

Application of Smart Antenna Technology in Wireless Communication Systems

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Abstract— Wireless communications is widely recognized as one of the fastest growing industries in today's global marketplace. As with any nascent industry faced with unexpectedly large demand for its products, growing pains are inevitable. Consumers are continually pressing system providers to expand their suite of services, and to provide these services at ever-decreasing costs. Unfortunately for system providers, there is only so much *product* to sell and technological limitations are in many instances becoming significant barriers in the quest to meet consumers' insatiable demand. In this article, a brief description of some of the current technical challenges facing wireless service providers is given, historical attempts to address these challenges are summarized, and an overview of intelligent antenna technology as a solution thereto is presented.

I. INTRODUCTION

In a majority of currently deployed wireless telecommunication systems, the objective is to sell a product at a fair price, the

product being information transmission from one or more points to one or more points. Cellular and next generation PCS systems, in some sense the *killer-apps* of wireless, are classic examples where operators sell point-to-point information transfer to consumers largely in the form of circuit-switched (voice) links over which standard phone calls can be placed.

From a technical standpoint, information transmission requires resources in the form of power and bandwidth. Generally, increased transmission rates require increased power and/or bandwidth independent of the medium. While transmission over wired segments of the links can generally be performed independently for each link (ignoring cross-talk in land lines), this is not the case for wireless segments. While wires (fibers) are excellent at confining most of the useful information/energy to a small region in space (the wire), wireless transmission is much less efficient. Reliable transmission over relatively short distances in space requires a large amount of transmitted energy, spread over large regions of space, only a very small por-

tion of which is actually received by the intended user. Most of the energy is considered *interference* to other potential users of the system (cf. frequency reuse).

Somewhat simplistically, the maximum range of such systems is determined by the amount of power that can be transmitted (and therefore received) and the capacity is determined by the amount of spectrum (bandwidth) available. For a given amount of power (constrained by regulation or practical considerations for example) and a fixed amount of bandwidth (the amount one can afford to buy at auction these days), 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: 1) how to acquire more capacity so that a larger number of customers can be served at lower costs in areas where demand is large, and 2) how to obtain greater coverage areas so as to reduce infrastructure and maintenance costs in areas where demand is relatively small.

II. THE QUEST FOR CAPACITY

In areas where demand for service exceeds the supply operators have to offer, the real game being played is the quest for capacity. Unfortunately, to date a universal definition of capacity has not evolved. Free to make their own definitions, operators and consumers have done so. To the consumer, it is quite clear that capacity is measured in the quality of each link he gets and the number of times he can successfully get such a link when he wants one. Consumers want the highest possible quality links at the lowest possible cost.

Operators, on the other hand, have their own definition of capacity in which great im-

portance is placed on the number of links that can simultaneously be established. Since the quality and number of simultaneous links are inversely related in a resource constrained environment, operators lean toward providing the lowest possible quality links to the largest possible number of users. That the war wages on is evidenced by churn and the lack of acceptance of current digital systems in markets where competitive analog service is available. Consumers are wanting better links at lower cost, and operators are continually trying to maximize profitability providing an increasing number of lower quality links at the highest acceptable cost to the consumer. Until the quest for real capacity is successful, the battle between operators and their customers over capacity, the precious commodity that operators sell to consumers, will continue.

Attempts to obtain more capacity to sell have recently centered around transitions to digital systems. Unfortunately, this transition has involved giving less capacity to each customer (through voice compression), and having long associated digital technology with superior performance at lower cost, consumers are largely disappointed with digital wireless performance and cost (you can't fool the wireless consumer!). Attempts at increasing system capacity have involved the development of sectorized antennas for cellular systems, culminating with the more recent attempts to develop cost effective microcellular concepts. Such systems suffer from trunking inefficiencies, and higher costs per line, but can represent a solution to increasing capacity where the costs can be justified. As a long-term solution however, providing *base stations everywhere for everyone* may not be economically viable.

III. THE REQUIREMENT FOR RANGE

There are many situations where coverage, not capacity, is a more important issue.

