DOCTOR THESIS

VHF ADAPTIVE ANTENNA USING A REAR DEFOGGER

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Abstract

This thesis presented the design of an adaptive beamforming antenna using a rear defogger. The main purpose of this project is to develop the vehicular adaptive antenna for VHF band, which does not require the installation space, does not spoil the industrial design, has low cost and low power consumption. In land communication, there is no clear line of sight between transmitter and receiver. The transmitted signal might be reflected, refracted because of the building or terrain. The receiver might receive a delayed, or reflected signal instead of the original signal. Adaptive antenna is the best candidate to mitigate the multipath fading effects. However, for VHF band, conventional adaptive antenna has a drawback of a large aperture size. Therefore, in this paper a rear defogger is proposed as an aperture to overcome the size problem of using a conventional adaptive antenna. A rear defogger of a vehicle can be used as an aperture, and in order to make it compatible with ESPAR antenna, several ports have been provided. One port is used as an active port or output port, while other ports are connected to the variable reactor. Downhill simplex method is used as an algorithm to form the adaptive beam for the proposed antenna. This algorithm is maximized the correlation coefficients. Simplex method has been chosen because it has several advantages. Simplex method has a fast convergence time, robust beamforming, and it can be used for multi-dimensional optimization. There are several steps in simplex method for optimization; reflection, expansion, contraction, and multiple contractions. IE3D software is used to model the defogger with the car and from the IE3D results it shows that the defogger can be used as an adaptive antenna because it has low voltage standing wave ratio (VSWR) to make it operate as an antenna, low spatial cross correlation (SCC) for better diversity and has high coupling between port (CBP) for better capability of beamforming. In the analysis, the VSWR is lower than 3, SCC is lower than 0.5, and the CBP is between -6 dB to -10 dB. For numerical simulation, MATLAB is used to make a program for simplex method. From the simulation results, it shows that almost 80 % of the signals have signal to interference noise ratio (SINR) greater than 20 dB. Besides that, null is performed for incoming interference and remained high gain for the desired signal. A Rear defogger is made from heating wire, therefore it is necessary to confirm the effects of the resistivity to the antenna's performance. The effects of the resistivity has been confirm through IE3D simulator and MATLAB programming by comparing it to the copper wire. From IE3D simulator, comparison has been made for VSWR, SCC, and CBP for both resistive and copper

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wire. The results show that the values of VSWR, SCC, and CBP for copper and resistive wires are nearly same. A statistical analysis has been carried out for copper and resistive wire, and the analysis show that the performance of the resistive wire is slightly decrease compared to copper wire. However, the different is very small, plus the resistive wire has more than 80% of the signal has SINR greater than 20 dB. The beam pattern is controlled by a varactor circuit. The varactor circuit is connected to the three passive elements. The reactance range is limited from $-j300\Omega$ to $j300\Omega$ in the simulation, consider manufacturing. It is difficult to manufacture a large range of reactance. The reactance value is different for each incoming DOAs. Measurement has been conducted in anechoic chambers for adaptive beamforming. It shows that after perform beamforming, null is performed for incoming interference, improved VSWR, BER and SINR over the bandwidth. The proposed antenna has a fast convergence times, the convergence time is less than 50 ms and the iteration number is less than 70. Measurement in Rayleigh fading environment also been conducted, it shows that by applying the beamforming the BER is improved. The experiment was conducted for 473 MHz and 900 MHz for horizontal (co-polarization) and vertical (cross-polarization). For both co-polarization and cross-polarization, BER show an improvement.

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LIST OF ABBREVIATIONS

LOS	Line of sight
CNR	Carrier to noise ratio
SINR	Signal to interference plus noise ratio
OFDM	Orthogonal frequency division multiplexing
RSAA	Reactively steerable adaptive array
SPE	Switch parasitic element
VHF	Very high frequency
ISDB-T_{sb}	Integrated service digital broadcasting-terrestrial sound broadcasting
ISDB-T_{mm}	Integrated service digital broadcasting-terrestrial multimedia
VSWR	Voltage standing wave ratio
SCC	Spatial correlation coefficient
CBP	Coupling between ports
ESPAR	Electronically steerable passive array radiator
CCDF	Complimentary cumulative density function
ISI	Inter-symbol interference
SNR	Signal to noise ratio
MSE	Mean square error
MMSE	Minimum mean square error
LMS	Least mean square
CMA	Constant modulus algorithm
TTL	Transistor-transistor logic
HGI	Head guard interval
TGI	Tail guard interval
BPSK	Binary phase shift keying
DOA	Direction of arrival
QAM	Quadrature amplitude modulation
DSP	Digital signal processing
BER	Bit error rate

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CHAPTER 1

Introduction

1.1 Problem statement

Nowadays, many electrical systems and devices have been incorporated in vehicles which contributed to easier and safety driving and also entertainment for driver and passengers. Therefore, the demands for those devices have been increased drastically. As far as vehicular antennas are concern, on glass antennas are rapidly been researched in order to fulfill this demands. However, many of the designed antennas have complex and bulky structure due to land mobile problems [1]-[3].

