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Advances in Mobile Communication by Implementation of Smart Antennas

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Abstract

The antenna is one of the fundamental distinctions between a wired and a wireless system. The design of the antenna impacts the development of each component-from the circuit design to the receiver structure and coding technique, as well as the channel access protocol - employed in future wireless communication networks. The adoption of smart antenna techniques in future wireless systems is expected to have a significant impact on the efficient use of the spectrum, the minimization of the cost of establishing new wireless networks, the optimization of service quality, and realization of transparent operation across multi technology wireless networks.

This paper presents brief account on smart antenna (SA) system in context of architecture, evolution and distinction of smart / adaptive antenna from the basic format of antenna. Further, about the radiation pattern of the antenna and why it is highly preferred in its relative field is explained. The capabilities of smart / adaptive antenna are easily employable to Cognitive Radio and OFDMA system.

Keywords

Smart /Adaptive Antenna, Beam Forming, DSP, SDMA, OFDMA

I. Introduction

This Global demand for voice, data and video related services continues to grow faster than the required infrastructure can be deployed. Engaging coaxial cable or power transmission line for communication suffers with its own limitation. Implementation of optical fiber for the same raises the cost exponentially. This is why more and more the wireless connection is being seen as an alternative to quickly and cost effectively meeting the need for flexible broadband links [1].

Over the last few years the demand for service provision via the wireless communication bearer has risen beyond all expectations. At the end of the last century more than 20 million users in the United States only utilized this technology [2]. At present the number of cellular users is growing annually by approximately 50 percent in North America, 60 percent in Western Europe, 70 percent in Australia and Asia and more than 200 percent in South America. The proliferation of wireless networks and an increase in the bandwidth required has led to shortages in the scarcest resource of all, the finite number of radio frequencies that these devices use. This has increased the cost to obtain the few remaining licenses to use these frequencies and the related infrastructure costs required to provide these services. Generally, increased transmission rates require increased power and bandwidth independently of medium. For a given amount of power (constrained by regulation or practical considerations) and a fixed amount of bandwidth (the amount one can afford to buy) there is a finite (small) amount of capacity (bits/sec/Hz/unit-area, really per unit-volume) that operators can sell to their customers, and a limited range over which customers can be served from any given location.

Thus, the two basic problems that arise in such systems are:

A. How to acquire more capacity so that a larger number of customers can be served at lower costs maintaining the quality at the same time, in areas where demand is large (spectral efficiency)?

B. How to obtain greater coverage areas so as to reduce infrastructure and maintenance costs in areas where demand is relatively small (coverage)?

This concern has led to the deployment of smart antenna systems throughout major metropolitan cellular markets. These smart antenna systems have typically employed multi-beam technologies, which have been shown, through extensive analysis, simulation, and experimentation, to provide substantial performance improvements in FDMA, TDMA and CDMA networks [3-7]. Multibeam architectures for FDMA and TDMA systems provide the straight-forward ability of the smart antenna to be implemented as a non-invasive add-on or appliqué to an existing cell site, without major modifications or special interfaces [8].

This paper mainly concentrate on use of smart antennas in mobile communications that enhances the capabilities of the mobile and cellular system such as faster bit rate, multi use interference, Space Division Multiplexing (SDMA), adaptive SDMA [9], increase in range, multipath mitigation, reduction of errors due to multipath fading, best suitability of multi-carrier modulations such as OFDMA. The best application of smart antennas is its suitability for demand based frequency allocation in hierarchical system approach (flexible antenna pattern are achieved electronically and no physical movement of receiving antennas is necessary). The advantage of smart antennas application in cellular systems are decreased inter symbol interference, decreased co-channel interference and adjacent channel interference, improved bit error rate (due to decreased amount of multipath and ISI), increase in receiver sensitivity, reduction in power consumption & RF pollution. Smart antennas are most appropriate for use of cognitive radio (software radio technology provides flexibility) and the greatest advantage of smart antenna is a very high security. The main impediments to high-performance wireless communications are interference from other users (co channel interference), the Inter-Symbol Interference (ISI) and signal fading caused by multipath. Co-channel interference limits the system capacity, defined as the number of users which can be serviced by the system. However, since the desired signal and co-channel interference typically arrive at the receiver from different directions, smart antennas can exploit these differences to reduce co-channel interference, thereby increasing system capacity. The reflected multipath components of the transmitted signal also arrive at the receiver from different directions, and spatial processing can use these differences to attenuate the multipath, thereby reducing ISI and fading. Since data rate and BER are degraded by these multipath effects, reduction in multipath through spatial processing can lead to higher data rates and better BER performance. In a cellular system, Omni-directional antennas have traditionally been used at base stations to enhance the coverage area of the base stations but it also leads a gross wastage of power that in-fact is the main cause of co-channel interference at neighboring base stations. The sectoring concept with diversity system exploits space diversity and results in improve reception by counteracting with negative effects of multipath fading. Adaptive / smart antenna technology represents the most advanced smart antenna approach to date. Using a variety of new signal-processing algorithms, the adaptive system takes advantage of its ability to effectively locate and track various types of signals to dynamically minimize interference and maximize intended signal reception. Both adaptive / smart systems attempt to increase gain according to the location of the user; however; only the adaptive system provides optimal gain while simultaneously identifying, tracking, and minimizing interfering signals.

