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ENHANCING CELLULAR NETWORK CAPACITY WITH ADAPTIVE ANTENNAS

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Abstract: With the exponentially increasing demand for wireless communications, the capacity of current cellular systems will soon become incapable of handling the growing traffic. Since radio frequencies diminish natural resources, a fundamental barrier to further capacity increase exists. The solution can be found in adaptive antenna systems. Adaptive antenna systems enable network operators to increase the wireless network capacity, where such networks are expected to experience an enormous increase in traffic. This is due to increased users and the high data rate service and applications. In addition, adaptive antenna systems offer the potential of increased spectrum efficiency, extended range of coverage, and a higher rate of frequency reuse. This paper aims to overview the technology, the fundamental system model, and the used algorithms.

Keywords: Adaptive antenna, smart antenna, steering vector.

I. INTRODUCTION

Wireless networks have been growing rapidly, both horizontally and vertically. Researchers have been working towards new techniques and standardizations to meet this wireless technology and service growth.

In wireless communication, the frequency spectrum is as expensive as gold. Wireless Service providers must pay a huge amount to purchase the right to use the frequency spectrum for communication. With the advancement of wireless communication systems in this decade, the new wireless communication system has frequently been used in the same area. Here, every user in the system requires a high data rate because of certain kinds of quality services, so demand for high bandwidth is compulsory. The number of subscribers also increases, resulting in the frequency domain's saturation drastically.

With the rapid development of mobile communications and the deployment of the 3rd generation WCDMA networks, there is a need for more radio frequencies. However, the frequency spectrum is a finite and valuable (and expensive) resource. There is a fundamental limit on the number of radio channels realized by wireless communication systems for a fixed spectrum bandwidth. Anticipating such limits, considerable work has been done on using time, frequency, and coding techniques to increase capacity. Adopting the adaptive antenna technique is expected to impact the efficient use of the spectrum significantly, minimize the cost of establishing new wireless networks, and optimize service quality [1]. In recent years, the wireless network capacities have increased with new technological advancements. Long-term evolution (LTE) technology, for example, provides the theoretical maximum peak data rate of 300 Mbps downlink and 75 Mbps uplink [2]. In the future, the data rates can be only expected to rise since even LTE does not yet meet the international mobile telecommunications-advanced (IMT-advanced, also marketed as 4G) requirements set by the International Telecommunication Union’s radio communication sector (ITU-R) [3]. This progress has had its part in the increasing popularity of wireless devices. Still, fundamental problems lie in the availability of free frequencies and the increasing complexity of the data transmission system.

Adaptive antenna systems consist of multiple antenna elements at the transmitting and/or receiving side of the communication link, whose signals are processed adaptively to exploit the spatial dimension of the mobile radio channel. Depending on whether the processing is performed at the transmitter, receiver, or both ends of the communication link [4], the adaptive antenna techniques are defined as multiple-input single-output (MISO), single-input multiple-output (SIMO), or multiple-input multiple-output (MIMO). Multiple-input multiple-output (MIMO) [5] - [8] systems were introduced to the performance of wireless communications systems to provide robustness, high data rates, and reliability by overcoming channel fading with the use of multiple antennas. A MIMO system offers redundancy through the multiple independent channels created between the system's transmitting and receiving antennas. Significant improvements are made in the coverage ranges of the communication systems and the data throughput without additional transmission power or bandwidth expansion using MIMO systems.

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Figure 1 shows a schematic diagram of a typical MIMO system. A MIMO system can provide both spatial diversity and spatial multiplexing gains. These concepts are defined in the next two paragraphs. It is important to note that all the gains provided by this scheme may not be realized simultaneously. Instead, there is a trade-off occurring between them. Real-time voice and image transmissions over wireless networks demand high data rates and quality of service (QoS). Space-time coding was developed to increase both reliability and link capacity. There are two broad categories of space-time (ST) codes: those targeted to increase the reliability/QoS of MIMO communications and those developed to offer higher data rates.

