EC0211

INTELLICELL
A FULLY ADAPTIVE APPROACH TO SMART ANTENNAS

Abstract

Cellular communications has reached mass-market status over the past decade with the emergence of two very successful standards: CDMA and GSM. Over this same decade, an important enabling technology, "smart antennas," has also matured. Combined with today's powerful, low-cost processors, advanced smart antenna technology is destined to become an important part of the cellular landscape over the next decade.

IntelliCell is the name for these developing smart antenna techniques and intellectual property for commercial cellular systems. Through eight years of practical and field implementation, IntelliCell has been perfected to make smart antennas practical and cost effective in actual commercial cellular systems. Today, IntelliCell technology is deployed in more than 90,000 commercial base station deployments worldwide.

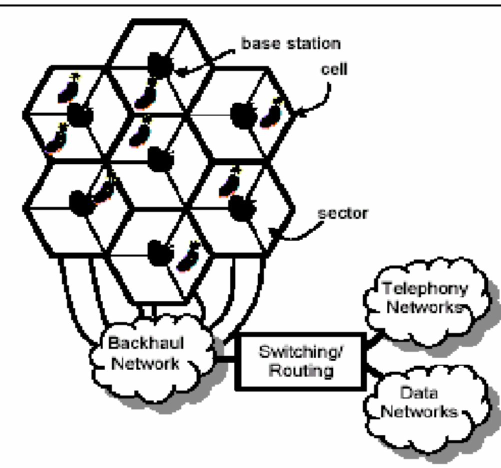
Finally, though this paper has focused on IntelliCell implementations at the base station, the technology is equally applicable to handsets and subscriber units. Today's trends in handset component costs and processing capabilities point to this being the next major frontier for IntelliCell and smart antenna technologies.

1.Introduction:

Smart antenna systems utilize multiple antennas at base stations or handsets to better pinpoint or focus radio energy and thereby improve signal quality. Since cellular communications systems employ radio signals that interact with the environment and each other, these improvements in signal quality lead to system-wide benefits with respect to coverage, service quality and, ultimately, the economics of cellular service. To some extent, the phrase "smart antennas" is misleading. There is nothing smart about the antennas themselves. What's smart is the sophisticated signal processing applied to simultaneous signals from an array or collection of multiple antennas.

Basic Cellular Architecture:

Figure 1: Basic Cellular Architecture



Cellular networks are composed of geographically separated base stations connected to a backbone network, with each base station serving an area called a cell. (See Figure 1.) In some systems, cells are further subdivided into sectors, for reasons that will be described later in this document. Handsets communicate with a nearby base station via radio signals. The information, voice or data, is digitized prior to transmission in all modern cellular systems. End-to-end connections with public or private data or telephony networks are made possible by a backhaul network that connects all of the base stations to a switching/routing function, which directs users' voice or data transmissions to and from their correspondents.

In the radio portion of the network, the "uplink" refers to the communication from the handset "up to" the base station. The handset or user terminal suitably digitizes and frames voice or packet data meant for the network. This digitized data then is modulated using digital and radio circuitry and transmitted via the antenna in the handset. The antennas and circuitry at the base station receive the radio signal, demodulate it and send the user's information on into the wired network.

The "downlink" refers to the reverse direction, where the communication is from the base station "down to" the handset or user terminal. The base station suitably digitizes and frames voice or packet data meant for the subscriber. This digitized data is modulated using digital and radio circuitry and is transmitted via the antennas at the base station. The antenna and circuitry at the handset receive the radio signal, demodulate it and send the information on to the subscriber. This type of cellular architecture has gained wide acceptance as the most economical and flexible architecture for delivering mass-market personal wireless services.

2. Coverage:

The base station range (cell area) determines the number of base stations required for a particular coverage area in the early days of deployment, when subscriber density is low. It is, therefore, one of the key determinants of system economics. When radio energy propagates in a cellular environment, the received signal level degrades as the distance between transmitter and receiver increases. This received signal has to exceed the inherent noise level in the radio receiver by a certain margin in order to be successfullydemodulated.