As we know, in land mobile communication, there is no clear line of sight (LOS) between transmitter and receiver especially for moving systems. The receiver might receive the reflected signals instead of the original signal. The LOS is often blocked by obstacles which will lead the signal to be reflected as shown in Figure 1.1. The received signal is consist of combination refracted signal, attenuation signal, reflected signal and diffraction signal. This effect is known as multipath fading effects. The carrier to noise ratio (CNR) is degraded because of multipath effects. Besides that, signal to interference plus noise ratio (SINR) also degraded because of frequency selective fading in multipath fading effects. Due to those effects, the transmission quality is definitely degraded.

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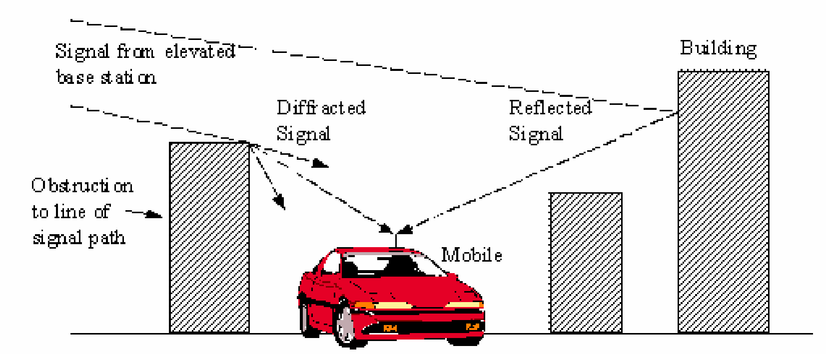

Figure 1.1. Multipath effects

Sklar in [9] has introduced several techniques to mitigate the effects of multipath fading. In order to combat the distortion caused by frequency selective fading, Sklar has proposed using adaptive equalization, spread spectrum, OFDM and pilot signal. He suggested several type of diversity to combat loss caused by flat-fading and slow fading.

Adaptive array antenna is the best candidate to overcome multipath effects [4]. Adaptive array antenna is one type of smart antennas. Smart antennas are an array antenna that can steer the beam toward the desired signal and eliminate the undesired signal (interference). There are two types of schemes for adaptive array antennas; digital beamforming and reactively steerable adaptive array (RSAA). Switched beam array antennas are antennas that only controlled the direction of maximum radiation. This antenna offers fixed beam direction. Meanwhile, the adaptive beamforming antennas controlled the radiation in all directions.

A reactively steerable adaptive array (RSAA) using dipole antenna has been introduced by Harrington [10]. This antenna is an adaptive array with single receiver. For reactively controlled antenna array, the beam pattern is control by varying the reactive loads. By optimizing the gain, we are able to steer the beam toward the maximum gain direction which is the desired signal Many researches on reactively steerable adaptive array has been conducted. In addition, switched parasitic elements (SPE) technologies also can steer a beam

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toward the desired direction. These are array antennas consisting of several radiating elements such as a dipole or patch. These antennas have serious problems such as a bulky structures and a large amount of calculation because of blind algorithm.

A conventional adaptive antenna consisted of several antennas and receivers. In case of low frequency such as very high frequency (VHF), the aperture size becomes large [36,49,50]. Installation of several large apertures for adaptive antenna is not proper for vehicular design. In addition, several receiver and coaxial cables connection antenna with receiver will increase the cost. Therefore, in this study a smart antenna using a rear defogger has been proposed. The defogger has been used as an array antenna by placing several ports on it. Then, RSAA concept is applied to form adaptive pattern. Downhill simplex method is used as an algorithm to optimize the cross correlation function. This algorithm has the fastest convergence time compared to other algorithm such as steepest descent and direct search method.

1.2 Objective of the study

Recently, most vehicles are equipped with entertainment equipment such as monitor, dvd player, radio, car navigation and etc. Each equipment has their own system. For example, to watch television in a vehicle we need an antenna to receive the broadcasting signal. The television broadcasting in Japan has fully shifted to digital broadcasting in July 2011. The frequency for Integrated Service Digital Broadcasting-Terrestrial for sound broadcasting (ISDB-T_{sb}) is 90-108 MHz, while for Integrated Service Digital Broadcasting-Terrestrial for multi media (ISDB-T_{mm}) is 207.5-222 MHz is planned. For this broadcasting systems, the receive antenna such as diversity antenna and adaptive antenna should be able to receive an orthogonal frequency division multiplexing (OFDM) signal.

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Therefore, new technology is needed to cope with this new system. The main objective of this study is to design an adaptive antenna for vehicular used in future digital radio broadcasting. A conventional adaptive antenna has drawbacks of aperture size and a number of receivers. For a low frequency such as VHF, if conventional adaptive antenna is used, the aperture size if large. To overcome the aperture size, we proposed a rear defogger as a shared aperture antenna by placing several ports on it. Every vehicle is equipped with rear defogger for defrosting purpose. Therefore, by using rear defogger, we can save a space in the vehicle, do not spoil the vehicle design and also inexpensive to design.

In order to make the defogger function as an array antenna, the antenna should have a low voltage standing wave ratio (VSWR), low spatial correlation coefficient (SCC) and high coupling between ports (CBP). To achieve high diversity gain, the SCC should be low and to achieve high beamforming capability, the CBP must be high. By adding vertical lines, we are able to make the defogger to be operated at the desired frequency bands; ISDB-T_{sb} and ISDB-T_{mm} and increased the CBP for a better beamforming capability.