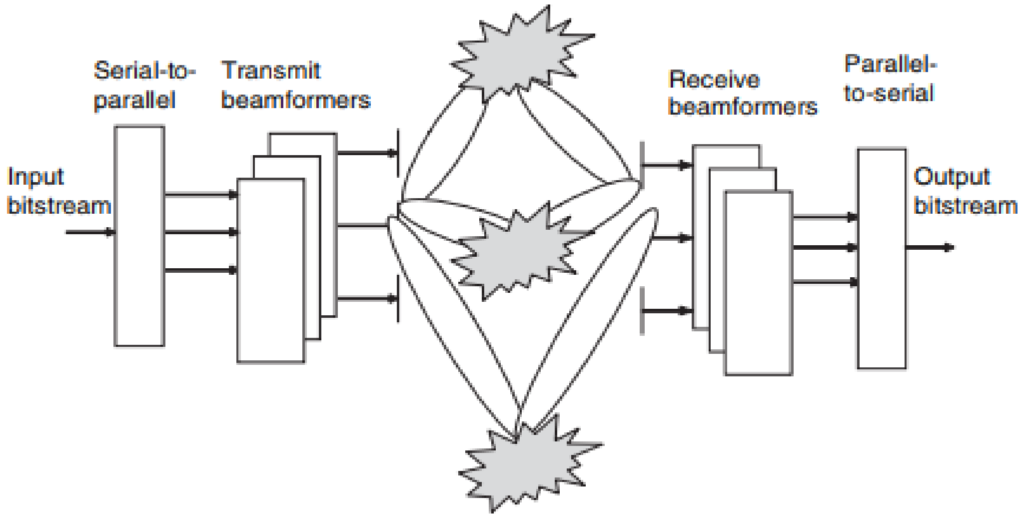

Figure 1. Basic MIMO

Exploiting the spatial dimension can increase the capacity of the wireless network by improving the link quality by mitigating several impairments of mobile communications, such as multipath fading and co-channel interface.

This study briefly surveys the adaptive antenna systems, their mathematical system model, proposed algorithms, and their applications.

II. RESEARCH EFFORTS

The current research effort in the area is focusing on the following critical issues;

- The design and development of advanced adaptive antenna processing algorithms that allow adaption to varying propagation and network conditions and robustness against network impairments.
- The design and development of innovative adaptive antenna strategies for optimization of performance at the system level and transparent operations across different wireless systems and platforms.
- Realistic performance evaluation of the proposed algorithms and strategies based on formulating an accurate channel and interface model and introducing suitable performance metrics and methodologies.
- Analysis of the implementation, complexity, and cost-efficiency issues in realizing the proposed adaptive antenna techniques for future-generation wireless systems.

III. ADAPTIVE ANTENNA BENEFITS

Multipath propagation, defined as the creation of multipath signal paths between the transmitter and the receiver due to the reflection of the transmitted signal by physical obstacles, is one of the major problems of mobile communications. It is well known that the delay spread and resulting intersymbol interface (ISI) due to multiple signal paths arriving at the receiver at different times critically impact communication link quality [9]. On the other hand, co-channel interference is the major limiting factor on the capacity of wireless communication systems, resulting from the reuse of the available network resources (e.g., frequency and time) by several users [10].

Adaptive antenna systems can improve link quality by combining the effects of multipath propagation and constructively exploiting the different data streams from different antennas.

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More specially, the benefits of adaptive antennas can be summarized as follows:

- **Increased range/coverage:** the array or beam forming gain is the average increase in signal power at the receiver due to a coherent combination of the signal received at all antenna elements. The adaptive antenna gain compared to a single-element antenna can be increased by an amount equal to the number of array elements, e.g., an eight-element array can provide a gain of eight (9 dB).