Everything else being equal, a higher nominal SNR translates into a higher possible data rate but at the cost of reduced base station range. Some systems operate at much lower SNRs by introducing large redundancy into transmitted data through a process known as “spreading.”

3.Spectral Efficiency:

Besides coverage, next-generation cellular systems face another challenge related to “spectral efficiency.” Spectral efficiency measures the ability of a wireless system to deliver information with a given amount of radio spectrum and is directly related to

***Table 1 Spectral Efficiency for various common systems.** The spectral efficiency of today's commercial systems is invariably about 0.1-0.2 bits/sec/Hz/cell, while systems utilizing intelliCell technology can achieve spectral efficiencies up to 4 bits/sec/Hz/cell.*

Air Interface	Carrier BW	Peak User Data Rate (kbps)	Average Carrier Throughput (kbps)	Spectral Efficiency	Comments
IS95A	1.25MHz	14.4	100	0.08	Source: Viterbi
IS95B	1.25MHz	115	125	0.1	Source: Viterbi
IS95C	1.25MHz	144	200	0.16	Source: Viterbi
cdma2000	5MHz	384	800-1,000	0.16-0.2	Source: Viterbi
GSM	200KHz	13.3	15.2 (13.3*8/7)	0.08	Reuse = 7
GSM (HSCSD)	200KHz	57.6	15.2	0.08	
PHS	300KHz	32	12.8	0.04	Effective reuse = 20
Intellicell System				Up to 4	Depends on communication system

system capacity. It determines the amount of radio spectrum required to provide a given service (e.g., 10 kbps voice service, 100 kbps data service) and the number of base stations required to deliver that service to the end-users.

Spectral efficiency is measured in units of bits/second per Hertz/cell (b/s/Hz/cell). It determines the total throughput each base station (cell or sector) can support in a given amount of spectrum. The key benefits of higher spectral efficiencies can be enumerated as follows: higher aggregate capacity (per-cell throughput); higher per-user quality and service levels; higher subscriber density per base station; small spectrum requirements; and lower capital and operational costs in deployment. The spectral efficiency for various systems can be calculated easily via the formula:

Spectral Efficiency = (Channel Throughput/Channel Bandwidth)

This simply sums the throughput over a channel in an operating network and divides by the channel bandwidth. This calculation is performed for a number of systems in Table 1.

The value of approximately 0.1 b/s/Hz/cell is generally representative of high-mobility 2G and 3G cellular systems, including CDMA systems of all types. It reflects the fact that the classical techniques for increasing spectral efficiency have been exhausted and that new techniques are necessary. Finally, it should be noted that the value of 0.1 b/s/Hz/cell represents a major stumbling block for the delivery of next-generation services. Without substantial increases in spectral efficiency, 3G systems are bound to spectral efficiencies like those of today's 2G systems. In a typical 3G system with a 5Mhz downlink channel block, this translates into a total cell capacity of approximately 500 kbps for the entire cell.

4. The Quest For Better Coverage And Spectral Efficiency:

A wide range of techniques and tradeoffs has been developed for enhancing coverage and spectral efficiency over the past 20 years. The most important and widely used are the following.

- **Frequency Planning:** A substantial amount of the effort in cellular systems is devoted to managing interference through the use of a "reuse pattern." Traffic channels are partitioned into groups.The resulting spatial separation ensures that the energy being used for a conversation in one cell has been sufficiently attenuated by the time it reaches another cell using the same channel that it does not pose significant interference. Reuse provides interference management, but at the expense of operational complexity and base station capacity..
- **Power control:** Power control is a technique whereby the transmit power of a base station or handset is decreased to near the lowest allowable level that permits communication. This reduces interference levels in the network, increasing spectral efficiency.
- **Modulation and Coding:**Modulation and coding techniques can improve the utilization of spectrum by allowing a faster throughput at a given signal quality. The benefits of any such techniques are ultimately limited, however, by the Shannon information rate.
- **Sectorization:** Sectorized antenna systems take a traditional cell area and subdivide it into "sectors," each covered by its own directional antenna sited at the base station location. Operationally, each sector is treated as an independent cell. Directional antennas have higher gain than omni-directional antennas, all other things being equal. Hence the range of these sectors is generally greater than that obtained with an omnidirectional antenna, roughly 35 percent greater. Sectorized cells can increase spectral efficiency by reducing the interference presented by the base station and its users to the rest of the network, and they are widely used for this purpose. Most systems in commercial service today employ three sectors per site. Although larger numbers of sectors are possible, the number of antennas and quantities of base station equipment become prohibitively expensive for most cell sites.

