i1} h_{i1}{}^H s(t - \tau_e(i))[\cos(2(2\pi f_0 t + \Theta_0 + \Theta_e(i)) + \Theta_{PLL}(i)) + \cos(\Theta_{PLL}(i))]/2 \quad (4)$$

After passing through low pass filter the double frequency term vanishes and multiplying with 2, output of demodulator is given by

$$A_i(t) = h_{i1} h_{i1}{}^H s(t - \tau_e(i))\cos(\Theta_{PLL}(i)) \quad (5)$$

As h_{i1}=1 and delay between master node and slave node is very small as compared to the time period and $\Theta_{PLL}(i)$ is very small, coefficients estimator estimates the channel coefficients.

In step 2 slave node modulates the channel coefficients and transmits to master node. Master node demodulates the channel coefficients and it updates its coefficients and these updated coefficients are used in step 5 for communication between master node and slave node.

In step 3 channel coefficients between slave node and base station are estimated, at start channel coefficients are 1, i.e. h_{i2}=1.

Received signal by base station is given by

$$B_i(t) = h_{i2} h_{i2}^H s(t) \cos(2\pi f_0 t + \Theta_0) \quad (6)$$

This signal is demodulated by the demodulator by multiplying it with the carrier, passing it through low pass filter and multiplying it by 2, as explained below.

The out put after multiplying with the carrier is give by

$$I(i) = h_{i2} h_{i2}^H s(t) \cos(2\pi f_0 t + \Theta_0) \cos(2\pi f_0 t + \Theta_0) \quad (7)$$

The above equation can also be written as

$$I(i) = h_{i2} h_{i2}^H s(t)[1 + \cos(2(2\pi f_0 t + \Theta_0))]/2 \quad (8)$$

After passing through low pass filter and multiplying with 2, output of demodulator is given by

$$D_i(t) = h_{i2} h_{i2}^H s(t) \quad (9)$$

As h_{i2}=1, coefficients estimator estimates the channel coefficients.

In step 4 base station modulates the channel coefficients and sends to slave node. Slave node's coefficients are updated and these updated coefficients are used in step 6 for communication between slave node and the base station.

In step 5 master node modulates the data $q(t)$ and this modulated signal is sent to slave nodes, slave nodes then pass the signal through PLL to lock itself with the frequency and phase.

In step 6 output of PLL is multiplied with channel coefficients h_{i2} and it is transmitted to the base station. Received signal at base station from slave node i, (i=1 to N) is given by

$$x_i(t) = h_{i2} h_{i2}^H q(t - \tau_e(i)) \cos(2\pi f_0 t + \Theta_0 + \Theta_e(i) + \Theta_{pll}(i)) \quad (10)$$

$$x_i(t) = h_{i2} h_{i2}^H q(t - \tau_e(i)) \mathrm{Re}[e^{j(2\pi f_0 t + \Theta_0 + \Theta_e(i) + \Theta_{pll}(i))}] \quad (11)$$

$$x_i(t) = h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t - \tau_e(i)) \mathrm{Re}[e^{j(2\pi f_0 t + \Theta_0)}] \quad (12)$$

With our assumptions that delay effect is very small as compared to phase error and can be ignored. The phase error due to displacement error creates problem to demodulate the signal and reduce the signal power at the base station side. So equation (12) becomes

$$x_i(t) = h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t) \mathrm{Re}[e^{j(2\pi f_0 t + \Theta_0)}] \quad (13)$$

The received signal by the base station is the sum of all the signals from the slave sensors and is given by.

$$r(t) = \sum_{i=1}^{N} x_i(t) \quad (14)$$

$$r(t) = \sum_{i=1}^{N} h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t) \mathrm{Re}[e^{j(2\pi f_0 t + \Theta_0)}] \quad (15)$$

The base station multiply the $r(t)$ with $\mathrm{Re}[e^{-j(2\pi f_0 t + \Theta_0)}]$ to demodulate the received signal. The output after multiplying is given by

$$A(t) = \mathrm{Re}[e^{-j(2\pi f_0 t + \Theta_0)}] \sum_{i=1}^{N} h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t) \mathrm{Re}[e^{j(2\pi f_0 t + \Theta_0)}] \quad (16)$$

$$A(t) = \sum_{i=1}^{N} [h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t)] \cos(2\pi f_0 t + \Theta_0) \cos(2\pi f_0 t + \Theta_0) \quad (17)$$

$$A(t) = \sum_{i=1}^{N} [h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t)] \cos^2(2\pi f_0 t + \Theta_0) \quad (18)$$

$$A(t) = \sum_{i=1}^{N} [h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t)] [1 + \cos 2(2\pi f_0 t + \Theta_0)] / 2 \quad (19)$$

$$A(t) = \sum_{i=1}^{N} [h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t) / 2] + \sum_{i=1}^{N} [h_{i2} h_{i2}^H \mathrm{Re}[e^{j(\Theta_e(i) + \Theta_{pll}(i))}] q(t) \cos 2(2\pi f_0 t + \Theta_0) / 2] \quad (20)$$

$A(t)$ is passed through low pass filter to eliminate the high frequency terms and multiplied by 2 to eliminate the low pass effect on magnitude of signal. The output of multiplier is given by

$$B(t) = \sum_{i=1}^{N}[h_{i2} h_{i2}^{H} \mathrm{Re}[e^{j(\Theta_e(i)+\Theta_{pll}(i))}]q(t)] \quad (21)$$

This out put is passed through the integrator and out put of the integrator is given by

$$D = \int_T q(t) \sum_{i=1}^{N} h_{i2} h_{i2}^{H} \mathrm{Re}[e^{j(\Theta_e(i)+\Theta_{pll}(i))}]dt \quad (22)$$

$$D = \sum_{i=1}^{N} h_{i2} h_{i2}^{H} \mathrm{Re}[e^{j(\Theta_e(i)+\Theta_{pll}(i))}]\int_T q(t)dt \quad (23)$$

D is random signal because it depends upon random variables Θ_{pll}, $\Theta_e(i)$, h_{i2} and h_{i2}^H so its average value is calculated and the output of average value calculator is given by

$$G = E[\sum_{i=1}^{N} h_{i2} h_{i2}^{H} \mathrm{Re}[e^{j(\Theta_e(i)+\Theta_{pll}(i))}]]\int_T q(t)dt \quad (24)$$

$$G = \sum_{i=1}^{N} E[h_{i2} h_{i2}^{H} \mathrm{Re}[e^{j(\Theta_e(i)+\Theta_{pll}(i))}]]\int_T q(t)dt \quad (25)$$

Degradation factor in the above equation is $E[h_{i2}h_{i2}^H \mathrm{Re}[e^{j(\Theta e(i)+\Theta pll(i))}]]$. If the Θ_{pll}, $\Theta_e(i)$, h_{i1} and h_{i2}^H is calculated in such a way that $E[h_{i2}h_{i2}^H \mathrm{Re}[e^{j(\Theta e(i)+\Theta pll(i))}]]=1$, then we can get maximum power at the base station.

Chapter 4
Analysis & Simulation

4.1. Analysis

Now we determine how placement errors, which translate into phase errors, affect the gains achieved by distributed transmit beamforming. Θ_{pll} and $\Theta_e(i)$ are random so we calculate the average received power (E[P_R]), where P_R denote the received signal power. When the transmit power is kept constant and array N is the number of slave sensors, we find that:

(a) The expected value of P_R increases as μN, where μ is function of the phase error distribution and $0 \leq \mu \leq 1$.

When there is no phase error, E[P_R] = N, meaning that beamforming with N elements gives a power gain of N over transmission with a single element. Thus, the degradation caused by phase errors is contained in the term μ.

(b) The variance of P_R also increases linearly with N, for both zero and nonzero phase errors. Of course, the existence of phase errors can only increase the variance over that of an ideal, error free system. Thus, as long as the distribution of placement errors is contained in such a way as to keep μ close to 1, large gains can be still be realized using distributed beamforming.