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1.3 Thesis outline

This thesis consists of 7 chapters stated as follows:

- Chapter 1 is an overview of the thesis. It consists of problem statements, objectives of the project, and the thesis outline.
- Chapter 2 is an introduction to smart antenna and the multipath fading. In the beginning, the principles of multipath fading is discussed followed by the techniques used to mitigate multipath in this thesis smart antenna will be discussed. The principles of digital beamforming and adaptive beamforming will be explained in this chapter. In this chapter, steerable antenna is also been

discussed for switched parasitic elements and reactively steerable adaptive array antennas.

- Electronically steerable parasitic array radiator (ESPAR) will be explained in Chapter 3. The first part of this chapter will discussed the principle and formulation of conventional ESPAR is explained in this chapter. Downhill simplex method also been explained in this chapter since it been used as an algorithm. The second part of this chapter will discuss the proposed antenna which is implemented the ESPAR concept to a rear defogger.
- Chapter 4 is about shared aperture antenna based on a rear defogger. The design process using IE3D start from modeling and also process to select the port location is explained in this chapter. Analysis for effect of vertical wire and also the effect of resistivity also included in this chapter. Finally is the process of designing the dual band defogger.
- Chapter 5 consists of simulation results conducted by MATLAB. The first part is the results for conventional ESPAR, and the second part is the results for the proposed antenna. The second part is basically consists of complimentary cumulative density function (CCDF) for selection of an output port, effect of resistivity, frequency characteristic and analysis for dual band.
- Chapter 6 explained about the manufacturing process for defogger and varactor circuit and experiment setup for adaptive beamforming and Rayleigh fading. It also consists of experiment results and discussion.
- Chapter 7 is summarizes everything in this thesis, and it also consists of future work to be done.

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CHAPTER 2

Smart Antenna

The demand for mobile communications systems has generated a great deal of research activities in order to cope with the needs such as, data throughput, mobility and cost. One of the new technologies that can cope with this demand is smart antenna. Smart antenna used adaptive beamforming to achieve maximum reception in a specified direction by estimating the signal arrival from a desired direction while signals of the same frequency from other directions are rejected. This can be achieved by varying the weight of each antenna elements. The basic idea is that, though the signals transmitted from different transmitter occupy the same frequency channel, they still arrive from different directions. This spatial separation is exploited to separate the desired signal and interference signal. In adaptive beamforming the optimum weights are iteratively computed using complex algorithms.

The advantage of using adaptive beamforming is, we can steer the beam toward the desired signal and eliminate the interference. This type of antenna is known as steerable antenna. Steerable antenna can be classified to two types; reactively steerable adaptive array (RSAA) and switched parasitic elements (SPE).

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2.1 Multipath Fading

In wireless communications, signal fading is caused by multipath effect. Multipath effect means that a signal transmitted from a transmitter may have multiple copies traversing different paths to reach a receiver [5,6,7,8,41]. Thus, at the receiver, the received signal should be the sum of all these multipath signals. Because the paths traversed by these signals are different; some are longer and some are shorter. The one at the direction of line of signal (LOS) should be the shortest. These signals interact with each other. If signals are in phase, they would intensify the resultant signal; otherwise, the resultant signal is weakened due to out of phase. This phenomenon is called channel fading.

2.1.1 Doppler spread

The channel adds noise to signal and cause a shift in the carrier frequency if the transmitter and receiver are moving. This effect is known as Doppler effects. If the transmitter and receiver is moving toward each other, the receive frequency is higher than the source and if the transmitter and receiver is moving away from each other, the receive frequency is decrease. The frequency is decrease because the wave is spread out since the distance between waves is increased. In mobile communication systems, this effect is very important to be taken care of.

The amount of frequency changes due to the Doppler effects depends on the relative motion between the source and receiver and on the speed of propagation of the wave. The Doppler shift in frequency can be written:

$$\Delta f \approx \pm f_0 \frac{v}{c} \tag{2.1}$$

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Where Δf is the change in frequency of the source seen at the receiver, f_0 is the source frequency, v is the speed difference between the source and the transmitter, and c is the speed of light.

2.1.2 Delay spread

The different signal paths between a transmitter and a receiver correspond to different transmission times. For an identical signal pulse from the transmitter, multiple copies of signals are received at the receiver at different moments. The signals on shorter paths reach the receiver earlier than those on longer paths. The direct effect of these unsimultaneous arrivals of signal causes the spread of the original signal in time domain. This spread is called delay spread.

The delay spread puts a constraint on the maximum transmission capacity on the wireless channel. Specifically, if the period of baseband data pulse is larger than that of delay spread, inter-symbol interference (ISI) will be generated at the receiver. That is, the data signals on two neighbouring pulse periods are received at the same time, which causes the receiver not to be able to distinguish them.

2.2 Antenna diversity

As discussed previously, multipath fading occurs in land mobile communication, therefore, the performance was degraded. To overcome this problem a special reception technique is used, namely the multiple receiver combining techniques which is known as diversity.

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Diversity techniques are used to mitigate the effects of the multipath phenomenon. There are several mechanisms to achieve diversity branches such as space diversity or spatial diversity, frequency diversity, angle diversity, polarization diversity, and pattern diversity.

