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Issues in Deploying Smart Antennas in Mobile Radio Networks

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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 are diminishing natural resources, there seems to be a fundamental barrier to further capacity increase. The solution can be found in smart antenna systems.

Smart or adaptive antenna arrays consist of an array of antenna elements with signal processing capability, that optimize the radiation and reception of a desired signal, dynamically. Smart antennas can place nulls in the direction of interferers via adaptive updating of weights linked to each antenna element. They thus cancel out most of the co-channel interference resulting in better quality of reception and lower dropped calls. Smart antennas can also track the user within a cell via direction of arrival algorithms. This implies that they are more advantageous than other antenna systems. This paper focuses on few issues about the smart antennas in mobile radio networks.

Keywords**—**Smart/Adaptive Antenna, Multipath fading, Beamforming, Radio propagation.

I. INTRODUCTION

WIRELESS Communication technologies have a great progress in recent years and the markets, especially the cellular telephone, have been growing enormously. Moreover the next generation communication services will use higher frequency band area and require more channel capacity and wider bandwidth for a high-speed data communication. As a large increase in channel capacity and high transmission rates for wireless communications, the technologies for the power saving and efficient frequency usability are required.

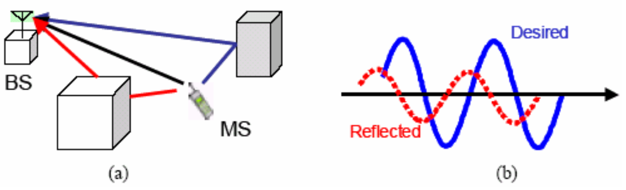

Fig. 1 (a) Effect of multi-path from a mobile user and
(b) Two out-of-phase multi-path signals

As a matter of fact in many communication environments there are several serious problems such as a multi-path fading caused by a reflection by any physical structures as in Fig. 1(a). When passing through multi-path, the signals are delayed and out of phase from the signals through direct-path, as shown in Fig. 1(b), that causes the signal strength to be weakened at a receiver and hence receiving quality is also reduced.

Generally it is known as “Raleigh Fading”. Wider band and higher transmission rate make it more critical problem in the improvement of the communication quality in the next generation communication [1]. To solve this problem many solutions have been already studied. However it is most important to configure receiver and transmitter flexibly in response to the signal environment. For example, spatial diversity techniques using composite information from the array to minimize fading and other undesirable effects of multi-path propagation have been studied in many applications. Several techniques such as phased array antenna and diversity antenna using active array configurations can adapt the antenna pattern according to the change of mobile communication environment [2].

To meet the requirements of the next generation wireless communications, a system capable of automatically changing the directionality of its radiation patterns (beams) in response to its signal environment must be indispensable. This can noticeably increase the performance characteristics such as capacity and quality of a wireless system.

One of the technologies that can contribute to the improvement of wireless systems is the adaptive/smart antenna. An “Adaptive/Smart Antenna” system uses spatially separated antennas called array antenna and processes received signals with a digital signal processor after analog to digital conversion and the name is derived from an “Adaptive Filter” or “Adaptive Filter Signal Processing”. This type of antenna that is combined with a digital signal processor is also called by the name of “Smart Antenna” or “Software Antenna” or “Digital Beamforming Antenna (DBF Antenna)” that all mean an intelligent antenna different from a conventional omni-directional antenna only receiving and transmitting signals without any considerations. The terms “Adaptive Antenna” and “Smart Antenna” are interchangeable.

II. RADIO PROPAGATION

The mobile radio propagation environment places fundamental limitations on the performance of wireless communication systems. Signals arrive at a receiver via a scattering mechanism and the existence of multipath with different time delays; attenuations and phases give rise to a

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highly complex, time-varying, transmission channel. The radio channel in a wireless communication system is often characterized by multipath propagation [4]. A fading signal results from interference between multipath components at the receiver.

Due to multipath propagation, the composite received signal is the sum of the signals arriving along different paths. As shown in Fig. 2, except for the line-of-sight (LOS) path, all paths are going through at least one order of reflection or diffraction before arriving at the receiver [5].