From equation (25) it is analyzed that received power depends upon factor

$$E[h_{i2}h_{i2}^H \operatorname{Re}[e^{j(\Theta e(i)+ \Theta pll(i))}]].$$

Let the total transmitted power by all the sensors P_T=1, so power transmitted by each sensor is 1/N then

$$E[P_R] = \frac{1}{N}\left\| \sum_{i=1}^{N} E[h_{i2}h_{i2}{}^H e^{j(\Theta_e(i)+\Theta_{pll}(i))}] \right\|^2 \quad (26)$$

Let $\Theta_f(i)$=$\Theta_e(i)$+ $\Theta_{pll}(i)$, then above equation becomes

$$E[P_R] = \frac{1}{N}\left\| \sum_{i=1}^{N} E[h_{i2}h_{i2}{}^H e^{j(\Theta_f(i))}] \right\|^2 \quad (27)$$

Here we discuss some propositions that will be used later to find analytical results

Proposition 1:

For finite N, and small Θ_f

$$E[P_R] = 1 + (N-1)(E[Cos(\Theta_f)]^2)$$

Proof:

$$E[P_R] = \frac{1}{N}\left\|\sum_{1}^{N} E[\|h_{i2}\|^2 e^{j2\Theta_f(i)}\right\|^2] = \frac{1}{N}\sum_{i=1}^{N} E[\|h_{i2}\|^2 e^{j2\Theta_f(i)} \sum_{l=1}^{N}\|h_{i2}\|^2 e^{-j2\Theta_f(l)}]$$

$$\frac{1}{N}E\left[\sum_{i=1}^{N}\|h_{i2}\|^2 e^{j2\Theta_f(i)} \sum_{l=1}^{N}\|h_{i2}\|^2 e^{j2\Theta_f(l)}\right] = \frac{1}{N}E\left[\sum_{l=1}^{N}\sum_{i=1}^{N}\|h_{i2}\|^2 e^{j2\Theta_f(i)}\|h_{i2}\|^2 e^{-j2\Theta_f(l)}\right]$$

as h_{i2} and $\Theta_f(i)$are i.i.d, we have two cases when i and l are equal and when they are not equal. When they are equal then it will give 1 and sum over interval N it will produce N and when not equal it can be reduced to.

$$\frac{1}{N}E\left[\sum_{l=1}^{N}\sum_{i=1}^{N}\|h_{i2}\|^2 e^{j2\Theta_f(i)}\|h_{i2}\|^2 e^{j2\Theta_f(l)}\right] = \frac{1}{N}[N + \frac{N(N-1)}{2}(2E[Cos\Theta_f(1) - Cos(\Theta_f(2)])\ )$$

where 1 and 2 are symbol used for different timing. Apply the trigonometric identity for the last term above expression will reduce to.

$$E[P_R] = 1 + (N-1)(E[Cos(\Theta_f)]^2) \tag{28}$$

In the absence of phase errors, Proposition 1 gives that E[P_R] = N, Using approximation cos(Θ)=1- Θ^2/2, equation (28) becomes

$$E[P_R] = 1 + (N-1)(1 - \frac{(\pi\Theta_f)^2}{2})]^2) \tag{29}$$

Note: Equation (29) is used to find the analytical results and these results are compared with the simulation results obtained from equation (25)

4.2. Simulation Model

Equation (29) shows that received power depends upon N (the number of sensors) and phase error. Phase error is random so we can take its expectation power. To simulate the mathematical model we run simulation model 60 times for four different phase errors. The pseudo code to get the average power is given below.

```
1. Begin
2. No_of_smaple=60
3. N=4
4. Displacement_error=.1;
5. temp=1;
6. for iN=2 to N
7.          for error_count=1 to 4
8.                 Displacement_error =.1*error_count;
9.                    for i=1 to No_of_samples
10.                       call simulink_block
11.                              for j=2 to N
12.                                     create slave_block
13.                                     j=j+1
14.                              end for
15.                       power_rec(temp,i)=call cal_power
16.                       i=i+1
17.                  end for
18.              error_count= error_count+1
19.         end for
20. end for
21. save resultn4 power_rec
22. Exit
```

The simulation model to simulate the mathematical model presented ***in section 4.1 is*** given in **Figure 4.1**. This simulation block is created in each iteration as shown in step 10 of pseudo code. For each simulation block the number of slave nodes is created as shown in step 12 of pseudo code.

Simulation model shown in Figure 4.1 is for 4 sensors (slave sensors). To produce the displacement errors individual sinusoidal generator are used. Each sinusoidal generator generates sinusoidal wave of 100 MHz frequency. One slave node comprises PLL System, Gain and Product represent. Master node sends the data to all slave nodes and slave nodes transmit the same data to base station. The modulated signals from all the sensors are added at base station. Base station demodulates the signals to get the data. The base station is shown in Figure 4.1.

We do not perform any phase synchronization at base station and use sine wave for demodulation.

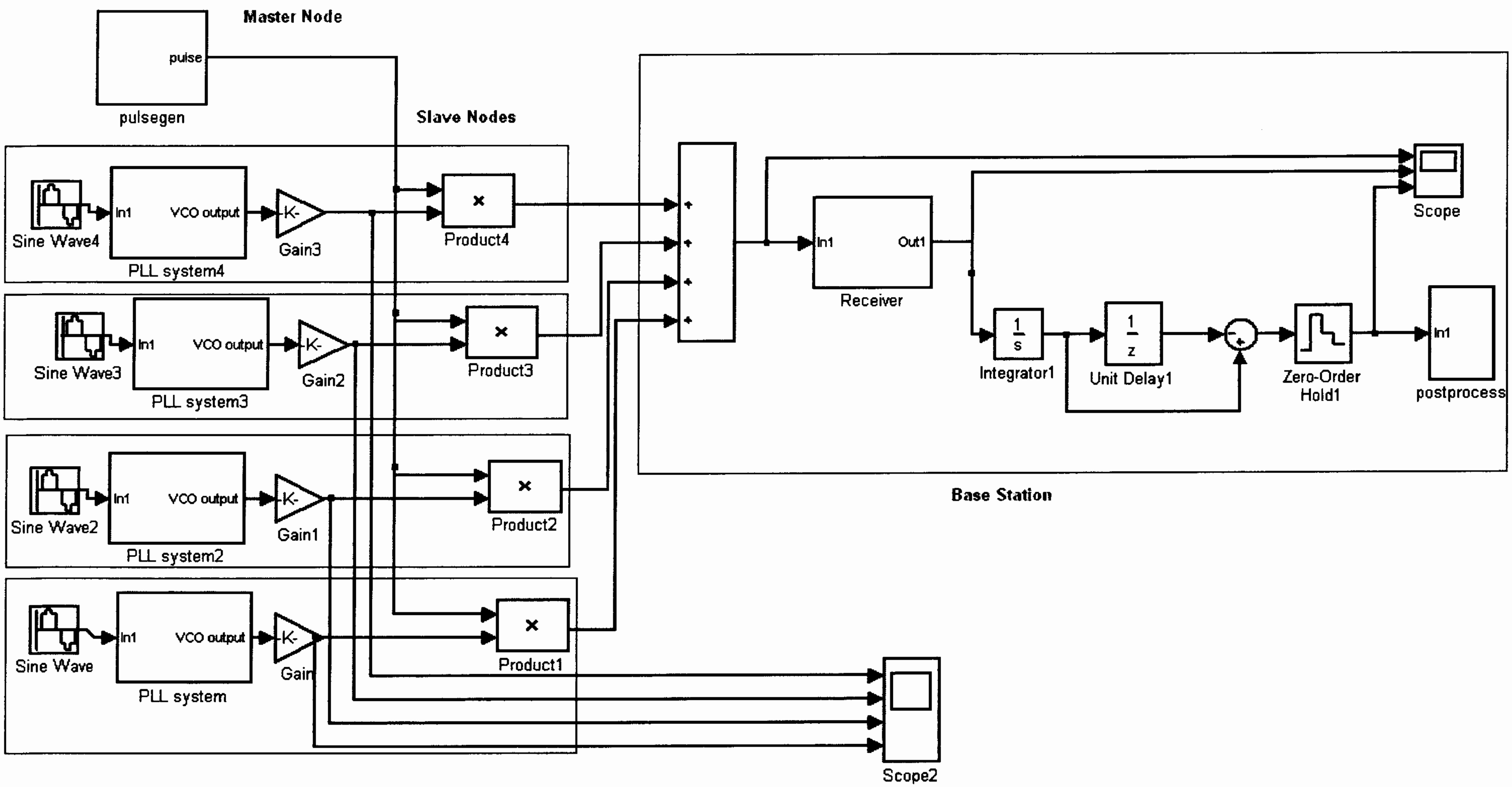

Figure 4.1: Detailed Simulation Block

The PLL systems shown in Figure 4.1 receive the sinusoidal signal. It adds a random signal to adjust the phase errors due to placement error. Phase Lock Loop receives the signal and produces the sinusoidal that is used to modulate the information data. Detailed PLL system is shown in Figure 4.2.