- **Improved system capacity:** one of the main reasons for the growing interest in adaptive antennae is the capacity increase. In density-populated areas, mobile systems are normally interference-limited, meaning that interference from other users is the main source of noise in the system. This means the signal-to-interference ratio (SIR) is much larger than the signal-to-thermal noise ratio (SNR). Adaptive antennas will, on average, increase the SIR. Experimental results report up to a 10 dB increase in average SIR in urban areas. For UMTS networks, a fivefold capacity gain has been reported for CDMA [9]

- **Lower power requirements and/or cost reduction:** Optimizing transmission towards the wanted user achieves lower power consumption and amplifier cost [11].

- **Improved link quality/reliability:** density gain is obtained by receiving independent replicas of the signal through independently fading signal components. Because one or more of these signal components will not be in a deep fade, the availability of multiple independent dimensions reduces the effective fluctuations of the signal.

- **Improved spectral efficiency:** spectral efficiency measures the amount of information-billable service carried by the wireless system per spectrum unit. It is measured in bits/second/Hertz/cell. Thus, it includes the effects of multiple access methods, modulation methods, channel organization, and resource reuse (e.g., code, timeslot, carries). Spectral efficiency is important since it directly affects the operator's cost structure. Moreover, for a given service and QoS, it determines the required amount of spectrum, the number of base stations, the number of sites, and associated site maintenance-, and ultimately, consumer pricing and affordability. Equation (1) shows a simplified formula to estimate the required number of cells per square kilometer [12]

$$\text{Number of cell/km}^2 = \frac{\text{offered load}}{\text{available spectrum} \times \text{spectral efficiency}} \qquad (1)$$

As can be predicated from equation (1), increasing the spectral efficiency would improve the operator economics by reducing the number of cells per square kilometer.

- **Security:** it is more difficult to tap a connotation since the intruder has to position himself in the same direction of arrival as the user.

- **Reduction of handoff:** There is no need to split the cells for capacity increase and, consequently, less handoff.

- **Spatial information:** the spatial information about the user would be available at any given time, which enables the introduction of Location Based Services.

In addition to the above-mentioned benefits, one must point out the following drawbacks (or cost) of the adaptive antennas:

- **Transceiver Complexity:** It is obvious that the adaptive antenna transceiver is much more complex than the conventional one. This comes from the fact that the adaptive antenna transceiver will need separate transceiver chains for each array element and accurate real-time calibration.

- **Resource management:** adaptive antennas are mainly a radio technology, but they will also put new demands on network functions such as resource and mobility management when a new connection is to be set up or the existing connection is to be handed over to a new base station, no angular information is available to the new base station, and some means to "find" the mobile station is necessary.

- **Physical size:** An array antenna with several elements is necessary for the adaptive antenna to obtain a reasonable gain. Typically, arrays comprising six to ten horizontally separated elements have been suggested for outdoor mobile environments. The necessary element spacing is 0.4-0.5 wavelengths. This means an eight-element antenna would

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be approximately 1.2 meters wide at 900 MHz and 60cm at 2 GHz. With a growing pupil demand for less visible base stations, this size, although not excessive, could provide a problem.

IV. BASIC PRINCIPLE

The technology behind the adaptive antennas has been introduced previously. The techniques have been used in electronic warfare (EWF) for many years as a countermeasure to electronic jamming.

There are, in principle, several different ways in which adaptively adjustable antenna beams can be generated.

The main philosophy is that interferers rarely have the same geographical location as the user. By maximizing the antenna gain in the desired direction and simultaneously placing minimal radiation patterns in the interferer's direction, the communication link quality can be significantly improved [13].

Several different definitions for adaptive antennas are used in the literature. One useful and consistent can be that the difference between a smart/adaptive antenna and a "fixed one is the property of having an adaptive and fixed lobe pattern, respectively. Figure 2 illustrates the concept of adaptive antenna.