Consider the roll-out of any new service such as PCS in the United States. Prior to initiating service, capacity is certainly not a problem; operators have no customers. Until a significant percentage of the service area is covered, service can not begin. Clearly coverage is an important issue during the initial phases of system deployment.

Consider also that in many instances only an extremely small percentage of the area to be served is heavily populated. Furthermore, the degree to which customers in those areas can be enticed to sign-on is a strong function of the coverage provided by the operator in the other 99.9% of the service area. The ability to cover the service area with a minimum amount of infrastructure investment is clearly an important factor in keeping costs down and customers happy.

As is often painfully obvious to operators, the two requirements, increased capacity and increased range, conflict in most instances. While current technology can provide for increased range in some cases, and up to a limit increased capacity in other cases, it rarely can provide both simultaneously. Operators who would like to keep infrastructure costs down by deploying fewer sites have to sacrifice revenue generating capacity, and those that opt for more capacity must pay the price. Intelligent antenna technology offers the potential to ease the pain by providing systems with the capability to both increase coverage and capacity at the same time, and more importantly, the flexibility to adjust to the particular needs of the operator as the system requirements evolve.

IV. SPACE - "THE FINAL FRONTIER"

Space is truly one of the *final frontiers* when it comes to next generation wireless communication systems. Spatially selective transmission and reception of RF energy promises substantial increases in wireless sys-

tem capacity, coverage and quality. That this is certainly the case is attested to by the significant number of companies that have been recently formed to bring products based on such concepts to the wireless marketplace. The approaches range from *switched-beam* to *fully-adaptive*, uplink only to uplink and downlink, with the benefits provided by the various approaches differing accordingly. Clearly, as Qualcomm's founder Andrew Viterbi stated: "Spatial processing remains as the most promising, if not the last frontier, in the evolution of multiple access systems."

A. Switched-diversity Technology

One the earliest attempts at addressing the difficulties of the mobile RF environment was to employ two identical antennas separated by several wavelengths, each instrumented with conventional receivers. The basic principle underlying such designs is that in complex RF environments, there is sufficient scattering of the RF fields to practically decorrelate signals received from antennas sufficiently far apart. The import of this is that the probability of the signals in both of the antennas becoming extremely weak at the same time is very small, and selection of the strongest signal will always improve matters. While these techniques are still in widespread use today, they do not increase range or capacity, though they do address an important problem facing mobile systems today, that of fading (uplink signal quality) in complex RF (dense urban) environments.

B. Switched-beam Technology

As an extension of the microcellular concept, switched-beam technology is being investigated by several companies as a possible solution to the requirement for range and the capacity crunch. The design of such systems involves high-gain, narrow azimuthal

beamwidth antenna elements (using conventional or Butler matrix array technology), and RF and/or baseband digital signal processing hardware and software to select which *beam* or *sector* to use in communicating with each user. In order to overcome the well-known trunking efficiency problem of small cells, pooling of radio resources is being investigated by several proponents of this technology. Additionally, many of the system related issues dealing with access and control channels require some special care, and there are certainly interesting challenges to be faced concerning the downlink in such systems. While previous unsuccessful attempts at such solutions date back to the 1970's when six-sectored systems were tested as improvements over three-sector technology, advances in DSP technology may provide solutions to the challenges faced by highly restricted fields-of-view in rapidly changing mobile environments.

C. Intelligent Antenna Technology

At the other end of the spectrum is Spatial Division Multiple Access (SDMA) technology, a technology currently being produced in ArrayComm's IntelliCell™ line of products. SDMA technology employs antenna arrays, standard RF and digital components, and multi-dimensional nonlinear signal processing techniques to provide significant increases in capacity and quality of many wireless communication systems. It is especially well-suited to the current and next generation cellular systems termed Personal Communication Networks (PCN) and Personal Communications Services (PCS) and wireless local loop (WLL) systems.

Antenna arrays coupled with adaptive digital signal processing techniques employed at base stations improve coverage, capacity and trunking efficiency allowing for lower cost deployments with reduced maintenance costs. In addition to these immediate bene-

fits, the flexibility of the technology also allows for the creation of new value-added services which can provide a significant competitive advantage to operators offering these services. SDMA is not restricted to any particular modulation format or air-interface protocol, and is compatible with all currently deployed air-interfaces.