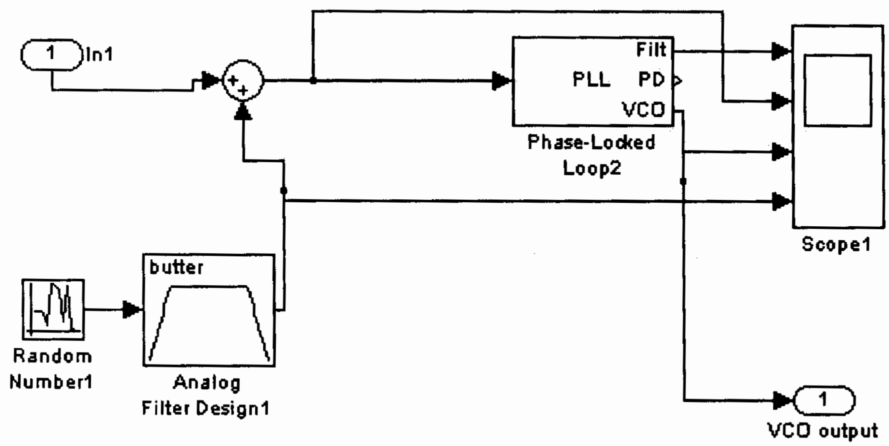

Figure 4.2: PLL System Simulation Model

Receiver is shown in Figure 4.3 and Figure 4.4 Receiver demodulates the received signal, Pass it from low pass filter and then integrates the signal and power of the signal is calculated. The power calculation is done by post process that is shown in Figure 4.4.

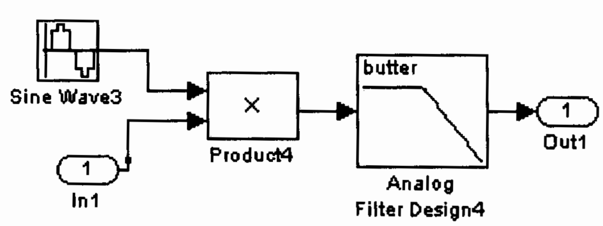

Figure 4.3.: Receiver Simulation Model

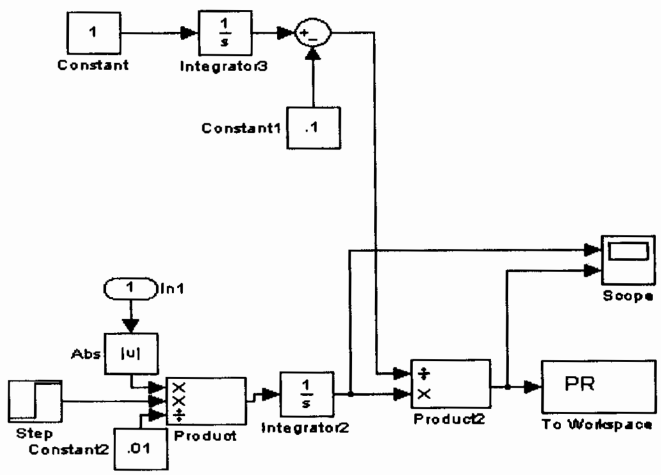

Figure 4.4: Post Process Simulation Model

4.3. Results

4.3.1. Beamforming out puts

Following four different filters were implemented for beamforming:

1. Match filter
2. Minimum Variance Distortionless Response
3. Minimum Power Distortionless Response
4. Minimum Mean Square Estimation.

These filters were simulated in four different ways

1. In absence of Noise and interference
2. In presence of AWGN
3. In presence of interference
4. In presence of both AWGN and Interference