The average received signal power decreases as the distance from transmitter increases. In addition, phase alignment or cancellation of arriving paths results in considerable amplitude fluctuation of the composite received signal from one location to another. The time dispersion and random amplitude and phase fluctuations in the received signal, a set of characteristics of channel effect, is termed *multipath fading* [6].

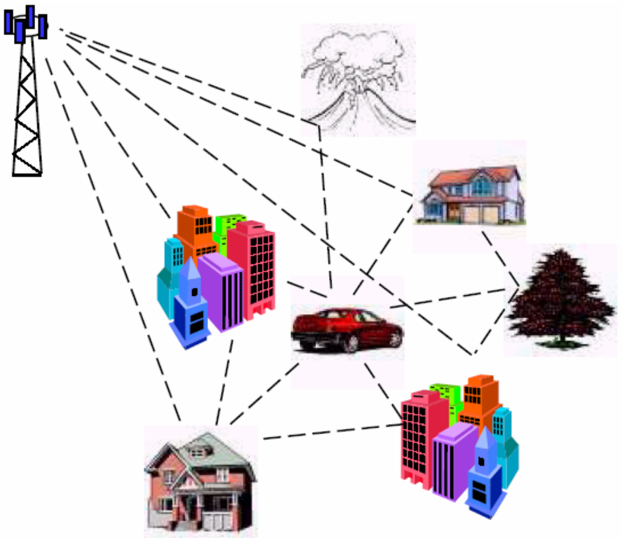

Fig. 2 A typical mobile radio propagation environment

The multipath channel impulse response is represented by

$$h(\tau;t)=\sum_{i=1}^{L}\beta_i(t)\delta(\tau-\tau_i(t))$$

where L is the number of paths, β_i and τ_i represent the complex gain and the delay of the i^{th} arriving path.

Delay Spread: The span of the time dispersion of arriving paths is referred to as *multipath delay spread* of the channel. Taken into account the signal intensity over the delay span, a good measure is the *root mean square (rms) delay spread*, given by

$$\tau_{rms}=\sqrt{\bar{\tau^2}-(\bar{\tau})^2}$$

where,

$$\bar{\tau^n}=\frac{\sum\tau_i^n|\beta_i|^2}{\sum|\beta_i|^2},\quad n=1,2$$

The inverse of the rms delay spread is referred to as the *coherence bandwidth* of the channel. Wideband signal has high data rate in comparison to the coherence bandwidth.

Doppler Spread: With the relative motion of the transmitter and the receiver, or the change of the transmission media, e.g. movement of reflectors, the received signal experiences Doppler frequency shift. The spreading within the maximum frequency shift is referred to as the *Doppler spread*. The adaptation time of algorithms used in the receiver must be faster than the Doppler spread of the channel in order to accurately track the fluctuations in the received signal [7] [8].

III. SMART ANTENNAS IN MOBILE COMMUNICATION

The technology of smart antennas for mobile communications has received enormous interest worldwide in recent years. The reason for introducing smart antennas is the possibility for a large increase in capacity: an increase of three times for TDMA systems and five times for CDMA systems has been reported [9] [10].

It is foreseen that in the future an enormous increase in traffic will be experienced for mobile and personal communications systems. This is due to increased number of users as well as new high bit rate data services being introduced. This trend is observed for second-generation systems and will most certainly continue for third-generation systems being introduced worldwide within a few years. The increase in traffic will put a demand on both manufacturers and operators to provide enough *capacity* in the networks. Presently, one of the most promising techniques for increasing the capacity in cellular systems by the amount necessary is *smart* or *adaptive antennas*.

Though smart antenna techniques are new in the area of mobile communications, the technology itself was introduced in 1960's. Early smart antenna technology was deployed in military communication systems, where narrow beams were used in order to avoid interference arising from noise and other jamming signals [11]. Extending the smart antenna concept further researchers worked on the technology to apply it to the personal communication industry to accommodate more users in the wireless network by suppressing interference.

Switched beamforming is a smart antenna approach in its simplest form, where multiple fixed beams in predetermined directions are used to serve the users. In this approach the base station switches between several beams that gives the best performance as the mobile user moves through the cell.