II. Evolution from Omni-Directional to Smart Antennas

An antenna in a telecommunications system is the port through which Radio Frequency (RF) energy is coupled from the transmitter to the outside world for transmission purposes, and in reverse, to the receiver from the outside world for reception purposes [10]. Base station antennas have up till now been Omni-directional or sectored. This can be regarded as a "waste" of power as most of it will be radiated in other directions than toward the user. In addition, the power radiated in other directions will be experienced as interference by other users. The idea of smart antennas is to use base station antenna patterns that are not fixed, but adapt to the current radio conditions. This can be visualized as the antenna directing a beam toward the communication partner only. The difference between the fixed and the smart antenna concept is shown in Fig. 1. Smart antennas will lead to a much more efficient use of the power and spectrum, increasing the useful received power as well as reducing interference.

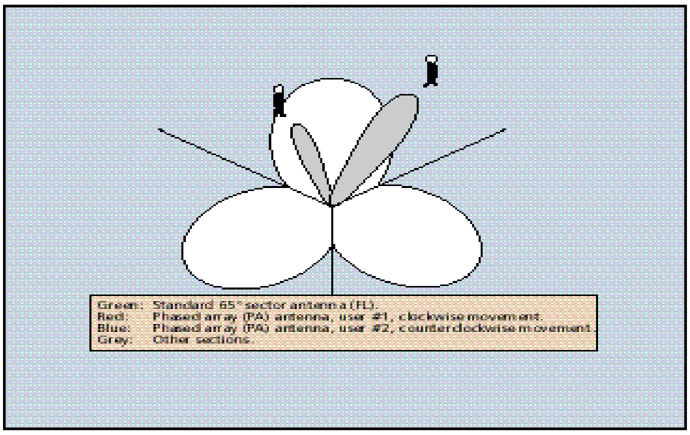

Fig. 1: Illustration of the Difference Between a Traditional Base Station Radiation Pattern and a Smart Antenna Base Station

III. Antenna Systems

An antenna can be made more intelligent if its physical design could be modified by adding more elements. Second, the antenna can become an antenna system that can be designed to shift signals before transmission at each of the successive elements so that the antenna has a composite effect. This basic hardware and software concept is known as the phased array antenna.

A. Sectorized Systems

The sectorized antenna systems take a traditional cellular area and subdivide it into sectors that are covered using directional antennas looking out from the same base station location. Operationally, each sector is treated as a different cell, the range of which is greater than in the Omni-directional case. Sector antennas increase the possible reuse of a frequency channel in such cellular systems by reducing potential interference across the original cell, and they are widely used for this purpose. As many as six sectors per cell have been used in practical service. When combining more than one of these directional antennas, the base station can cover all directions.