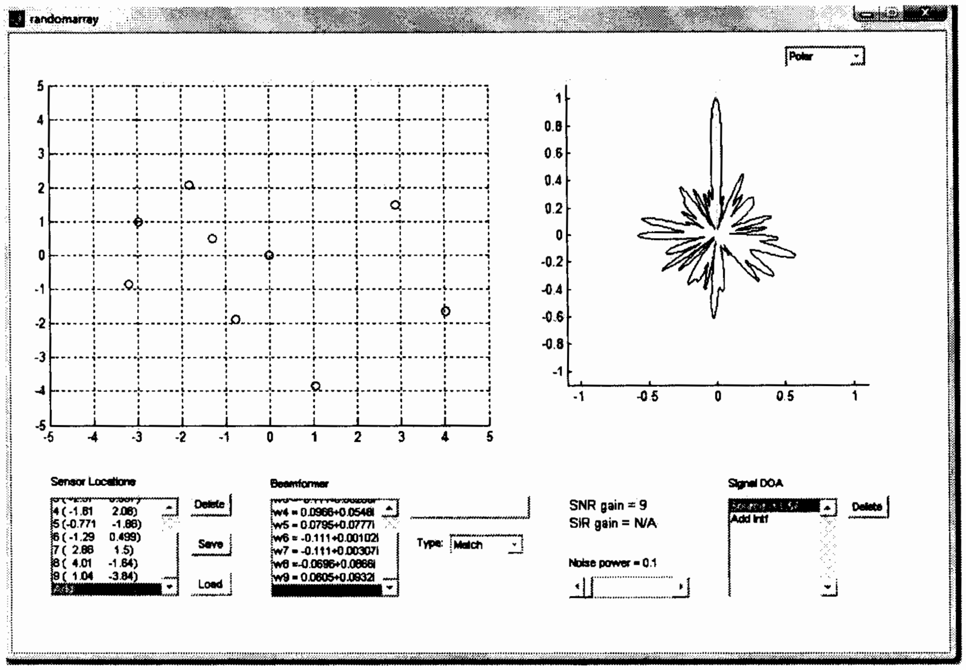

Figure 4.5: Match Filter output without noise and interference

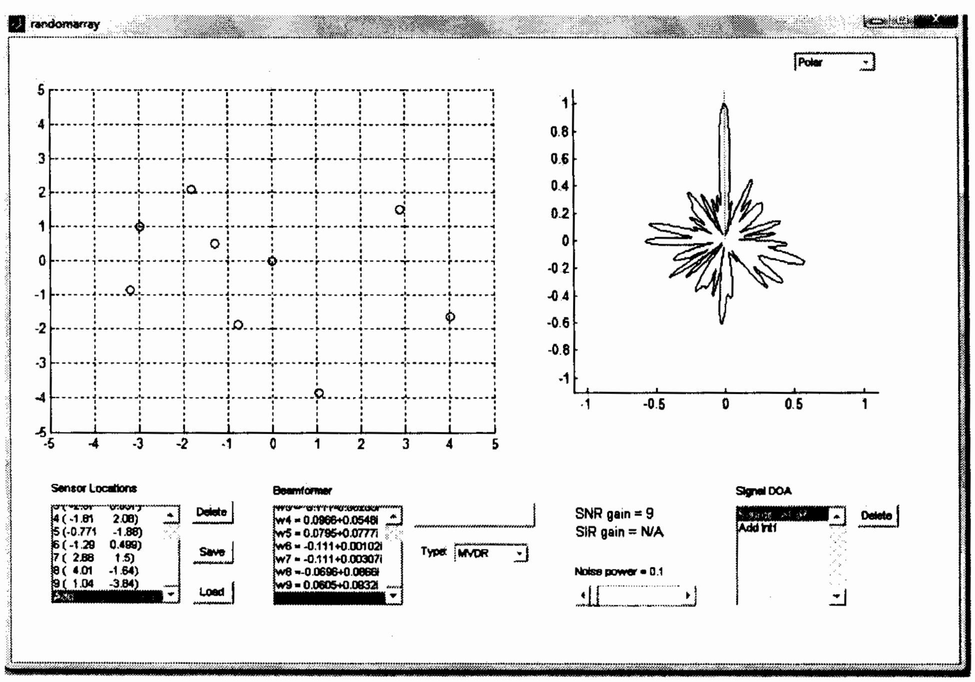

Figure 4.6: MVDR Filter output without noise and interference

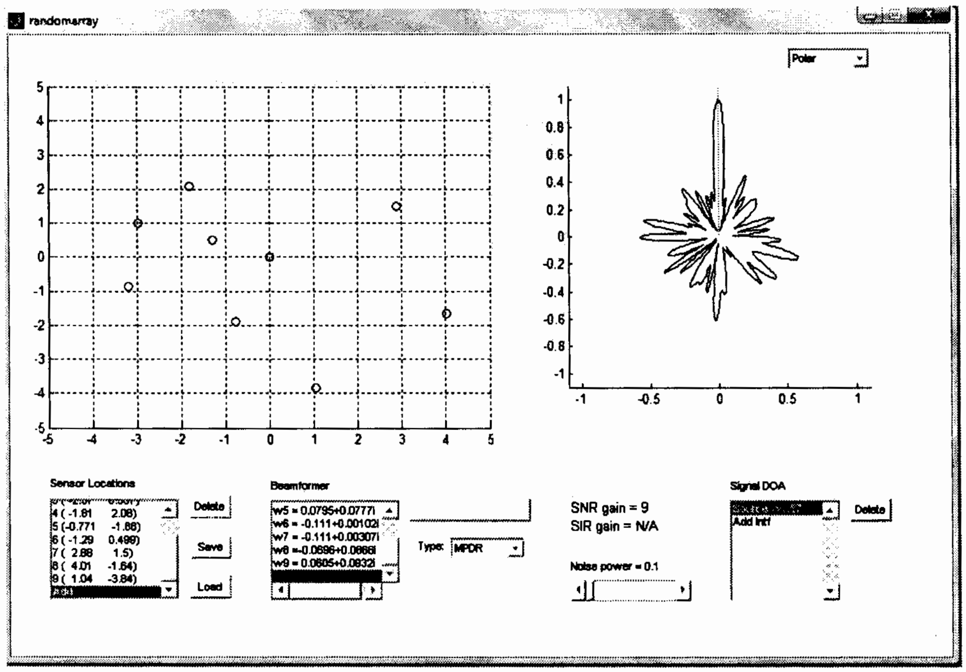

Figure 4.7: MPDR Filter output without noise and interference

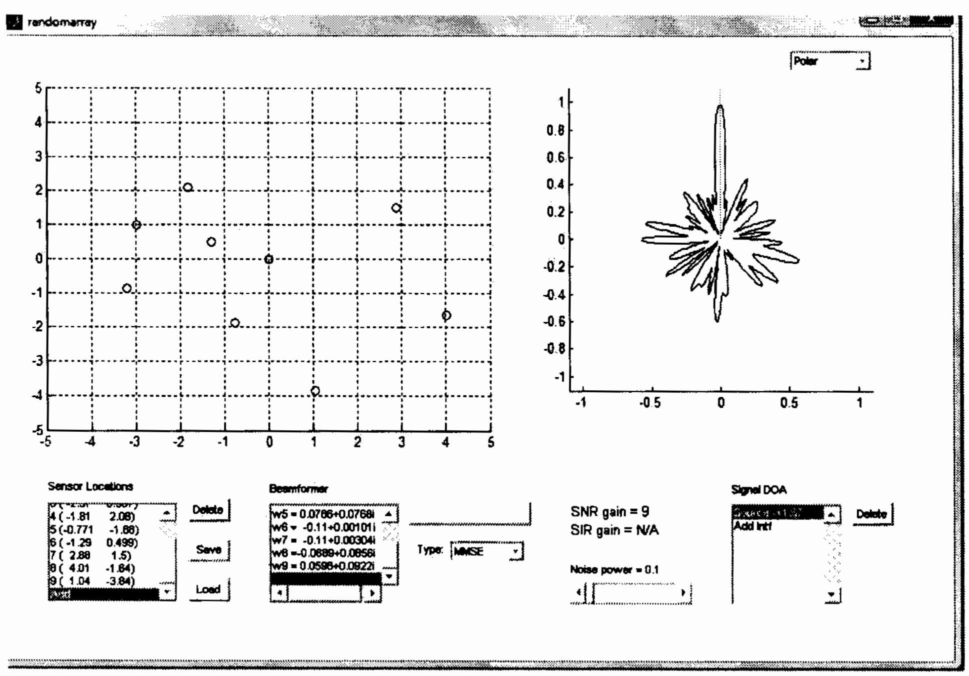

Figure 4.8: MMSE Filter output without noise and interference

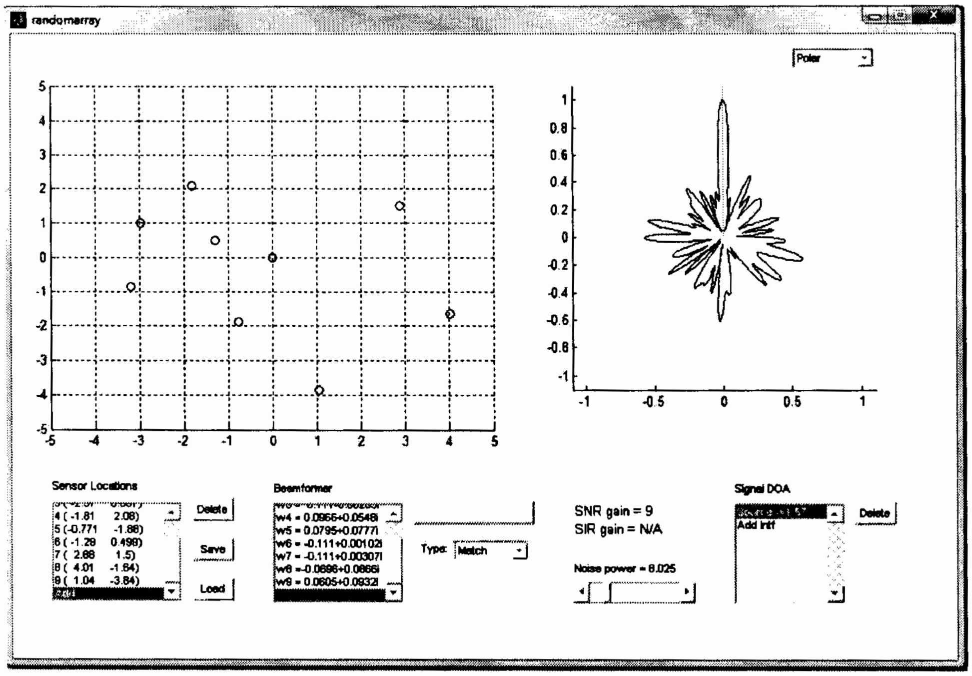

Figure 4.9: Match Filter output with noise

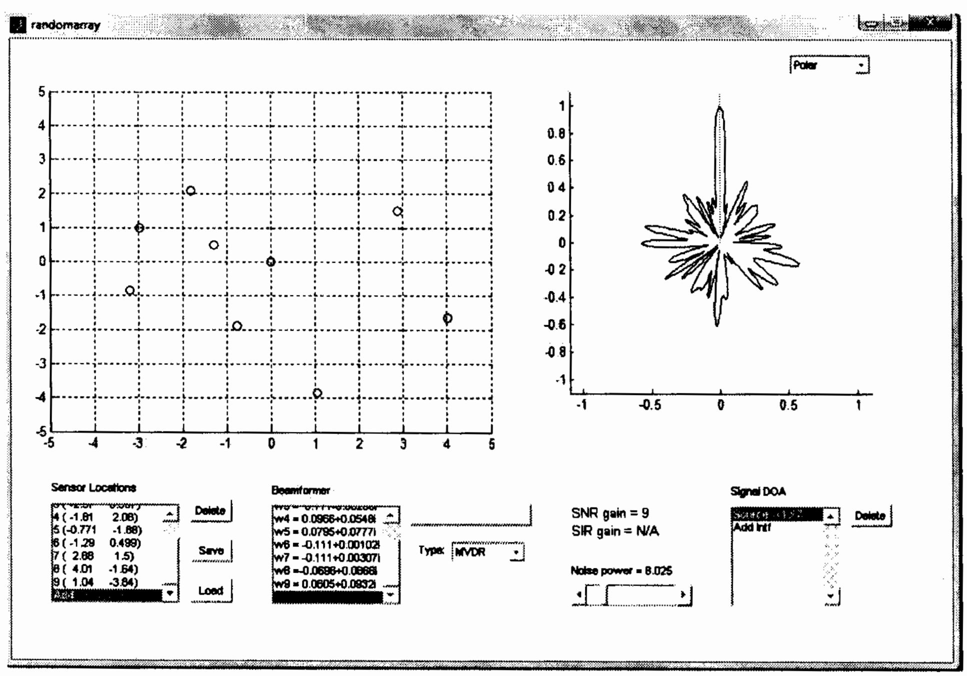