Most advanced approach based on smart antenna technique, known as adaptive beamforming uses antenna arrays backed by strong signal processing capability to automatically change the beam pattern in accordance with the changing signal environment. It not only directs maximum radiation in the direction of the desired mobile user but also introduces nulls at interfering directions while tracking the desired mobile user at the same time. Multiplying the incoming signal with complex weights and then summing them together to obtain the desired radiation pattern achieve the adaptation. These weights are computed adaptively to adapt to the changes in the signal environment. The complex weight computation based on different criteria is incorporated in the signal processor in the form of software algorithms [12].

1) Why Now?

In the last couple of years smart antennas for mobile communications have received enormous interest worldwide. So why is the interest appearing now, and not few years ago? The answer probably lies with the fact that for most operators there has not been much reason to worry about capacity and spectrum efficiency. Also, as will be apparent later on, if the base station is to track a large number of users simultaneously, the computational cost will be large. Only recently are processors with sufficient power becoming available. In addition to increased capacity, smart antennas also introduce a number of other advantages to cellular networks, including *increased range*, *a higher level of security,* and the *possibility for new services*.

Basic Principles

What do we mean by the term "smart antenna?" The theory behind smart antennas is not new. The technique has for many years been used in electronic warfare (EWF) as a countermeasure to electronic jamming. In military radar systems similar techniques were already used during World War II. There are in principle a number of ways in which an adaptively adjustable antenna beam can be generated, for instance by mechanically steered antennas. However, the technology almost exclusively suggested for land-based mobile and personal communications systems is *array antennas*.

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 pattern in the directions of the interferers, the quality of the communication link can be significantly improved [13]. In personal and mobile communications, the interferers are other users than the user being addressed.

2) Concepts

Several different definitions for smart antennas are used in the literature. One useful and consistent definition can be that the difference between a smart/adaptive antenna and a "dumb"/fixed antenna is the property of having an adaptive and fixed lobe-pattern, respectively. Normally, the term "antenna" comprises only the mechanical construction transforming free electromagnetic (EM) waves into radio frequency (RF) signals traveling on a shielded cable and vice versa. We may call it *the radiating element*.

What are smart antennas?

In the context of smart antennas, the term "antenna" has an extended meaning. It consists of a number of radiating elements, a combining/dividing network and a control unit. The control unit can be called the smart antenna's intelligence, normally realized using a digital signal processor (DSP).

Evolutionary Path

The evolution can be divided into three phases:

Phase 1: Smart antennas are used on *uplink* only. By using a smart antenna to increase the gain at the base station, both the sensitivity and range are increased. This concept is called *high sensitivity receiver* (HSR) and is in principle not different from the diversity techniques implemented in today's mobile communications systems.

Phase 2: In the second phase, directed antenna beams are used on the *downlink direction* in addition to HSR. In this way, the antenna gain is increased both on uplink and downlink, which implies a spatial filtering in both directions. Frequencies can be more closely reused, thus the system capacity increases. The method is called *spatial filtering for interference reduction* (SFIR). It is possible to introduce this in second-generation systems.

Phase 3: The last stage in the development will be full *space division multiple access* (SDMA). This implies that more than one user can be allocated to the same physical communications channel simultaneously in the same cell, only separated by angle. In a TDMA system, two users will be allocated to the same time slot and carrier frequency at the same time and in the same cell.

In phase 2, the capacity is increased due to closer frequency reuse allowing more carriers per base station. In phase 3, an additional increase in capacity is achieved by allowing more users per carrier. Introducing SDMA in second-generation TDMA systems will be difficult and maybe undesirable, but it may become a natural component in third-generation systems.

IV. BASIC CONFIGURATION

Generally an adaptive/smart antenna system consists of a lot of functions including an array antenna and an RF and IF circuitry and beamforming network and an adaptive controller. Fig. 3 illustrates the basic configuration.