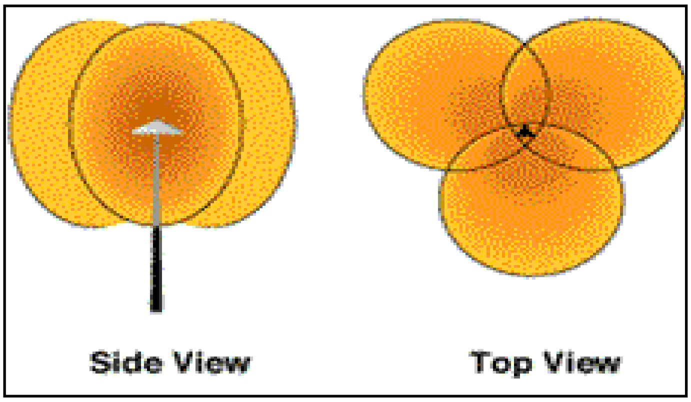

Fig. 2: Sectorized Antenna and Coverage Patterns

B. Diversity Systems

The diversity system incorporates two antenna elements at the base station, the slight physical separation (space diversity) of which has been used historically to improve reception b counteracting the negative effects of multipath. Diversity offers an improvement in the effective strength of the received signal by using one of the following two methods:

Switched diversity-Assuming that at least one antenna will be in a favorable location at a given moment, this system continually switches between antennas (connects each of the receiving channels to the best serving antenna) so as always to use the element with the largest output. While reducing the negative effects of signal fading, they do not increase gain since only one antenna is used at a time.

Diversity combining-This approach corrects the phase error in two multipath signals and effectively combines the power of both signals to produce gain. Other diversity systems, such as maximal ratio combining systems, combine the outputs of all the antennas to maximize the ratio of combined received signal energy to noise.

Because macro cell-type base stations historically put out far more power on the downlink (base station to user) than mobile terminals can generate on the reverse path, most diversity antenna systems have evolved only to perform in uplink(user to base station).

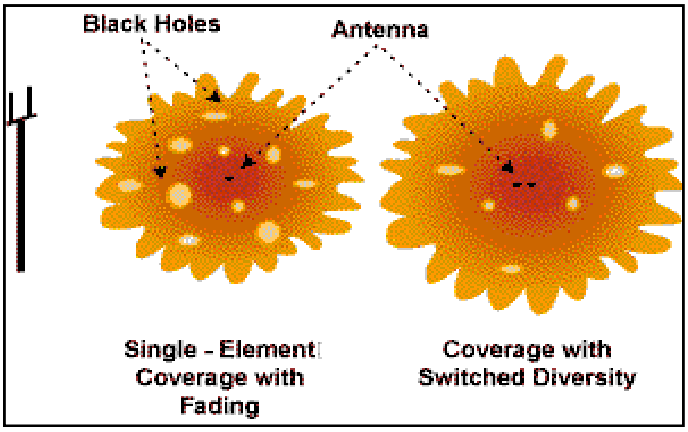

Fig. 3: Switched Diversity Coverage With Fading and Switched Diversity

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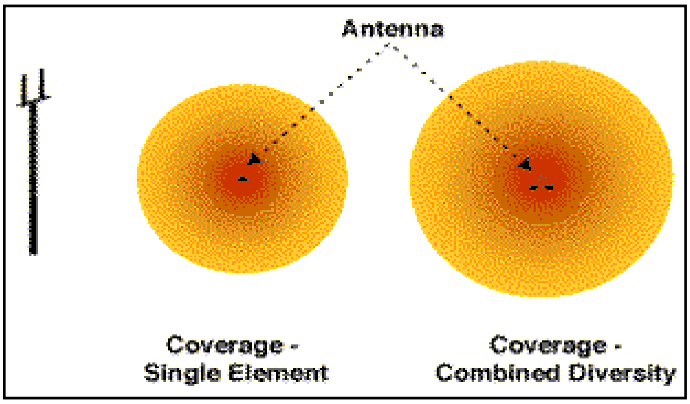

Fig. 4: Combined Diversity Effective Coverage Pattern With Single Element and Combined Diversity

Diversity antennas merely switch operation from one working element to another. Although this approach mitigates severe multipath fading, its use of one element at a time offers no uplink gain improvement over any other single element approach. In high-interference environments, the simple strategy of locking onto the strongest signal or extracting maximum signal power from the antennas is clearly inappropriate and can result in crystal-clear reception of an interferer rather than the desired signal. The need to transmit to numerous users more efficiently without compounding the interference problem led to the next step of the evolution antenna systems that intelligently integrate the simultaneous operation of diversity antenna elements.IV. Concept of smart antennas

A smart antenna system combines an antenna array with a digital signal-processing capability to transmit and receive in an adaptive, spatially sensitive manner. In other words, such a system can automatically change the directionality of its radiation patterns in response to its signal environment. This can dramatically increase the performance characteristics (such as capacity) of a wireless system.