The most common and simple mechanism for achieving diversity branches is space diversity [38,43,66]. By using two antennas with a distance between them, the phase delay makes multipath signals arriving at the antenna differ in fading. The minimum spacing between the antennas at a mobile terminal is required for sufficient low correlation between fading signals. In this thesis, spatial diversity will be discussed in details.

2.2.1 Selection combining

Another popular diversity combining technique, known as selection combining, is shown in Figure 2.1. In this method, the receiver monitors the level of the incoming signal using switch logic. When the signal level drops below a predefined threshold a switch changes the path to the other antenna. This method performs better than passive combining in that the two signal paths cannot add destructively. The problem with selection combining is that the switching does not take place until a fade has already occurred. There is also the possibility that the signal at the other antenna will be at an even lower signal level.

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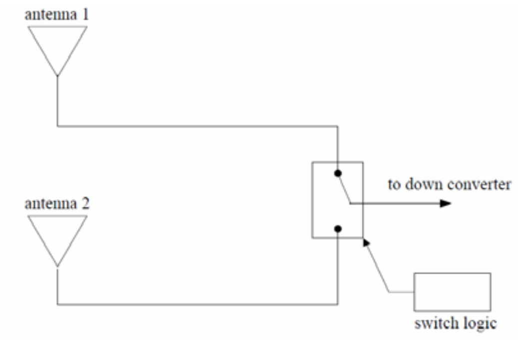

Figure 2.1. Selection combining

2.2.2 Maximal ratio combining

Maximal ratio combining is similar to equal gain combining in that the signals are co-phased in the branch receivers by applying phase shifts of φ1 and φ2 as shown in Figure 2.2. Maximal ratio combining differs from equal gain combining in that each branch is weighted by a factor, indicated by α1 and α2.

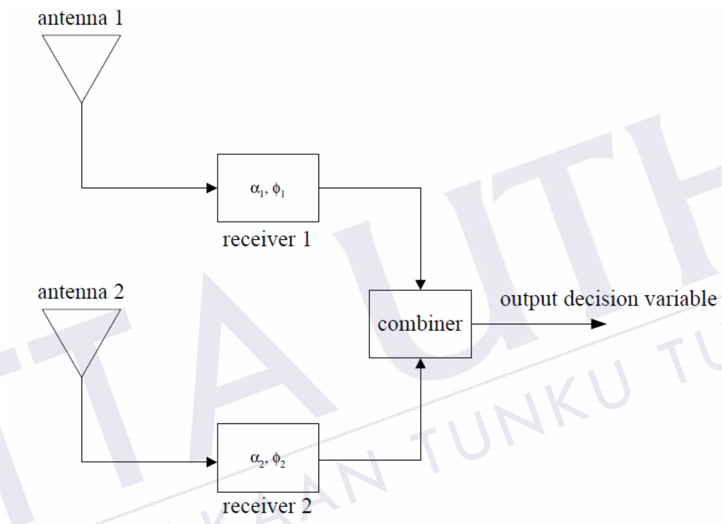

Figure 2.2. Maximal ratio combining

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2.3 Adaptive antenna

An antenna array uses an array of simple antennas such as omni-directional antennas, and combines the signals to form an array output. The direction where the maximum gain would appear is controlled by adjusting the phase between the different antenna elements. The adjusted and gain is known as weights, the output from the antenna is combined and the desired output is achieve [33,43]. The properties of the antenna array may vary over time in order to optimize the systems performance with respect to different optimization criterion including maximum power, maximum SNR, minimum interference and maximum SINR. An adaptive antenna's parameters are automatically adjusted, in order to obtain an optimal or near-optimal array output. The optimization cost function and the method used to achieve this state are dependent upon the optimization algorithm chosen.

2.3.1 Temporal reference techniques

Temporal reference techniques refer to the design of array processors which optimize the received antenna array weights. For this technique, a reference signal is used for easily identify the desired signal and distinguish the unwanted signal.

Figure 2.3 shows the structure of a temporal reference beamformer, where the array output is substracts from the reference signal, r(t) which assists in identifying the desired user. In order to generate the error signal $e(t) = r(t) - \mathbf{w}^H \mathbf{x}(t)$, which is then used to control the weights. The weights are adjusted such that the mean squares error (MSE) between the array output and the reference signal is minimized, where the error is expressed as

$$e^2(t) = [r(t) - \mathbf{w}^H \mathbf{x}(t)]^2 \qquad (2.2)$$

Taking the expected values of both sides of equation (2.2), we get

$$E[e^2(t)] = E[r^2(t)] - 2\mathbf{w}^H z + \mathbf{x}^H R\mathbf{w} \qquad (2.3)$$

Where $z = E[\mathbf{x}(t) * r(t)]$ is the cross correlation between the reference signal and the array signal vector $\mathbf{x}(t)$ and $R = E[\mathbf{x}(t)\mathbf{x}^H(t)]$ is the correlation matrix of the array output signals. The MSE surface is a quadratic function of complex array weight vector $\mathbf{w}$ and it is

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minimized by setting its gradient with respect to $\mathbf{w}$ equal to zero,