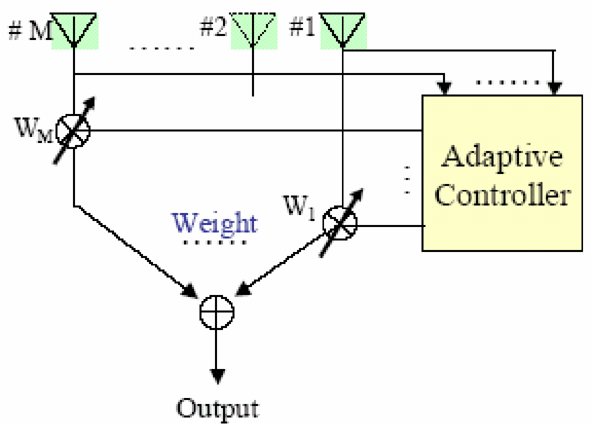

Fig. 3 Diagram of Basic Adaptive Antenna System

There are various physical arrangements of an array such as linear, circular, rectangular, etc. The structure of an array antenna is determined in consideration of the characteristics and the applications. Most functions of the RF/IF circuitry are frequency downconversion, filtering and amplifying. The beamforming network performs a phase and amplitude control of input signals fed from array antenna, which plays a role in combining beampattern of the array antenna operating as a spatial filter. An adaptive controller determines the optimum weight for beamforming. There are various algorithms for obtaining optimum weight [14] [15].

The basic structure to explain the principle of adaptive antenna signal processing is illustrated by Fig. 4.

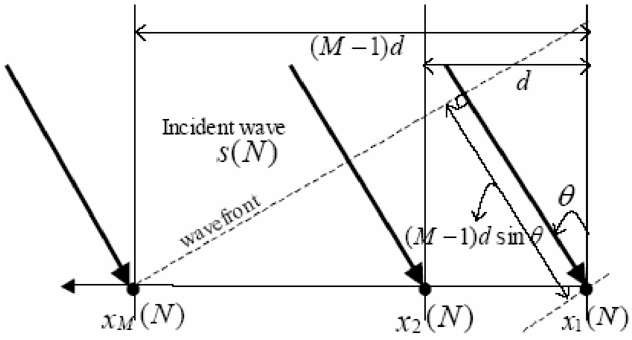

Fig. 4 Uniform Linear Array of *M*-Element

The array antenna is assumed to be a uniform equidistance linear array of identical and omni-directional *M* elements and an electromagnetic wave arriving at array antenna is an approximately plane and narrowband signal. Let the angle between wave normal and incident angle θ, the far-field expression of the electrical signal at *k*-th element at any discrete time *N* is given by

$$x_k(N) = s_k(N)\cdot\exp(-j\frac{2\pi}{\lambda}dk\sin\theta) \qquad k = 1, 2, \cdots, M \tag{1}$$

where $s_k(N)$, λ and θ is the envelop, wavelength and Direction-Of-Arrival (DOA) angle of an incident wave respectively and *d* is the distance spaced between each antenna. In this equation if $s_k(N)$ is a narrow band signal the temporal delay caused by different path between elements corresponds to the phase difference. The output of array antenna is produced by the inner product (multiply-accumulate operation) of input signals and weight coefficients determined by adaptive algorithms as in equation (2).

$$y(N) = \sum_{k=1}^{M} w_k^{*}\cdot s_k(N)\cdot\exp(-j\frac{2\pi}{\lambda}dk\sin\theta) \tag{2}$$

They can be also re-written by vector expression as (3)-(4).

$$\mathbf{X} = [x_1(N) \quad x_2(N) \quad \cdots \quad x_M(N)]^T \tag{3}$$

$$y = \mathbf{W}^H\mathbf{X} \tag{4}$$

Basically adaptive antenna technique forms the antenna radiation pattern toward intended direction by digital signal processing. There are two kinds of work. One is beam-steering toward desired direction and the other is null steering toward undesired interferences, which may be more important function and the original concept of an adaptive antenna. Furthermore historically the first adaptive antenna is Howells' intermediate frequency (IF) side-lobe canceller for nulling out the effect of one jammer [16].

On the other hand, to determine the optimum weight, most of the beamforming algorithms such as LMS, RLS, CM, etc. whose solutions are based on solving Wiener-Hopf equation require the information of DOAs of desired signals and interferers in advance.

V. EFFECTIVENESS OF SMART ANTENNAS

The various factors that have to considered in designing a wireless system and the challenges to be met can be listed as follows:

- A multipath time-varying propagation environment
- Limited radio spectrum
- Batteries - size and the duration they operate
- Dropped calls
- Co-channel interference
- Capacity of the system in terms of traffic it can handle and subscriber base

The main advantages of using adaptive antenna arrays in a wireless communication system are listed below. Their implementation will have a large impact on the performance of cellular networks. It will also affect many aspects of both the planning and deployment of mobile systems.