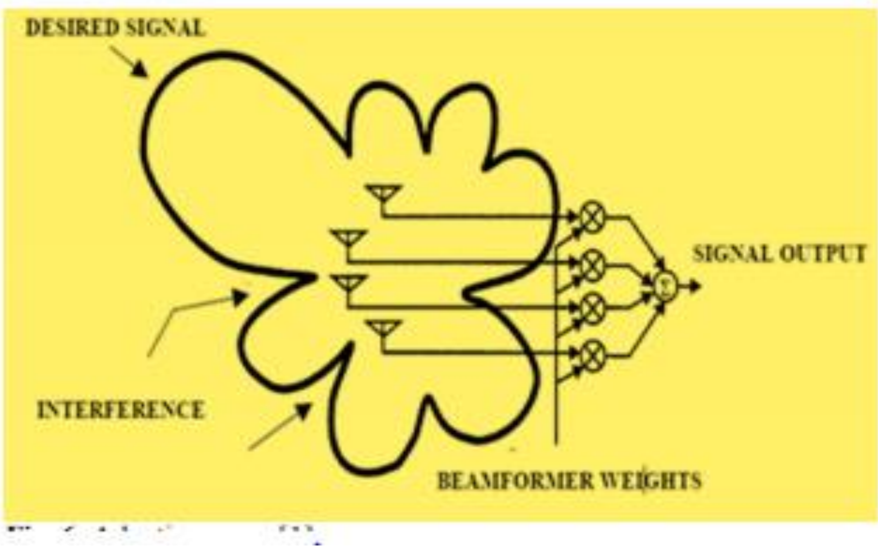

Figure 2. Adaptive antenna basic concept.

Normally, the term "antenna" comprises only the mechanical construction of transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable or vice versa. In the context of "adaptive antenna," the term "antenna" has an extended meaning. It consists of several radiating elements, a combining/dividing network, and a control unit. The control unit can be called the adaptive antenna's intelligence, normally realized using feeder parameters for the antenna based on several inputs to optimize the communications link. Different optimization criteria can be used.

V. IMPLEMENTATION

The adaptive antenna technology is based on an array antenna where the radiation pattern is altered by adjusting the amplitude and relative phase of the different array elements.

A. Antenna Arrays

Electrically steerable antenna patterns are most often generated using array antennas. These antennas consist of several antenna elements on which the signal is divided or combined in phase and amplitude. Generally, any combination of elements can form an array.

However, usually, equal elements in regular geometry are used. Using an array antenna, it is possible to obtain very good control of the radiation pattern, e.g., the shape of the main lobe and the side lobe level (SLL).

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A. System Model

To develop the system mathematical model, consider Figure 3.