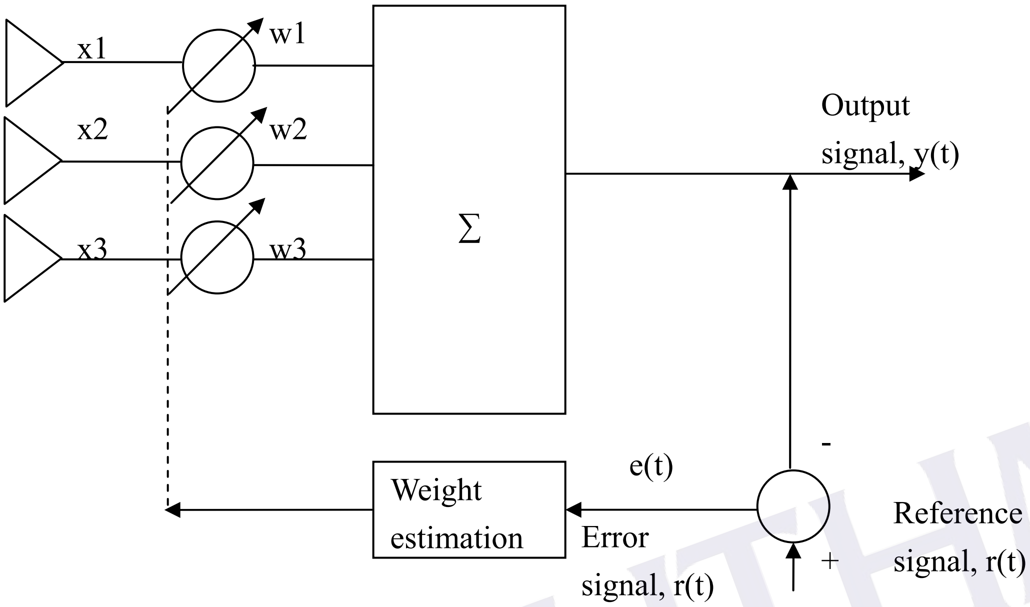

Figure 2.3. The structure of temporal reference based beamformer with 3 antenna elements

$$\nabla_w(E[e^2(t)]) = -2z + 2R\mathbf{w} = 0 \tag{2.4}$$

Yielding the weill-known Weiner-hopf equation for the optimal weight vector in the form of

$$\mathbf{w}_{opt} = R^{-1}z \tag{2.5}$$

The minimum mean square error (MMSE) is given by

$$MMSE = E[|r(t)|^2] - z^H R^{-1} z \tag{2.6}$$

Beside MSE and MMSE, there is a least mean square (LMS) is based on the steepest descent method, a well-known optimization technique that recursively computes and updates the weight vector. The algorithm updates the weights at each iterations by estimating the gradient of the quadratic error surface and then changing the weights in the direction opposite to the

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gradient by a small amount in an attempt to minimize the MSE. The desired response, generated by inputting the reference sequence to the modulator is supplied to the algorithm, allowing the estimation error and thus the error surface to be calculated. The constant that determines the amount by which the weights are adjusted during each iterations is referred as the step size. When the step size is sufficiently small, the process leads these estimated weights to the near optimal weights

2.3.2 Blind adaptation

Blind adaptation of the array weights has several advantages over the temporal reference technique. As for temporal reference technique, assisted system must achieve synchronization and perform demodulation before weights adaptation can commence. In contrast, a blind adaptation does not required training sequences or any information concerning the antenna array's geometry.

The constant modulus algorithm (CMA) operates on the principles that the amplitude of the received antenna array output should remain constant, unless the interference causes fluctuations. If the transmitted signal, s(n) has a constant envelope, then the combiner output, y(n) should also have a constant envelope. The objective of CMA is to restore the array output to a constant envelope signal. This can be achieved by adjusting the array weight vector, w in such a way so as to minimize a cost function. The cost function for CMA is given by

$$J_{(n)} = \frac{1}{2} E[(|y(n)|^2 - y_0^2)^2] \qquad (2.7)$$

Where y_0 is the desired amplitude in the absence of interference.

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2.4 Parasitic elements

2.4.1 Switched Parasitic Elements

Switched parasitic elements (SPE) is the simplest smart antenna technique and several studies have been conducted for SPE, wired and patch antennas has been used in the studies. The concept of switched parasitic elements is adopted from Yagi-uda dipole array. The Yagi-uda consists of reflection dipole, single active dipole and a numbers of director dipoles as shown in Figure 2.4 [32].

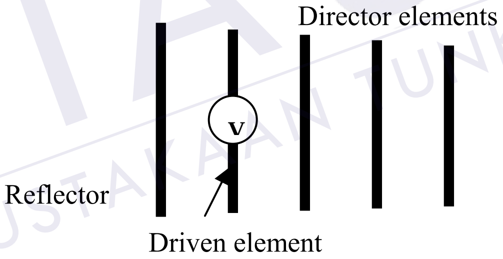

Figure 2.4. Yagi-uda configuration using dipole elements

Parasitic elements are used to generate a directional beam. Usually, a numbers of parasitic elements are used to surround the active elements or driven elements. Numerous director elements are used to achieve a highly focused radiation. The reflector is the backbone of a switched parasitic array [21,22,31,32].

The basic principle of switched parasitic element is if the current distribution of the parasitic elements is changed, the input impedance and radiation characteristic of the array also changed. The current of parasitic elements changed because of a current is induced from

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active elements to the parasitic element by mutual coupling. For circular wired parasitic element, the number of beam obtained depends on the number of monopoles [26,34].