SDMA is an adaptive array approach, and is realized as a combination of antennas (antenna arrays), analog radio frequency (RF) and digital electronics, and estimation and detection algorithms. Resource allocation algorithms to effect efficient use of system resources are also employed. A block diagram of a typical intelligent antenna system configuration is shown in Figure 1.

With this basic configuration, the issues of capacity and coverage can be addressed with a common architecture. Optimal processing of the outputs of multiple antennas at a base station yields significant improvements in signal quality through increasing desired signal strength and reducing levels of interference (*i.e.*, increased SINR). While the details of the algorithms in a particular implementation certainly depend upon various factors including the temporal modulation format and the complexity of the RF environment, the objective of maximizing capacity and quality remains the same.

Shown in Figure 2 are field test results in a suburban environment with an 8-element intelligent antenna DCS-1800 system developed in cooperation with Alcatel. The cumulative histograms collected during 25 minutes of driving at ranges from 5 to 15 kilometers from the base station show the improvement obtained by using an intelligent antenna system compared to a single antenna system, a 2-element switched diversity system (antenna separation approximately 4 wavelengths), and a switched-beam system with 8 beams covering a 120° sector. These results clearly indicate the potential uplink im-

provement intelligent antenna systems provide over conventional single antenna and switched-diversity systems, as well as over proposed switched-beam systems, even those with extremely narrow beamwidths (nominally 15° in this case). The improvement over switched-beam is in accordance with that expected given the particular switched-beam parameters chosen. The improvement over a single antenna system is expected to be 9 dB which is indeed the case. Also as expected in such environments, switched-diversity performance is quite similar to that of a single antenna system. Note that the 9 dB improvement in uplink signal quality significantly increased the range at which the mobile unit's signal could be successfully demodulated (roughly a factor of 2 in these tests).

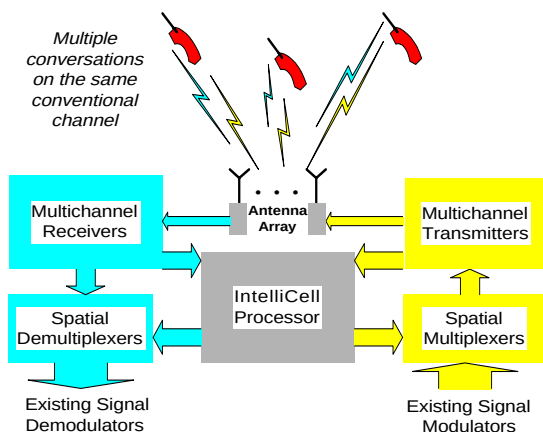


Figure 1: Typical Intelligent Antenna System Configuration

In Figure 3, the potential ability of intelligent antenna technology to handle multiple cochannel signals is clearly manifest. Shown are bit-error-rate (BER) measurements (using DCS-1800 signals) made for each of the aforementioned systems in the presence of an

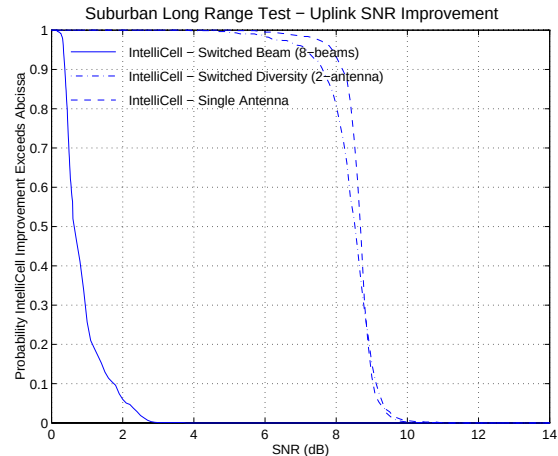


Figure 2: Suburban Environment Uplink Field Test Results Comparing Intelligent Antenna Technology to Switched-beam, Switched-diversity and Single Antenna Conventional Systems

interfering signal of varying strength approximately 15° separated in angular position from the *desired signal*. The noted improvement in signal-to-interference-plus-noise ratio (SINR) not only means signals can be received from greater distances (increased uplink range), but more than one can be received simultaneously (increased uplink capacity). It is interesting to note that actually *interference* in mobile systems is more often than not the consequence of another *customer* attempting to use the system in another cell (spatial location).