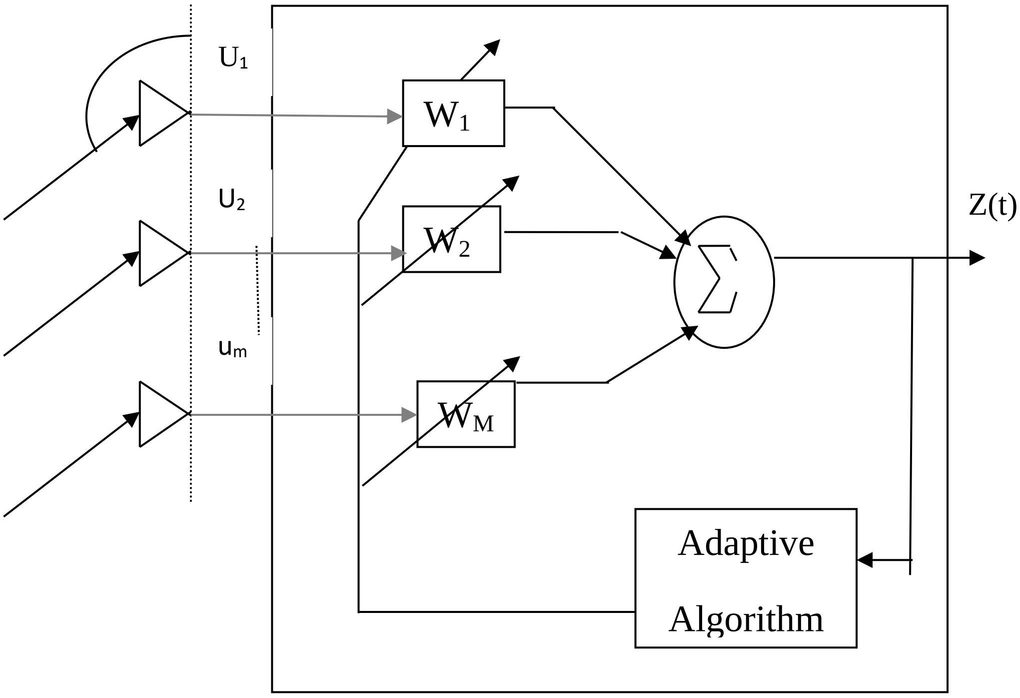

Figure 3. Array Antenna

The phase difference between the antenna element m and a reference element at origin is given by $\Delta\Psi_m = \beta\Delta d_m$

$= \beta(x_m \cos(\Phi)\sin(\Theta)) + y_m \cos(\Phi)\sin(\Theta) + z_m \cos(\Phi)\sin(\Theta))\ldots$ (2)

Where Φ and Θ are the elevation and azimuth angles, respectively, β is the phase propagation factor, and x_m, y_m, z_m are the Cartesian coordinates of the antenna element m concerning a reference element at origin. The output signal can be expressed as the following:

$Z(t) = \sum_{i=I}^{m} ui = (t)wi$ ....(3)

If the received signal at the reference antenna element is $u_i(t)$, the received signal at other elements will be phase-shifted replies of $u_i(t)$ $u_i(t)$. Hence, and for more than one user, we expand (3) to:

$Z(t) = I \sum_{i=I}^{m} u_i(t) e^{-j\beta(xi\cos(\Phi)\sin(\Theta) + yi\cos(\Phi)\sin(\Theta) + zi\cos(\Phi)\sin(\Theta))wi}$ … (4)

And in a more compact form, (4) can be rewritten as the following:

$Z(t) = \underline{w}^H \underline{u}(t)$ … (5)

Where

$\underline{U}(t) = [e^{-j\Delta\Psi i}\, e^{-j\Delta\Psi 2} \ldots e^{-j\Delta\Psi m}]^T$ …….. (6)

$= u_1(t)\underline{a}(\Phi, \Theta)$

Taking the first element as the reference so that $\Delta\Psi_1 = 0$, we can define the steering vector as the following:

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$\underline{a}$ (Φ, Θ) ……. (7)

The input signal at each element is the convolution between the transmitter and the channel impulse response as in the following equation:

u_{ij} (τ, t) = s_i (t) ∗h_{ij} (τ, t) ………. (8)

Where s_i (t) is the transmitted signal from user i, and h_{ij} (τ, t) is the channel response between user i and antenna element j. The channel between the mobile station and the base station can be modeled using the vector Channel Impulse Response (VCIR) as:

$\underline{h}_i$ (τ, t) = $\sum_{k=1}^{B_i} a_i$ (Φ $_k$, $Θ_k$) $\propto_{ik}$ (t) δ(t- $τ_k$) …..(9)

Where a_i is the steering vector, $\underline{h}_i$ is the channel impulse response, $τ_k$ is the time delay of the signal of user i, and $\propto_{ik}$ is the complex channel gain, given as:

$\propto_{ik}$ (t) = $\sqrt{p_{ik}} e^{j(2\pi^{fik+\Psi ik)}}$ …………… (10)

Where p_{ik} is the channel gain given by:

$p_{ik} = \approx \frac{A_{ik}}{A_{ik}^{\eta ik}}$ ………(11)

Where A_{ik} is the log-normal shading effect for path k of user i, d_{ik} is the distance between path k , η_{ik} is the path loss exponent of user i through path k, f_{ik} is the Doppler shift, and Ψ_{ik} is the phase shift.