Figure 4.10: MVDR Filter output with noise

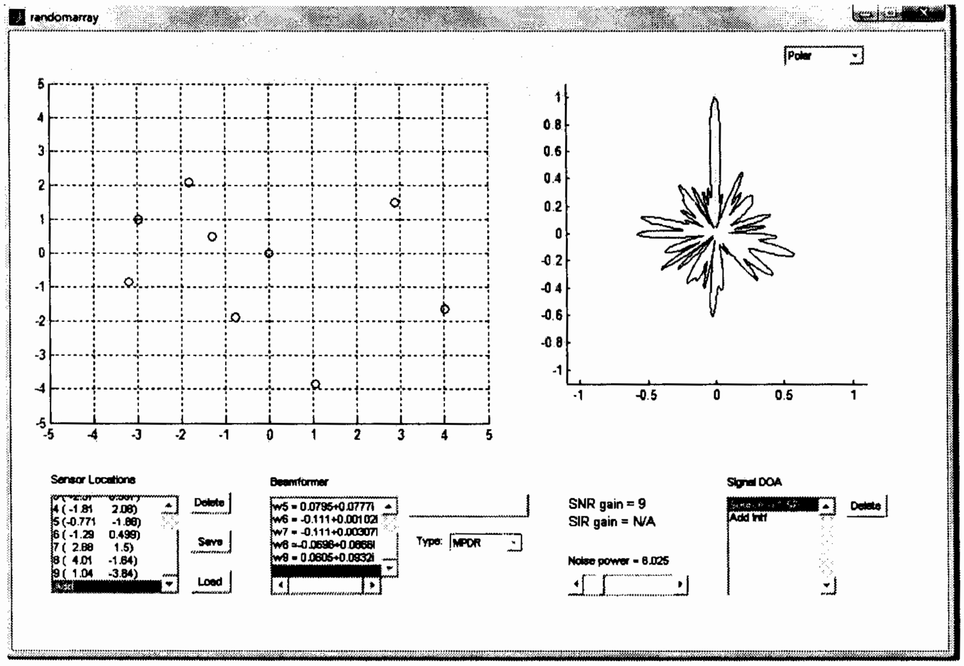

Figure 4.11: MPDR Filter output with noise

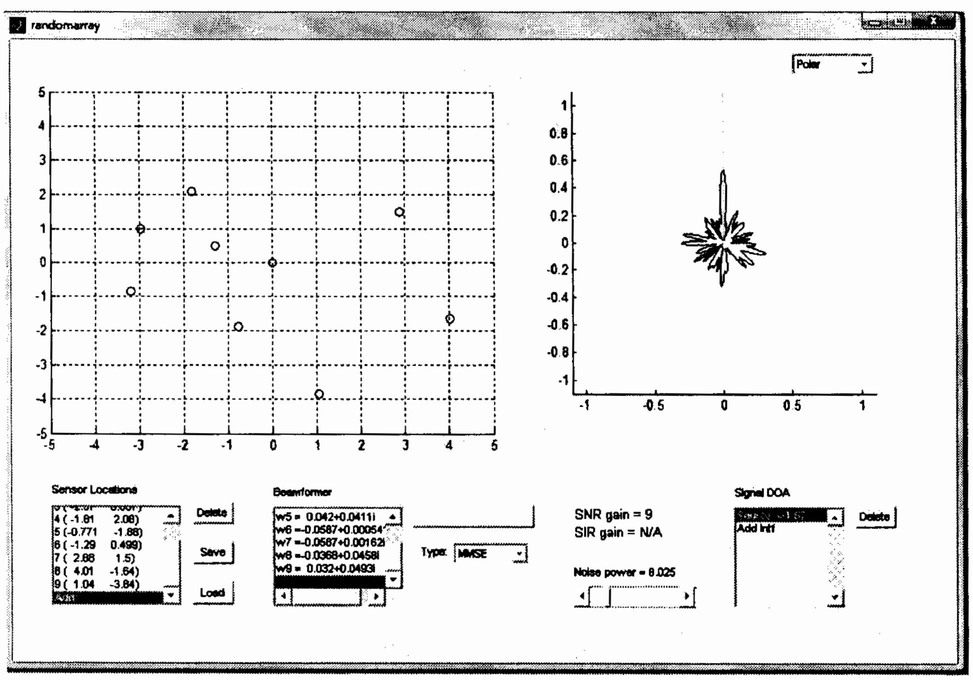

Figure 4.12: MMSE Filter output with noise

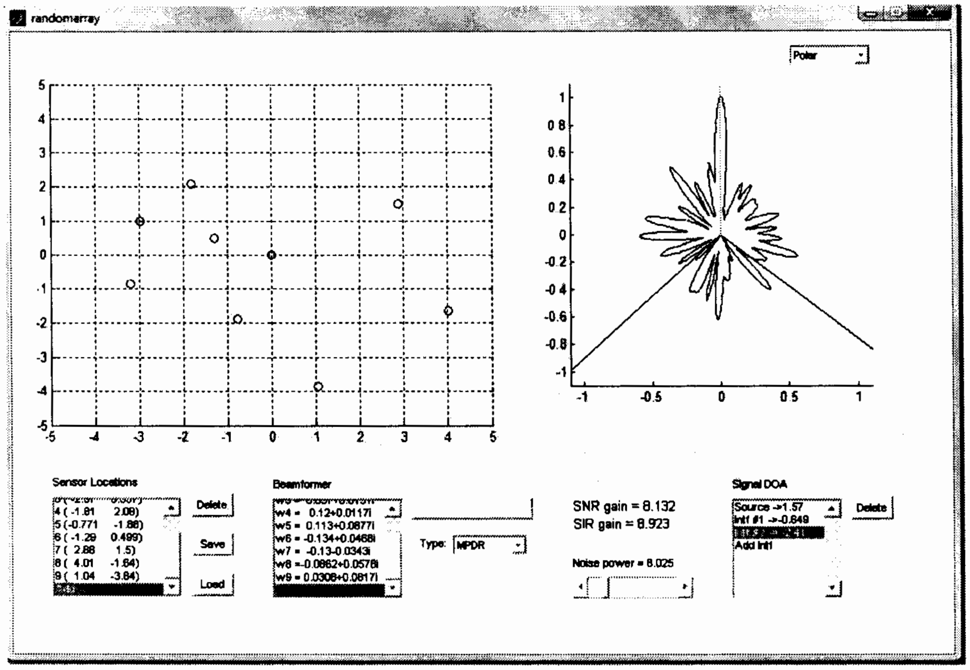

Figure 4.15: MPDR Filter output with Interference

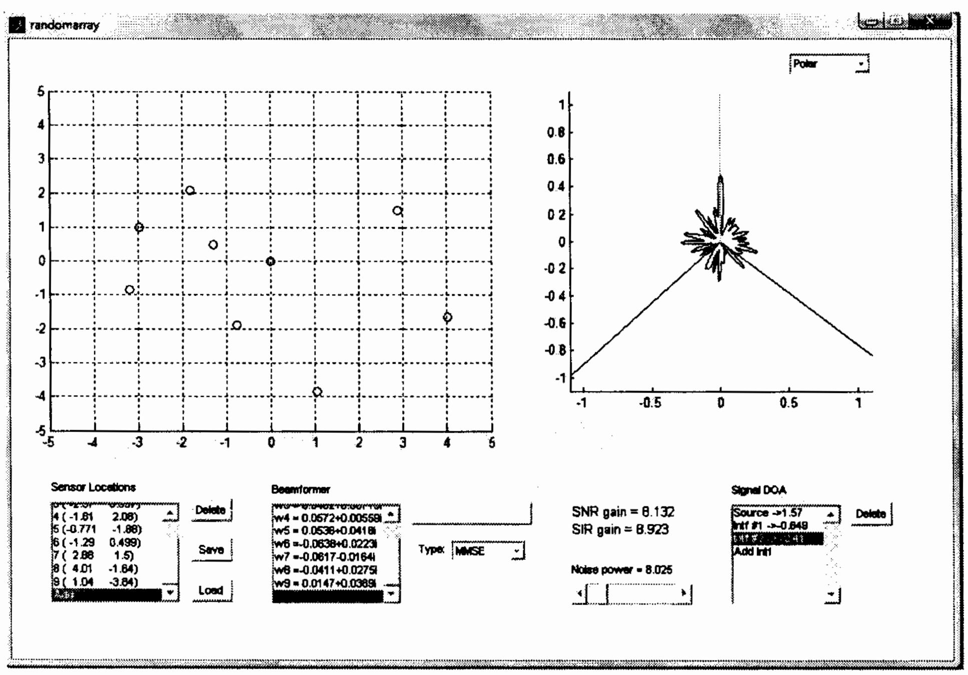

Figure 4.16: MMSE Filter output with Interference

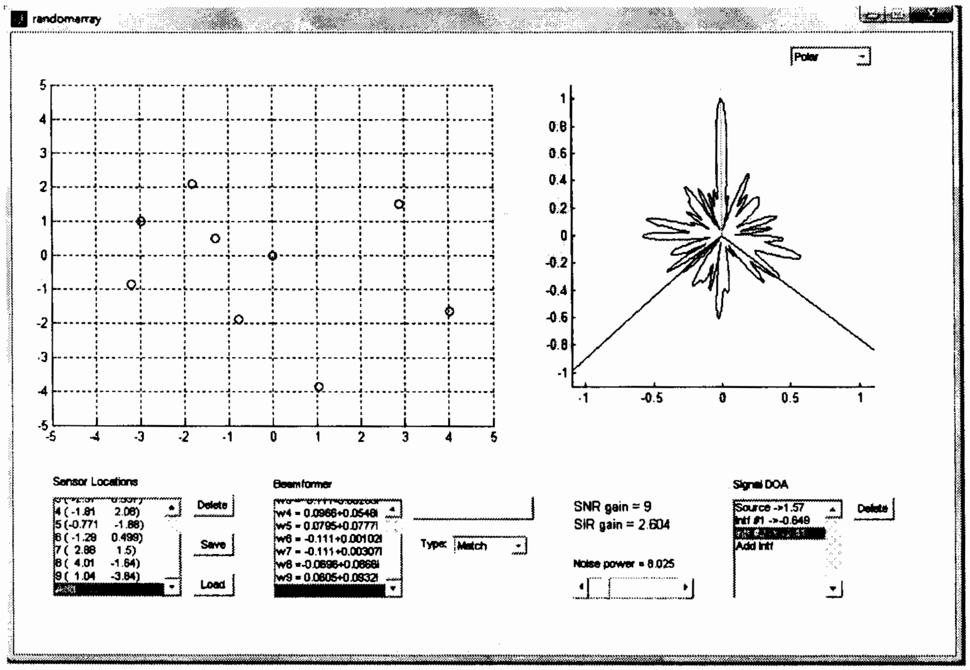

Figure 4.13: Match Filter output with Interference

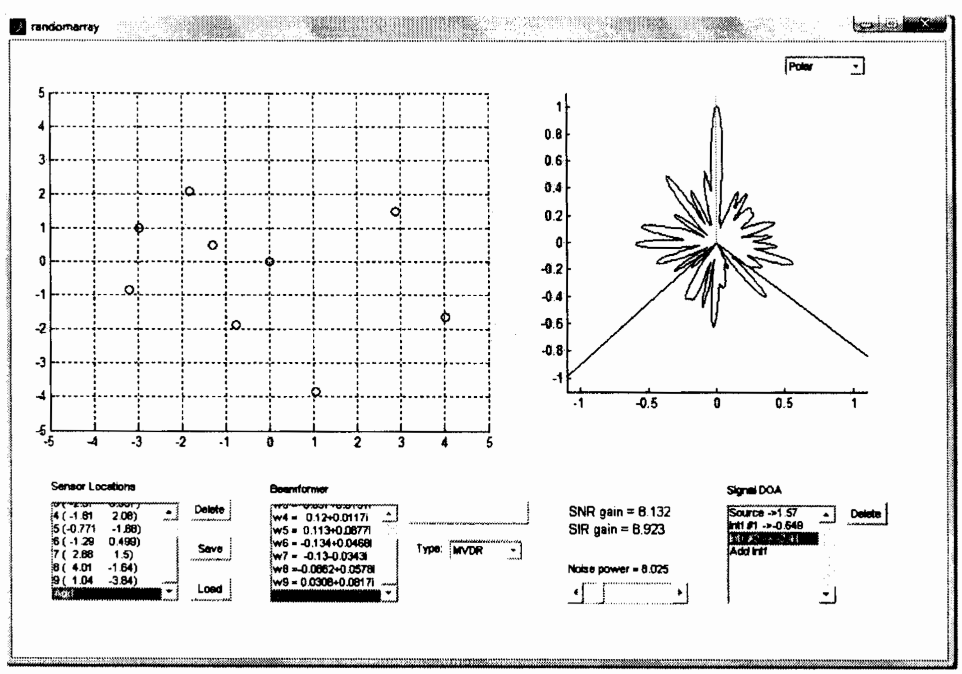