In the downlink direction, multiple low-power transmitters are used to selectively transmit information to one or more users on the same channel at the same time, reducing the total amount of transmitted power required (interference to other users in other cells) while increasing capacity and range. Figure 4 indicates the ability to selectively transmit signals on a common communication channel to different users in an experimental 800 MHz intelligent antenna system. Shown are cumulative histograms from data collected during a 10 minute drive test in a suburban environment indicating the amount

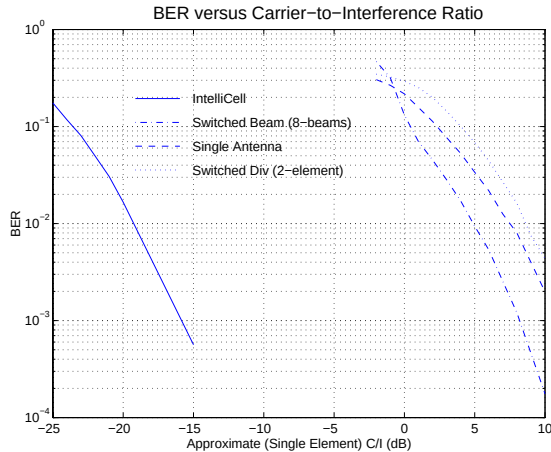


Figure 3: Cochannel Interference Tolerance Test Results Comparing Intelligent Antenna Technology to Switched-beam, Switched-diversity and Single Antenna Conventional Systems

of signal versus interference and noise received at one of several mobile units being communicated with simultaneously on a single channel during the test. Similar results were obtained for the other mobiles. The results clearly indicate the potential of intelligent antenna systems to establish multiple links simultaneously and thereby increase capacity at a single cell site.

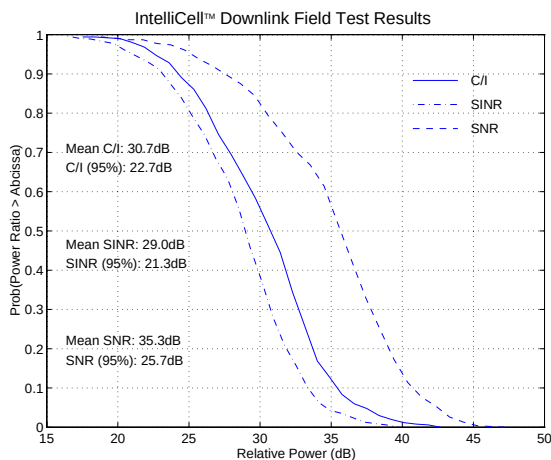


Figure 4: Suburban Environment Downlink Spatial Selectivity Field Test Results Using Intelligent Antenna Technology

To quantify the system-level benefits of intelligent antenna technology, Table 1 pro-

vides numerical examples of the improvement that could be expected deploying a 10-element array and assuming $R^{3.5}$ range-dependent attenuation. Note that for SINR improvements in excess of the stated SNR improvement, there must be the requisite amount of *interference* present. Also, the reduction in base station emissions relates to traffic channels and does not account for broadcast channel requirements associated with many mobile system protocols.

Uplink Related

- SNR Improvement 10 dB
- Range (Area) Increase 1.9 (3.7)
- SINR Improvement > 25 dB

Uplink & Downlink Related

- DL Tx Power Reduction 90%
- Real Capacity Increase > 2

Table 1: Potential 10-element Intelligent Antenna System Performance Improvements ($\gamma = 3.5$)

In summary, there is a growing need for improvements that increase coverage, capacity, and quality in many wireless communication systems. Optimal exploitation of the spatial dimension through intelligent antenna technology has the potential to meet these needs in addition to providing operators the ability to offer new value-added services to their customers.

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