(i) They enhance the range of coverage and thus reduce the initial deployment cost of a wireless system

In rural and sparsely populated areas, a range increase potential is available because smart antennas are more directive than traditional sector or omni-directional antennas. Since smart antennas employs collection of individual elements in the form of an array they give rise to narrow beam with increased gain when compared to conventional antennas using the same power [17]. The increase in gain leads to increase in range and the coverage of the system. Therefore fewer base stations are required to cover a given area.

(ii) Reduction in co-channel interference

Smart antennas has a property of spatial filtering to focus radiated energy in the form of narrow beams only in the direction of the desired mobile user and no other direction. In addition they also have nulls in their radiation pattern in the direction of other mobile users in the vicinity [18]. Therefore there is often negligible co-channel interference.

(iii) Can be applied to the various multiple-access schemes such as TDMA, CDMA and FDMA.

(iv) Help mitigate the effects of multi-path and improve Quality of service as compared to the scenario when conventional antennas were used.

By using a narrow antenna beam at the base station the multipath propagation can be somewhat reduced.

(v) Improve system capacity

In densely populated areas, interference from other users is the main source of noise in the system. This means that the signal to interference ratio, SIR, is much larger than the signal to thermal noise-ratio, SNR. Adaptive antenna arrays increase the received SIR by simultaneously increasing the useful received signal level and lowering the interference level. In TDMA systems, the implication of the increased SIR is the possibility for reduced frequency reuse distance. In CDMA too, the main source of noise in the system is the interference from other users. This means that the expected capacity gain is even larger for CDMA than for TDMA [18] [19].

(vi) Can lead to new services

Smart antennas can give wireless networks access to spatial information about the users. This information can be used to estimate the positions of the users much more accurately than in existing networks. Positioning can be used in services such as emergency calls and location-specific billing.

(vii) Increased security

It is more difficult to tap a connection when smart antennas are used. To successfully tap a connection the intruder must be positioned in the same direction as the user as seen from the base station.

(viii) Reduction in transmitted power

Ordinary antennas radiate energy in all directions leading to a waste of power. Comparatively smart antennas radiate energy only in the desired direction. Therefore less power is required for radiation at the base station [20]. Reduction in transmitted power also implies reduction in interference towards other users.

(ix) Lower handset power consumption
(x) Increased data rate
(xi) There is lower specific absorption rate (SAR)
(xii) Improved spectral efficiency [21]
(xiii) It combines the signal it receives directly from the base station with the reflections of the same signal whereas a conventional handset normally tunes into the strongest signal it can find.
(xiv) It is possible to combine the signals from the antennas in a particular way that both the SNR and CIR levels are improved.
(xv) Research done on outdoor mobile communication systems indicates that addition of adaptive circuitry can overcome most of the impairments by the effects of multipath fading [22] [23].

VI. CONCLUSION

Many discussions of possible future technologies for wireless networks assume the adoption of multiple antenna techniques. The advantages of such a system are indisputable. One problem with MIMO technology is getting sufficient decoupling between the antennas, so each antenna provides uncorrelated signal samples. At present the technique is better suited to larger devices (laptops) than for small hand-held devices (mobiles).

It has been indicated that there are many significant – and perhaps insuperable – problems in adopting these powerful multiple antenna techniques into the existing structure of mobile radio networks. At the frequencies in use for mobile radio systems, multiple antennas are physically large, and a single antenna configuration cannot easily support multiple transmitters and receivers. The question is whether the existing organizational structure of mobile radio networks could be changed in such a way as to allow the advantages of these potentially beneficial techniques to be achieved more rapidly.

One characteristic of current practice is that each mobile network operator currently rolls out a complete network of base stations. At some locations these occupy common supporting structures while in other locations each network builds a separate structure. The antenna installations are almost always independent, with each group of physical antenna arrays serving one operator. At many locations each of the network operators installs radio equipment and antennas operating on several different frequency bands. The antennas for each frequency band are sometimes physically combined in a single physical device, but they are often separate – an arrangement which allows more operational flexibility in allowing the physical networks at each band to be optimised and upgraded independently.

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