Figure 4.14: MVDR Filter output with Interference

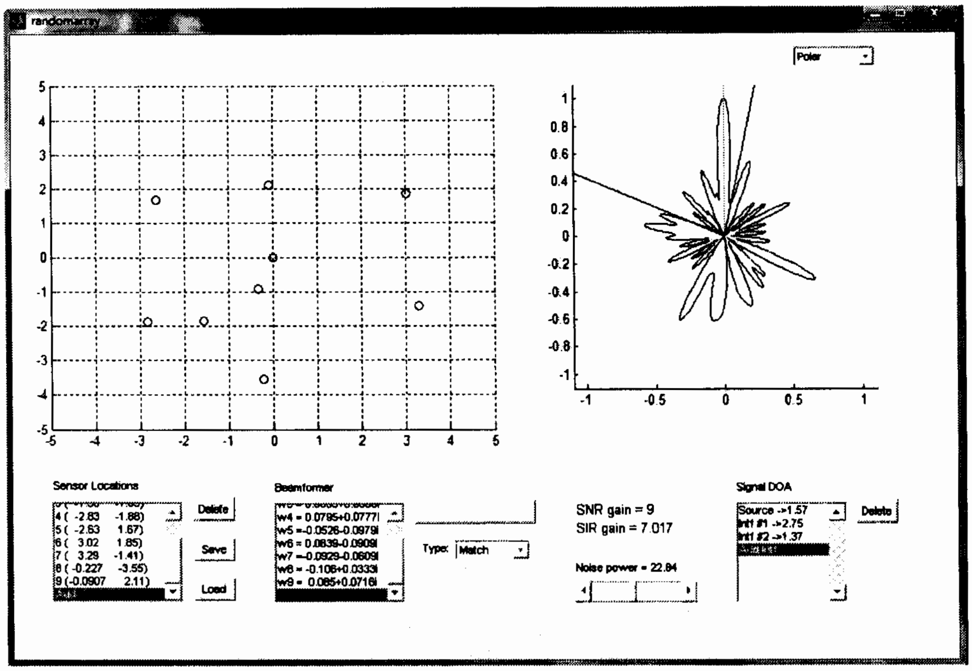

Figure 4.17: Match Filter output with Interference & Noise

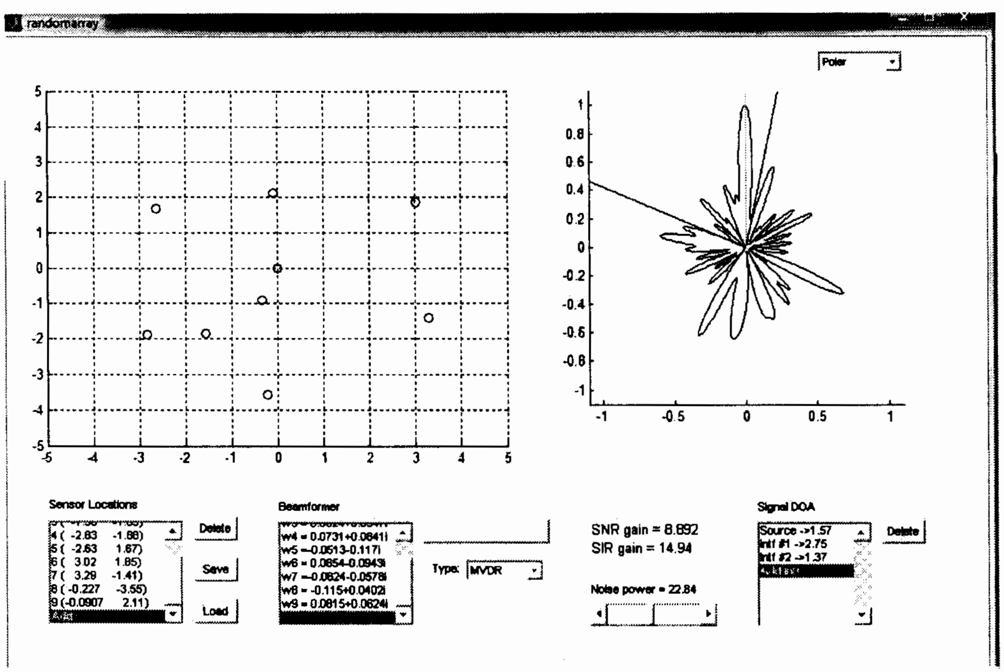

Figure 4.18: MVDR Filter output with Interference & Noise

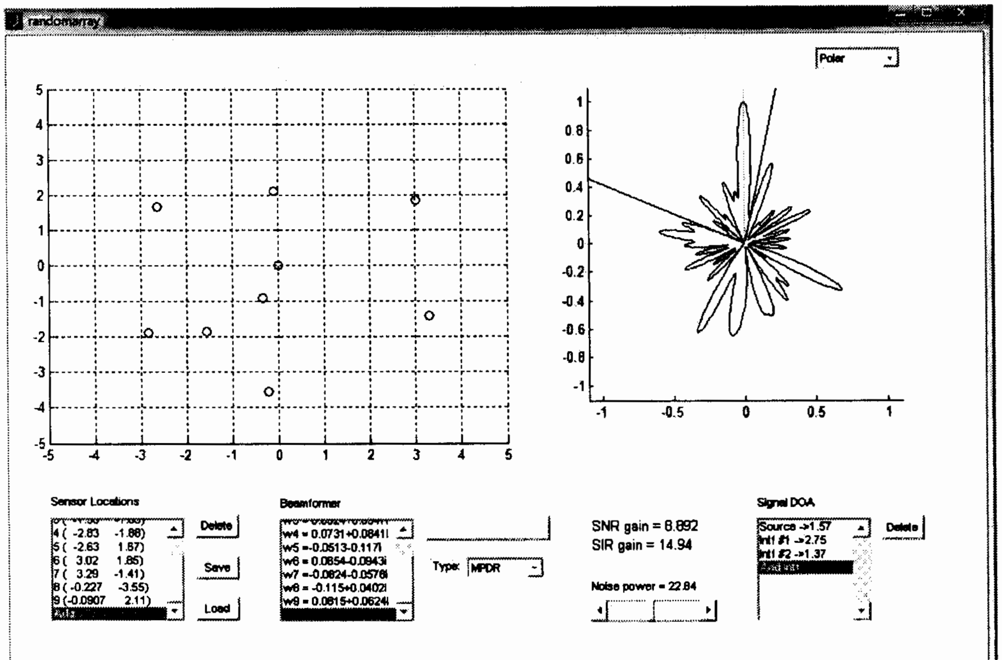

Figure 4.19: MPDR Filter output with Interference & Noise

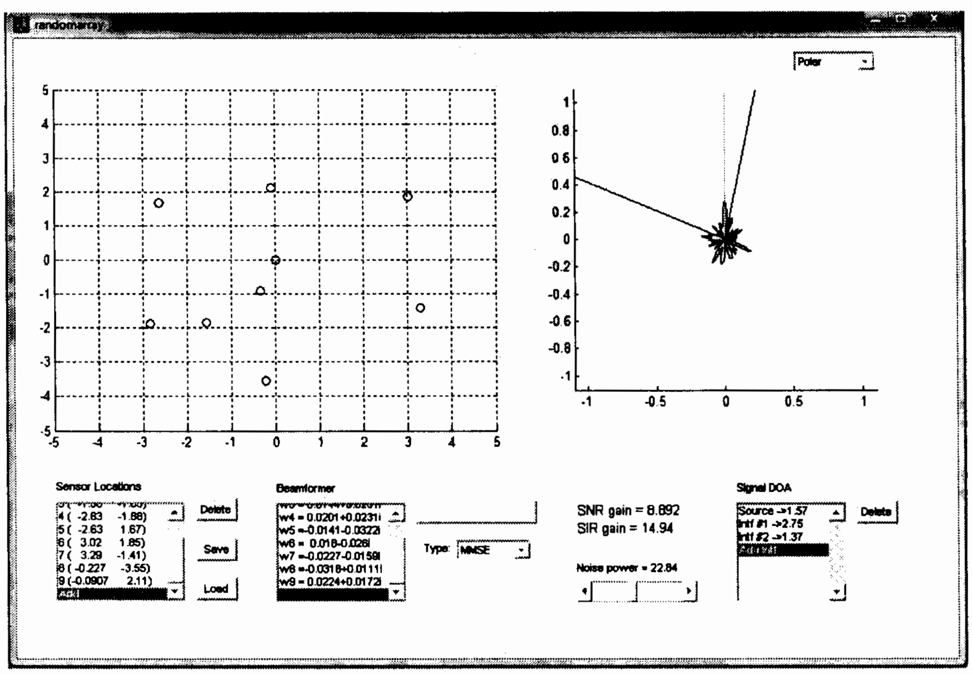

Figure 4.20: MMSE Filter output with Interference & Noise

From above results it is analyzed that if the interference is not towards the direction of interest then it does not affect the Beam power, Noise effect the signal to some extent in case of the MMSE filter. Even small variation due to noise is amplified due to square effect.

The model discussed above is simulated in MATLAB. The analytical results from equation (29) are also analyzed and are normalized to unit power are compared with the simulated results for different values of Phase errors and are shown in Figure 4.5. It is clear that simulation results match with the analytical results.