Smart antenna solutions are required as the number of users, interference, and propagation complexity grow. Their smarts reside in their digital signal-processing facilities. Like most modern advances in electronics today, the digital format for manipulating the RF data offers numerous advantages in terms of accuracy and flexibility of operation. Speech starts and ends as analog information. Along the way, however, smart antenna systems capture, convert, and modulate analog signals for transmission as digital signals and reconvert them to analog information on the other end.

A. Types of Smart Antennas

Terms commonly heard today that embrace various aspects of a smart antenna system technology include intelligent antennas, phased array, SDMA, spatial processing, digital beam forming, adaptive antenna systems, and others. Smart antenna systems are customarily categorized, however, as either switched beam or adaptive array systems. The following are distinctions between the two major categories of smart antennas regarding the choices in transmit strategy:

1. Switched Beam

Switched beam antenna systems form multiple fixed beams with heightened sensitivity in particular directions. These antenna systems detect signal strength, choose from one of several predetermined, fixed beams, and switch from one beam to another as the mobile moves throughout the sector Instead of shaping the directional antenna pattern with the metallic properties and physical design of a single element (like a sectorized antenna), switched beam systems combine the outputs of multiple antennas in such a way as to form finely sectorized (directional) beams with more spatial selectivity than can be achieved with conventional, single-element approaches.

2. Adaptive Array

Adaptive antenna technology represents the most advanced smart antenna approach to date. Using a variety of new signal-processing algorithms, the adaptive system takes advantage of its ability to effectively locate and track various types of signals to dynamically minimize interference and maximize intended signal reception. Both systems attempt to increase gain according to the location of the user however, only the adaptive system provides optimal gain while simultaneously identifying, tracking, and minimizing interfering signals.

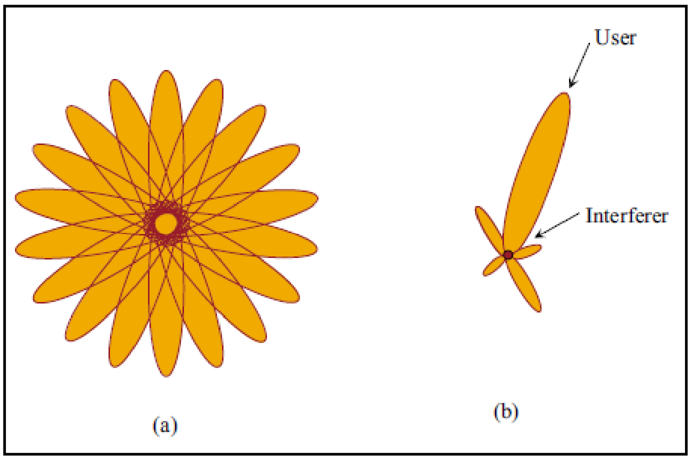

Fig. 5: Switched Beam System Coverage Patterns (a) and Adaptive Array Coverage (b).

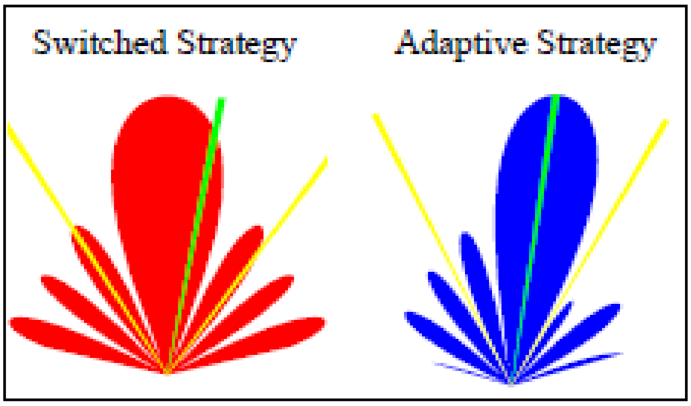

Fig. 6: Beam Forming Lobes and Nulls That Switched Beam (Red) and Adaptive Array (Blue) Systems Might Choose for Identical User Signals (Green Line) and Co-Channel Interferers (Yellow Lines)

B. What Makes Them so Smart?

A simple antenna works for a simple RF environment. Smart antenna solutions are required as the number of users, interference, and propagation complexity grow. Their smartness resides in their digital signal-processing facilities. Like most modern advances in electronics today, the digital format for manipulating the RF data offers numerous advantages in terms of accuracy and flexibility of operation. Speech starts and ends as analog information. Along the way, however, smart antenna systems capture, convert, and modulate analog signals for transmission as digital signals and reconvert them to analog information on the other end. In adaptive antenna systems, this fundamental signal-processing capability is augmented by advanced techniques (algorithms) that are applied to control operation in the presence of complicated combinations of operating conditions.