In SPE, there are several possible configurations. First is switching between active elements and leave all other parasitic elements at resonance condition. By using this configuration, RF switch is use to switch the generator between active elements and also PIN diodes to switch the elements between active and parasitic [21,22]. The control circuit for one element is given by Figure 2.5. The PIN diode is switched between being shorted to the ground or an open circuit and it is controlled by transistor-transistor logic (TTL). The RF switch is also controlled by the logic signal. The choke prevents the RF signal from flowing back to the TTL logic circuit and the resistor is used to control the current through the diode. For TTL= 0 V, RF power is delivered to the antenna and the diode has high impedance. For TTL = 5 V, the antenna feeds are grounded and the RF line is not connected. The phase shifter provides a phase difference between the two feeds of each antenna.

Another configuration is required one central active elements surrounded by parasitic elements. The parasitic element is switched in and out of resonance using PIN diodes [23] as shown in Figure 2.6. For this array, polar pattern is obtained by two cases. First is when the parasitic element is short circuit and second is when the parasitic element is open circuit. When the parasitic element is open circuit, the parasitic element is no effect to the radiation pattern. The radiation pattern is same as for a half wave dipole. PIN diode is used to switch from open to short circuit. Open circuit is obtained by applying unbiased current, while short circuit is obtained by applying forward current.

Preston et. al, has introduced a switched parasitic using rectangular patch antennas. For a patch antenna structure, the current distribution can be altered by shorting a point location located at the maximum current position [25]. When the point of maximum current is shorted, the parasitic elements acts as a reflector and if there is no shorted, it operates as a

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director element in the array. The number of beam obtained is limited to the number of shorted pin. Kamarudin et.al has introduced a disc loaded monopole array for beam control [27-28]. In this paper, they propose to make an open circuit at one parasite to form a directional beam at this element.

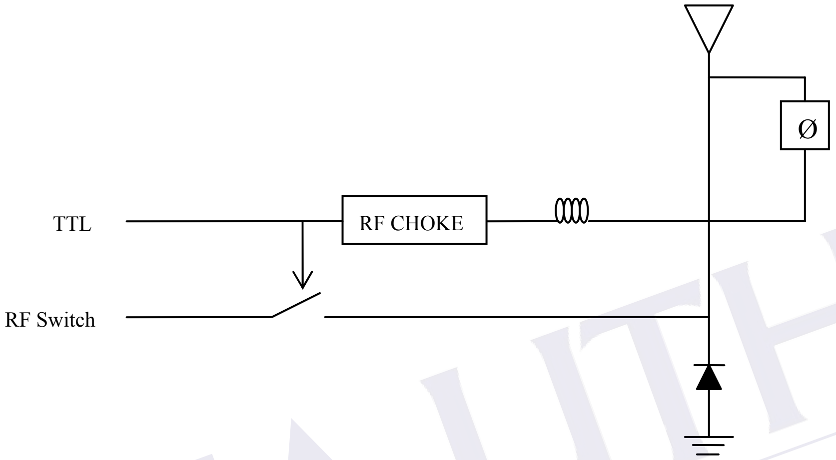

Figure 2.5. Control circuit for one element.

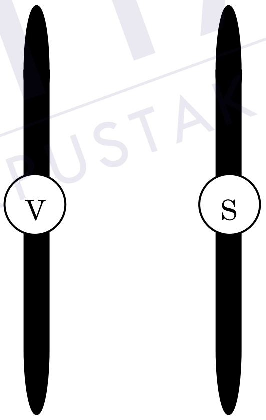

Figure 2.6. Two element wires antenna with voltage (V) and PIN diode as switch(S)

A dual band SPE has been design in [29,30]. In these papers, authors used genetic algorithm to determine the total wire length, load position, load reactance and the ring radius for 900 MHz and 1900 MHz. The beam can be switched for the desired two resonance frequency. In contrast with this, Lu et. al [51] has proposed an SPE with two beam operates

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simultaneously by arranging two concentric ring. The number of switched beam is depends on the number of elements.

2.4.2 Reactively Steerable Adaptive Array

The adaptive concept is far superior to the performance of a SPE. Adaptive array antenna can locate and track signals and adjust the antenna pattern to enhance reception, while minimizing the interference using algorithms. Reactively loaded has been used in the adaptive array to improve the reception quality. Reactively loaded antenna is defined to be an N-port radiating system with reactive elements at the ports. The excitation of the antenna is a voltage source at one of the ports. Meanwhile, a reactively controlled antenna array is the reactance loads are varied to control the radiation pattern.

Harrington proposed a seven element dipole as shown in Figure 2.7 [10]. It has one active element in the middle and surrounded by several passive elements. Each passive element is connected to the variable reactance load. In this method, variable reactance load is used to control the radiation pattern of the antenna. By using an appropriate beamforming algorithm, the antenna has ability to steer toward the desired signal and form nulls at interference.

The beamforming algorithms optimize reactive loads to maximize the signal to noise ratio (SNR). Many studies have been conducted using various types of optimization algorithms. Harrington has proposed pattern synthesis method to maximize the gain, while Dinger [11] has proposed a RSAA using microstrip patch elements and used steepest descent algorithm to maximize the output interference power.