Equation (29) shows that received power depends upon the N (Number of sensors) and phase error. Different phase errors e.g. 0.1, 0.2, 0.3 and 0.4 radians are analysed also analysis of the relationship between phase error and displacement error is performed.

Let $d_e(i)$ is the displacement error between master node and the slave node then the phase error due to displacement error is given by $\Theta_e(i)= 2\pi f_0\, d_e(i)/c$

For phase error 0.1 radian= 5.73^0, frequency 100 MHz, C=3*10^8, Displacement error $d_e(i)$=0.047 meters=4.70 cm.

For phase error 0.2 radian = 11.64^0, frequency 100 MHz, C=3*10^8, Displacement error $d_e(i)$=0.095 meters=9.50 cm.

For phase error 0.3 radian= 17.19^0, frequency 100 MHz, C=3*10^8, Displacement error $d_e(i)$=0.141 meters=14.10 cm.

For phase error 0.4 radian= 23.28^0, frequency 100 MHz, C=3*10^8, Displacement error $d_e(i)$=0.190 meters=19.0 cm.

Figure 4.5 shows that unit received power reduces slightly as the number of sensors are increased and unit received power reduces as phase error increases. It is also analyzed that 65% power can be received in the presence of displacement error of 19cm. it is also clear that frequency and displacement error tolerance are inversely proportional to each other.

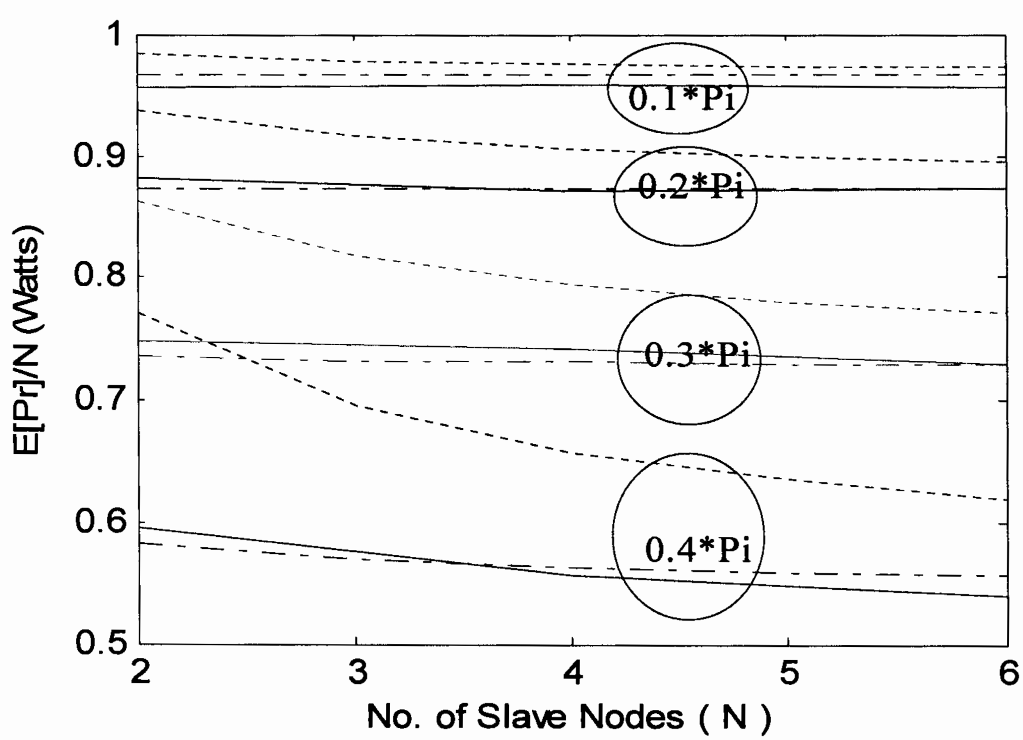

Figure 4.17: Simulated and Analytical Results for unit Received power for phase errors 0.1, 0.2, 0.3, and 0.4 radians

Figure 4.17 shows the unit received power and Figure 4.18 shows the total received power (Watts) at the base station when each slave node has power 1 Watt for different values of the phase error. Figure 4.18 shows that received power increases as the number of sensors are increased and received power reduces as phase error increases.

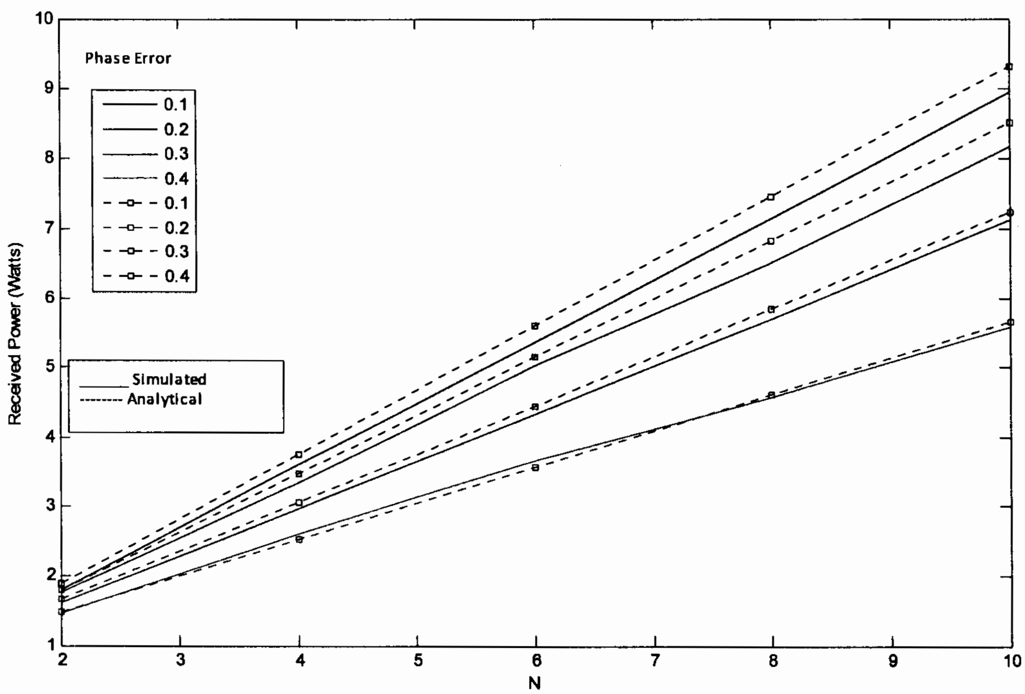

Figure 4.18: Simulated Results for average received power for phase errors 0.1, 0.2, 0.3 and 0.4

Chapter 5
Conclusion

5.1 Conclusion

From the surveyed literature, it is concluded that distributed beamforming in the sensor network is possible. It is also concluded that phase errors play an important role in distributed beamforming in the sensor network for information transfer. It is observed that the phase error produces significant reduction in received power. The main aim of this research was to develop a digital phase estimator that produces accurate phase information in the presence of noise and interference. The accurate phase information will increase the received power at the base station. It is also observed that as number of slave nodes increases the received power increases. So received power is a function of N, where N is the number of slave nodes, increased number of slave nodes leads to wards the better beamforming. The results were analyzed analytically and by simulation.

5.2 Future Enhancements

As the research area is comparatively new so having a lot of research scope, these includes

1) Investigation of the trade-off between the operational power of the network with the power saved using collaborative communication.
2) Investigation of the imperfect Frequency Synchronization Effect.
3) Investigation of the consequences related to the system behaviour under uncertainties in the estimation of sensor nodes distance.
4) Mathematical and Simulation analysis of coding techniques like STBC, Convolution etc. with Collaborative Communication.
5) Mathematical and Simulation analysis of the imperfect Time Synchronization effect
6) Investigation of techniques for Channel Estimation
7) Accurate knowledge of the position of the sensor nodes
8) Effects of Multi path fading

Appendix-A
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