V. Objectives of Smart Antenna System

The dual purpose of a smart antenna system is to augment the signal quality of the radio-based system through more focused transmission of radio signals while enhancing capacity through increased frequency reuse.

Feature	Benefit
Signal Gain—Inputs from multiple antennas are combined to optimize available power required to establish given level of coverage.	Better Range / Coverage—Focusing the energy sent out into the cell increases base station range and coverage. Lower power requirements also enable a greater battery life and smaller/lighter handset size.
Interference Rejection —Antenna pattern can be generated toward co channel interference sources, improving the signal-to-interference ratio of the received signals.	Increased Capacity—Precise control of signal nulls quality and mitigation of interference combine to frequency reuse reduce distance (or cluster size), improving capacity. Certain adaptive technologies (such as space division multiple access) support the reuse of frequencies within the same cell.
Spatial Diversity—Composite information from the array is used to minimize fading and other undesirable effects of multipath propagation.	Multipath Rejection—can reduce the effective delay spread of the channel, allowing higher bit rates to be supported without the use of an equalizer, improved bit error rate (due to decreased amount of multipath and ISI).
SDMA-SDMA continually adapts to the radio environment through intelligent / smart antenna.	Providing each user with uplink and downlink signals of the highest possible quality and can adapt the frequency allocation to where the most users are located.
Power Efficiency—combines the inputs to multiple elements to optimize available processing gain in the downlink (toward the user)	Reduced Expense—Lower amplifier costs, power consumption, and higher reliability will result. Lower power consumption reduces not only interferences but also reduces RF pollution (ease health hazard). It will also result in reduction of scares energy resource (diesel consumption) and save foreign currency.

VI. Consequences

The introduction of smart antennas 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. This chapter will discuss the potential benefits and cost factors, and will also briefly describe the implications on radio planning.

A. Improvements and Benefits

1. Capacity Increase

The principle reason for the growing interest in smart antennas is the capacity increase. In densely 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 that the signal to interference ratio, SIR, is much larger than the signal to thermal noise-ratio, SNR. Smart antennas will on average, by simultaneously increasing the useful received signal level and lowering the interference level, increase the SIR. Especially, the adaptive array will give a significant improvement. Experimental results report up to 10 dB increases in average SIR in urban areas [11].

In TDMA systems, the implication of the increased SIR is the possibility for reduced frequency reuse distance. An example is shown in Fig. 6, where the traditional seven-cell cluster has been reduced to a three-cell cluster. This will lead to a capacity increase of 7/3 as all the cells can be allocated this amount more carriers. Simulations performed on a FH-GSM network with 1/3 reuse distance utilizing SFIR reports that a capacity increase of 300 percent can be expected [12].

CDMA systems, such as IS-95 or UMTS, are more inherently interference-limited than TDMA systems. The main source of noise in the system is the interference from other users due to the spreading codes being non-ideally orthogonal. This means that the expected capacity gain is even larger for CDMA than for TDMA. A fivefold capacity gain has been reported for CDMA in [13].

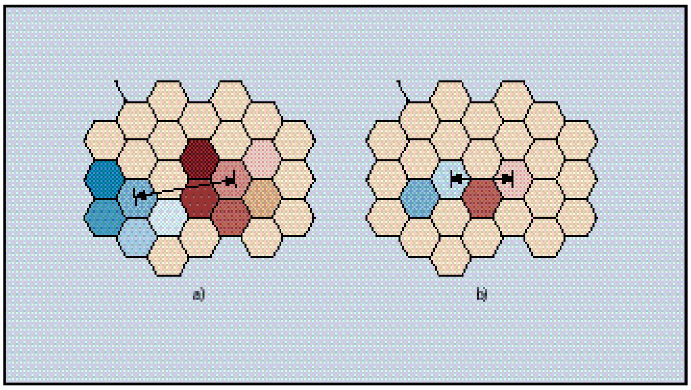

Fig. 7: Illustration of Reduced Frequency Reuses Distance: a) Traditional 7-Cell Cluster; b) Cluster Enabled by Interference Reduction Like e.g. Smart Antennas

2. Range Increase

In rural and sparsely populated areas radio coverage rather than capacity will give the premises for base station deployment. Because smart antennas will be more directive than traditional sector or Omni directional antennas, a range increase potential is available. This means that base s tat ions can be placed further apart, potentially leading to a more cost-efficient deployment. The 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).