Recently, electronically steerable passive array radiator (ESPAR) antennas have attracted considerable attention because of its ability to significantly improve the performance of wireless systems by automatically eliminating surrounding interference. With a very simple

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architecture, it has a significantly low power dissipation and inexpensive to manufacture. The direction of maximum gain is controlled by varying the load reactance.

Ohira et. al [12-15,44-46,48,56,58,62,64] introduced ESPAR and used various algorithm such as the steepest descent algorithm, and the genetic algorithm, for beamforming, while Kuwahara [16] used direct search method for ESPAR. Vlasis et. al [24], introduced a stochastic beamforming algorithm for ESPAR. ESPAR concept also been tested for patch antenna in [47,60], corner-reflector ESPAR [42], and also a dielectric embedded ESPAR (DE-ESPAR) [47,57]. A dual-band ESPAR [59], tri-band ESPAR [69], and broadband ESPAR [61,67] has been design using various algorithm. In [35], an ESPAR with switched load at parasitic elements has been design. The same authors also proposed the same structure for multiband ESPAR [53].

Many researches on ESPAR antenna has been conducted, since ESPAR antenna offers more advantage over SPEs [63,65,68]. One of the advantage of using RSAA is it can control the beam to the various directions. It is not limited as SPE antennas.

The RSAA discussed here are using mutual coupling between elements as dipoles and patches in the array antenna. In this thesis, we are proposing the defogger as the array antenna by providing several ports on it. Which means only a single aperture is used instead of an array antenna.

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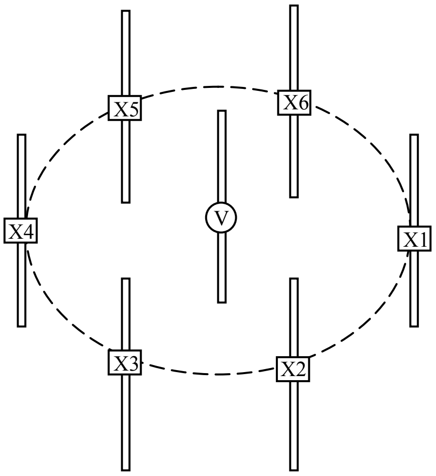

Figure 2.7. A seven element dipole array.

CHAPTER 3

Adaptive Beamforming

In this section, adaptive beamforming using the ESPAR antenna will be discussed and also the implementation of the ESPAR concept to a rear defogger. ESPAR antenna is one of the smart antennas that can steer and eliminate interference automatically by varying the reactance load connected at passive elements. ESPAR antenna is introduced by Ohira using seven element; one active element at the center and six passive elements around it.

3.1 ESPAR

3.1.1 ESPAR Formulation

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This section briefly describes the configuration of ESPAR and how we adapt the same configuration to the downhill simplex method. As shown in Figure 3.1(a), an ESPAR antenna basically comprises one active element and surrounded by six passive elements (M=6).

All passive elements are terminated by a variable reactance denoted as x_M. The reactance x is written as

$$\mathbf{x} = [x_1, x_2, \ldots, x_M]^T \tag{3.1}$$

The output of ESPAR, $y(t)$ is given by

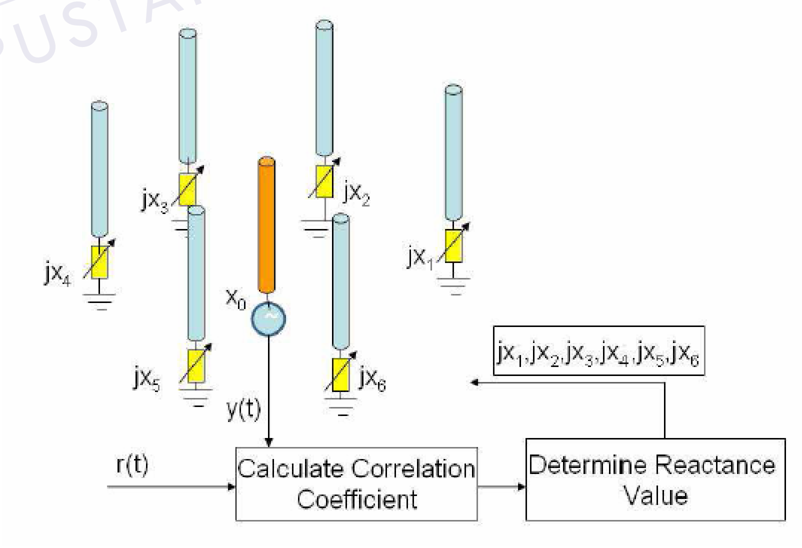
$$y(t) = \mathbf{i}^T \mathbf{s}(t) \tag{3.2}$$

where, I is a current vector of (M+1)-elements that is expressed as

$$\mathbf{i} = [i_0, i_1, \ldots, i_M]^T \tag{3.3}$$

V is a RF voltage vector and it is expressed by

$$\mathbf{v} = [v_0, v_1, \ldots, v_M]^T \tag{3.4}$$



(a) Configuration of ESPAR

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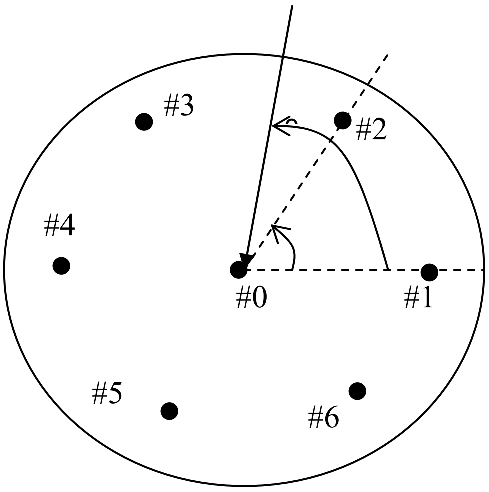