5. Intellicell: The Fully Adaptive Smart Antenna Approach:

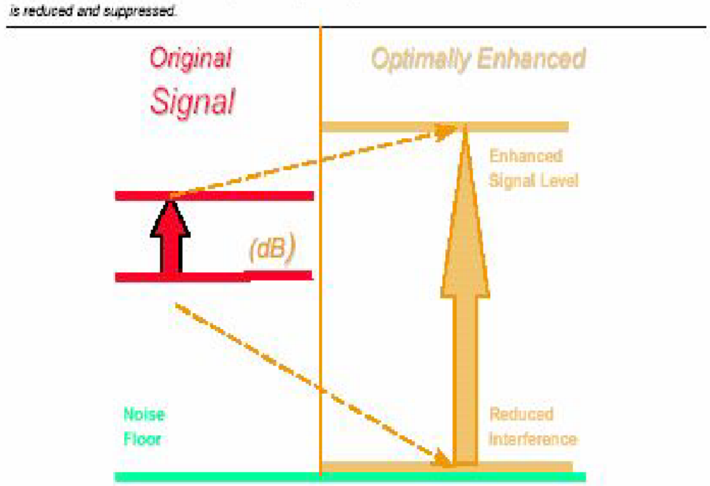
Arrays of multiple antennas, combined with digital beam-forming techniques and advanced, low-cost signal processing open a new and promising area for enhancing wireless communication systems.

Terms commonly used to embrace various aspects of smart antenna system technology include intelligent antennas, phased arrays, spatial processing, digital beam forming, adaptive antenna systems, etc. IntelliCell is a battery of techniques and intellectual property that make smart antenna systems commercially viable.

A base station utilizing IntelliCell employs a small collection (array) of simple, off-the-shelf antennas (typically 4 to 12) coupled with sophisticated signal processing to manage the energy radiated and received by the base station. This improves coverage and signal quality and mitigates interference in the network on both the uplink and the downlink. The processes on the uplink and downlink are as follows:

5.1 The IntelliCell Uplink (reception at the base station)

Figure 2 Effects of IntelliCell on Signal Quality. The signal level itself is enhanced while the level of interference is reduced and suppressed.



Typically, the received signal from each of the spatially distributed antenna elements is multiplied by a weight, a complex adjustment of amplitude and phase. These signals are combined to yield the array output. An adaptive algorithm controls the weights according to predefined objectives such as “tuning in” to a particular user while “tuning out” interference and noise. This processing is performed independently and simultaneously for each of the users being served by the base station.These dynamic calculations enable the system to tune itself for optimized signal reception:The equivalent received signal level is improved by a factor of 10log10 (number of antennas),which, for example, is 10 dB for a 10-antenna system. At the same time, interference is rejected by many orders of magnitude, anywhere from 30 to 50 dB if an interfering signal is strong enough to warrant it. This rejection and the analogous suppression on the downlink are high enough that, in TDD/TDMA implementations of IntelliCell, frequency planning can be done away with completely. These gains and how they relate to overall gains in signal quality are summarized in Figure 2

5.2 The Intellicell Downlink (Transmit From The Base Station)

Similar gains occur on the downlink. The signals to be transmitted are multiplied by weighting factors of different amplitude and phase for each antenna. The weighting factors are chosen dynamically to ensure that the transmitted signals constructively combine and add at the user of interest while at the same time presenting no interference to other co-channel users2. The weight factors are again chosen dynamically based on predefined objectives. These dynamic calculations

enable the system to tune itself for optimized signal transmission: the equivalent transmitted-power signal level is a factor of 20log10 (number of antennas) over the power emitted by a single antenna at the base station. This is, for example, 20dB for a 10- antenna system. This is a monumental improvement in equivalent signal level. Because the signals constructively interfere at the targeted user.