3. New Services

When using smart antennas the network will have 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. The FCC (Federal Communications Commission) in the United States has decided that by October 2001 user location information with accuracy of 125 meters RMS error must be provided [14].

4. 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.

5. Reduced Multipath Propagation
By using a narrow antenna beam at the base station the multipath propagation can be somewhat reduced. The actual reduction depends on the scenario, and is not always significant. Although channel equalizers and RAKE receivers most often will handle and even exploit the multipath components, on very high-speed connections this may not be the case. Potentially, the reduction of multipath propagation can be used to ease the requirement on future modem design.

B. Cost Factors
Although the benefits of using smart antennas are many, there are also drawbacks and cost factors. The gain should always be evaluated against the cost.

1. Transceiver Complexity
It is obvious that a smart antenna transceiver is much more complex than a traditional base station transceiver. The antenna will need separate transceiver chains for each of the array antenna elements and accurate real-time calibration of each of them. In addition, the antenna beam forming is a computationally intensive process, especially if adaptive arrays are to be used (see earlier section). This means that the smart antenna base station must include very powerful numeric processors and control systems. There will be a growing need for the development of efficient algorithms for real-time optimizing and signal tracking. Smart antenna base stations will no doubt be much more expensive than conventional base stations.

2. Resource Management
Smart 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. This can be handled by letting the base station continuously sweep through the cell with a “search” beam looking for candidates for a new connection or a handover. Another possibility is to use an external system for positioning, e.g., GPS. As far as handover is concerned, a third possibility is available: directional information from the existing cell can be used by the network to provide an “educated guess” about which cell to hand the connection over to.

As it was explained earlier, SDMA involves different users using the same physical communication channel in the same cell, separated only by angle. When angular collisions between these users occur, one of them must quickly switch to another channel so that the connection is not broken. This means that in systems providing full SDMA, there will be much more intra-cell handovers than in conventional TDMA or CDMA systems, and more monitoring by the network is necessary. The animation in fig. 1 shows what is meant by an angular collision.

3. Physical Size
For the smart antenna to obtain a reasonable gain, an array antenna with several elements is necessary. Typically arrays consisting of six to 10 horizontally separated elements have been suggested for outdoor mobile environments [15-17]. The necessary element spacing is 0.4–0.5 wavelengths. This means that an eight-element antenna would be approximately 1.2 meters wide at 900 MHz and 60 cm at 2 GHz. With a growing public demand for less visible base stations, this size, although not excessive, could provide a problem. Figure 7 shows a picture of an eight-element antenna array at 1.8 GHz.

Fig. 10: Picture of an 8-Element Array Antenna at 1.8 GHz. (Antenna Property of Telia Research AB, Sweden)

VII. Conclusion
The main goal of this article has been to provide an overview of smart antenna technologies with respect to third-generation mobile communication systems. Obviously that smart antennas at the base stations will be an important technology to provide the necessary capacity and coverage. It also helps to realize new services, e.g., based on user location. From a technology point of view, smart antennas can be seen as an extension of the “conventional” resource allocation schemes used in radio communications. In addition to dividing the space into cells, it will now also be possible to employ space division inside each cell. Different degrees of utilization of the spatial dimension are possible, and different steps have been described here. Smart antenna technology is a broad concept and implementations range from simple techniques that involve switching between lobes to advanced algorithms maximizing the received signal-to-interference ratio. Implementation of smart antennas is done using array antennas. The techniques for Beam forming with array antennas are well known, and must be employed in both duplex directions for the improvements to be substantial. However, with rapid channel variations it is not a trivial task to provide optimum beam forming, especially for the downlink direction. The use of smart antennas is not purely a radio transmission issue. It also influences network services such as handover and connection setup. Introducing the spatial domain in the resource management system makes this more complex.

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