(b) ESPAR geometry

Figure 3.1. ESPAR

The RF voltage imposed on the reactance x_m is defined as

$$v_m = -jx_m i_m \qquad m = 1,2,\ldots,M \tag{3.5}$$

While, RF voltage at the central element is represented by

$$v_0 = V_s - Z_0 i_0 \tag{3.6}$$

The notation of Z_0 is the output impedance of the transmitter and it is not affected by the mutual coupling of other elements. The value of Z_0 is assumed as 50 Ω without any loss. V_s is the internal source RF voltage. According to the theorem of reciprocity, the receive mode radiation pattern array factor of the ESPAR antenna is same as transmit mode. Assume $V_s = 1$ and arrange equation [3.5] and [3.6] in a vector form yields,

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$$\mathbf{v} = \begin{bmatrix} 1-50i_0 \\ -jx_1 \\ -jx_2 \\ \vdots \\ -jx_M \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} - X\mathbf{i} \tag{3.7}$$

where $\mathbf{i} = [i_0, i_1, ..., i_M]^T$, and X is a diagonal matrix

$$X = diag[50, jx_1, jx_2, ..., jx_M] \tag{3.8}$$

Current vector and RF voltage vector have a relationship

$$\mathbf{i} = Y\mathbf{v} \tag{3.9}$$

where Y is referred as admittance matrix. Substitute equation (3.7) into (3.9) yields

$$\mathbf{i} = (I + YX)^{-1}\mathbf{y_0} \tag{3.10}$$

Where I the identity matrix and $\mathbf{y_0}$ is the vector of first column of Y matrix.

$$\mathbf{y_0} = [y_{00}, y_{10}, y_{20}, ..., y_{M0}]^T \tag{3.11}$$

The steering vector $\mathbf{a}(\theta)$ is defined based on the array geometry in Figure 3.1(b)

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$$\mathbf{a}(\theta)=\begin{bmatrix}1\\ e^{j\frac{\pi}{2}\cos(\theta-\phi 1)}\\ e^{j\frac{\pi}{2}\cos(\theta-\phi_2)}\\ \vdots\\ e^{j\frac{\pi}{2}\cos(\theta-\phi_M)}\end{bmatrix} \tag{3.12}$$

Suppose there are a total number of Q signals $u_q(t)$ with DOAs (θ_q,ϕ_q) $(q=1,2,...,Q)$. Let $s_m(t)(m=1,2,...,M)$ denote the signal induced at the M-th port, and let $\mathbf{s}(t)=[s_1(t),s_2(t),...,s_Q(t)]^T$ be the column vector with M-th components $s_m(t)$. $s_m(t)$ is the superposition of all Q signals.

$$s_m(t)=\sum_{q=1}^{Q}\mathbf{a}_m(\theta_q,\phi_q)u_q(t) \qquad (m=1,2,...,M) \tag{3.13}$$

Where $\mathbf{a}_m(\theta_q,\phi_q)$ is a steering vector defined in equation (3.12), then the column vector $\mathbf{s}(t)$ can be expressed as

$$\mathbf{s}(t)=\sum_{q=1}^{Q}\mathbf{a}(\theta_q,\phi_q)u_q(t) \tag{3.14}$$

Finally, the output of the ESPAR antenna can be written as

$$y(t)=\mathbf{i}^T\mathbf{s}(t)=\sum_{q=1}^{Q}\mathbf{i}^T\mathbf{a}(\theta_q,\phi_q)u_q(t) \tag{3.15}$$

Notice that the current vector $\mathbf{i}$, and thus $y(t)$, is a function of the reactance vector, $\mathbf{x}$ of equation (3.1).

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3.1.2 Beamforming by simplex method

3.1.2.1 Description of simplex method

This section will describe about the downhill simplex method. It is an iterative search technique to minimize a function that is nonlinear in parameters. This method also known as Nelder-Mead method. The advantage of using Simplex method is it can be used to solve N-dimensional geometry. Simplex is a geometrical figure consisting N dimensions of N+1 points and all interconnecting line segments and polygonal faces. For example, in two dimensional, simplex is viewed as triangle.

Simplex method starts with defining, P_0 which is consists of N+1 points. After that all points in P_0 will be classified to highest point (x_h), second highest point (x_{sh}) and lowest point (x_l) [39]-[40]. Simplex method has several possible steps such as reflection, expansion, contraction and multiple contractions as shown in Figure 3.2. All this steps are required in order to discard the highest point.

The process starts by reflecting the highest point, x_h to a new point denoted as, x_r. x_r is defined as

$$x_r = (1+\alpha)\bar{x} - \alpha x_h \tag{3.16}$$

Where, α is a reflection coefficient, and $\bar{x}$ is a centroid point defined as

$$\bar{x} = \frac{1}{M}\sum_{i=1}^{M} x_i \qquad i \neq h \tag{3.17}$$

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