Hence, the output signal at antenna element j can be expressed as:

$u_i = s_i(t) * \sum_{k=1}^{B_i} \ ^{j\Delta\Psi jk} \sqrt{p_{ik}} e^{j(2\pi^{fik+\Psi ik)}} \delta(t-\tau_k) + n_i(t)$…..(12)

$= \sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik} e^{j(2\pi f_{ik} t+\Psi_{ik})s_i}}(t-\tau_k) + \underline{n}_i(t)$

Where $\underline{n}_i(t)$ is the additive noise at the antenna element j.

In channels where the time differences between paths are small relative to the symbol period $s(t)$ we can approximate the latest equation as:

$$u_{ij} = s_i(t-\tau_0) \sum_{k=1}^{B_i} e^{-j\Delta\Psi_{jk}} \sqrt{\rho_{ik}} e^{j(2\pi f_{ik}+\Psi_{ik})} + \underline{n}_i(t)$$

$$\Rightarrow u_i = s_i(t-\tau_0) \sum_{k=1}^{B_i} \underline{a}\,(\emptyset_{ik}) a_{ik}(t) + \underline{n}_i(t) \qquad \dots\dots \ (13)$$

$$= s_i(t-\tau_0)\underline{b}(t) + \underline{n}_i(t)$$

In (13), $\underline{b}(t)$is called the spatial signature of the narrowband (flat fading) channel.

VI. ADAPTATION TECHNIQUES

Beamforming techniques are methods of steering the antenna array pattern in a particular direction to maximize the output performance of array such as SINR (signal to interference noise ratio), BER (bit error rate), and throughput. Beamforming techniques have been applied to radar, sonar [14], spatial microwave filtering, imaging applications (ultrasonic, optical and tomographic), geophysical and astrophysical explorations [15], underwater acoustic imaging, remote sensing, industrial applications (e.g. sensor array processing in manufacturing processes, automatic monitoring and fault detection/localization), environmental applications (e.g. chemical sensor arrays), medical sectors (e.g. treatment of tumors, electrocardiograms, and biomagnetic sensor arrays) [16], radio astronomy [17], and the business sectors of wireless cellular communication [18], [19].

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Other interesting applications include BTS tracking [20], land-mobile satellite communications [21], cellular base stations with multibeam antennas suitable for SDMA applications [22], and mobile communications [23]. In these applications the beamforming antenna acts as an adaptive array antenna to achieve a high diversity gain [24].

A. Conventional beamformer

In the conventional Beamformer, the weights are selected to be the conjugate of the steering vector, i.e., for one path case the weights are selected as:

$\underline{W}^H \underline{a} = c$ …………… (14)

Where c is real constant >0.

The main advantages of this method are its simplicity and it provides maximum output SNR if the noise is uncorrelated and there are no directional jammers. It is clear that this method is not reasonable to be used in mobile communication systems where there are so many users sharing the same frequency (for CDMA) so there are many unintentional jammers.

B. Null Steering Beamformer

If there are Q users in the cell, and the weights are calculated for user i, then the desired weight vector is the solution of the following system of nonlinear equations:

$\underline{W}_i^H \underline{a}_i = 1$

$\underline{W}_i^H \underline{a}_k = 0, \ \forall k \in [1, Q]$ and $k \neq i$ ……. (15)

The above system of linear equations can be solved perfectly if the number of users is less than or equal to the number of antenna elements. Generally, the problem could be solved as:

$\underline{W}_i = \underline{D}^T (\underline{A}^H \underline{A})^{-1} \underline{A}^H$ ……. (16)

Where $\underline{D} = [0 \ldots 1 \quad 0 \ldots 0]^T$ 1at i^{th} element,

$= [a_1 \ldots\ldots \ a_m]$.

C. Minimum Variance Distortion Less Response Beamformer (MVDR)

The concept of MVDR beamformer is based on minimizing the average output array power while marinating unity response in the look direction. Mathematically as:

Min E [$|z(t)|^2$], subject to $\underline{w}^H i \ \underline{a}_i = 1$…… (17)

The weights obtained by solving the above optimization problem will minimize the total noise, including interferences and uncorrelated noise. Thus, MVRD beamformer maximizes the output SINR.

Langrange multiplier method can be used to solve the problem, and to get:

$\underline{W} = \frac{R^{-1} a_i}{a_i^H R^{-1} a}$, where $\underline{R} = E[\underline{uu^H}]$…… (18)

D. Minimum Mean Square Error Beamformer

If the transmitter sends a reference signal known to the receiver (e.g., pilot signal), then this signal can be used to calculate the optimum weights even if there is no information about the Direction of Arrival (DoA) or about the channel characteristics. One of the methods which uses a reference signal is MMSE which is based on finding the optimum weights that minimizes the mean square error as

$\underline{\hat{W}}_i = \arg\min E [\, |w_i^H \underline{u}(k) - d_i(k)|^2]$…..(19)

d_i (k) is the training sequence for user i at time k. the weight vector that achieves that (19) is

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$\underline{\hat{W}}_i = \underline{R}^{-1}\, \underline{P}$ …… (20)

Where

$\underline{R} = E[\underline{u}\underline{u}^H]$ and $P = E[\underline{u}d_i^*]$

E. Least Square Despread Respread Multitarget Array (LSDRMTA)

This algorithm is based on the respreading of the receiver data bits. The respreaded signal is compared with the received signal (before the despreading) and the difference is used as an error signal. This error minimized by adjusting the antenna weight. Figure 4 shows the block diagram of the LS-DRMTA for users.

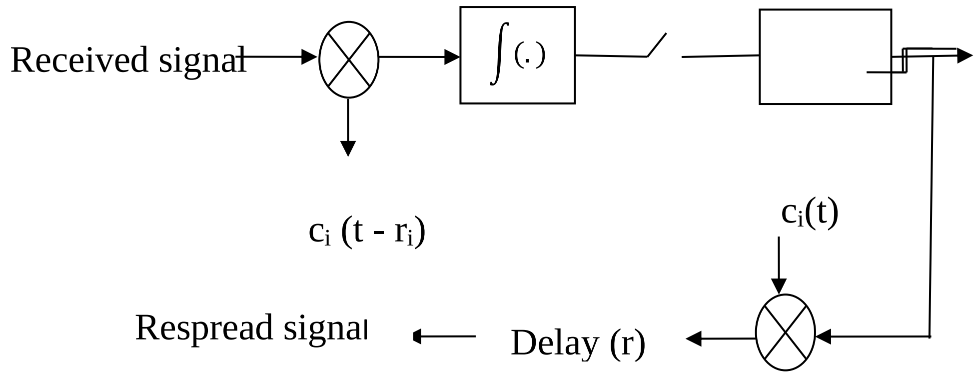

Figure 4. The block diagram of the IS-DRAMTA

The respreaded signal is given by:

$$r_i(t) = b_{in} C_i(t - \tau_i), \quad (n-1)T_b \le t \le nT_b \; \ldots .(21)$$

The LS-DRMTA is used to minimize an error function by adjusting the weight vector w_i. the cost function is given by:

$$F(\underline{w}) = \sum_{k=1}^{k} |y_I(k) - r_i(k)|^2 = \sum_{k=1}^{k} |w_i^H \underline{x}(k) - r_i(k)|^2$$

VII. CONCLUSION

The objective of this study was to give an insight into adaptive antenna systems, as well as general overview of its benefits, techniques, and algorithms.

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