Smaller-power amplifiers are more reliable and less expensive than larger ones, and the loss of a single transmitting element from the array has only a small effect on base station downlink performance. An important point here is that the type and performance of the downlink processing used depends on whether the communication system uses time division duplex (TDD) schemes, which transmit and receive on the same frequency (e.g., 802.11, PHS and DECT) or frequency division duplex (FDD) schemes, which use separate frequencies for transmit and receiving (e.g., GSM, EDGE, W-CDMA, cdma2000).

6. System-Level Benefits Of Intellicell

At the simplest level, IntelliCell systems fundamentally improve the coverage and spectral efficiency tradeoffs of wireless systems. Wireless system design, nevertheless, still involves a series of tradeoffs between cost, coverage and capacity. The improvements from IntelliCell fundamentally allow much more flexibility in system-level designs. The benefits are summarized in Table 2 and further explained in detail.

6.1 Selective Uplink Gain: 10log10(M)

As mentioned before, IntelliCell significantly improves uplink link budgets by a factor of the number of antennas. More formally, this can be seen as follows. For example, if **M** copies of the some signal, **s**, are received, one per antenna, where **M** is the number of antennas. Assuming that the signals arrive with the same power, an appropriate application of weights will lead to the signals adding together coherently:

Uplink Received Signal After Processing = s + s + ... + s

Similarly, after the application of the weights, the noise processes, **Ni**, in each of the antenna receivers add.Since the received signals add coherently and the noise powers add independently (since the noise processes are independent and identically distributed), this leads to:

Multiple Antenna Uplink SNR = (Ms) 2 / M□2 = Ms2 / □2 = M (Single Antenna SNR)

where **s2** is the signal power, □□ is the noise power per antenna, and as before, **M** is the number of antennas. Taking log10 of both sides, we obtain a 10log10(M) gain in signal-to-noise ratio. With 10 antennas and under typical propagation conditions, this leads to approximately a doubling of range and quadrupling in coverage. Of course, this increase in range can be traded off against other system parameters such as the required user terminal transmit output power.

6.2 Selective Downlink Gain: 20log10(M)

Table 2 System-Level Benefits of IntelliCell

Gain	System-Level Significance
Selective Uplink Gain • Receive processing at base station	Increased Range, Coverage, Link budget • 10*log10(M) gain • 13dB – 17dB diversity gain • Lower terminal transmit power • Uplink multipath immunity • Lower-complexity equalization
Uplink Interference Mitigation • Receive processing at base station	Improved Signal Quality • Robust to interference from multiple uplink interferers • 30dB – 40dB interference immunity • Higher spectral efficiency
Selective Downlink Gain • Transmit strategy based on uplink information and feedback from terminal	Increased Range, Coverage, Link budget • 20*log10(M) gain • 13dB – 17dB diversity gain • Reduced base station PA sizing • Reduced downlink multipath • Lower-complexity equalization at terminal
Downlink Interference Mitigation • Transmit strategy based on uplink information and feedback from terminal	Improved Signal Quality • Automatically reduces signal transmission to co-channel interference • Increases system-wide downlink signal quality • 30dB – 40dB interference immunity • Higher spectral efficiency

A similar calculation to the above can be performed on the downlink. In the downlink case, **M** copies of the same signal, **s,** are transmitted, one per antenna. Assuming that the signals arrive with the same power, an appropriate use of the transmit weighting factors will lead to the signals adding together coherently at the handset:Downlink Received Signal at Handset = s + s + … + s

In this case, the receiver noise floor at the handset is independent of the antenna weightings used for base station transmit, so the multiple antenna and single antenna SNR can be compared as follows:

Multiple Antenna Downlink Snr = (Ms) 2 / σ2 = M2s2 / σ2 = M2 (Single Antenna Downlink SNR)

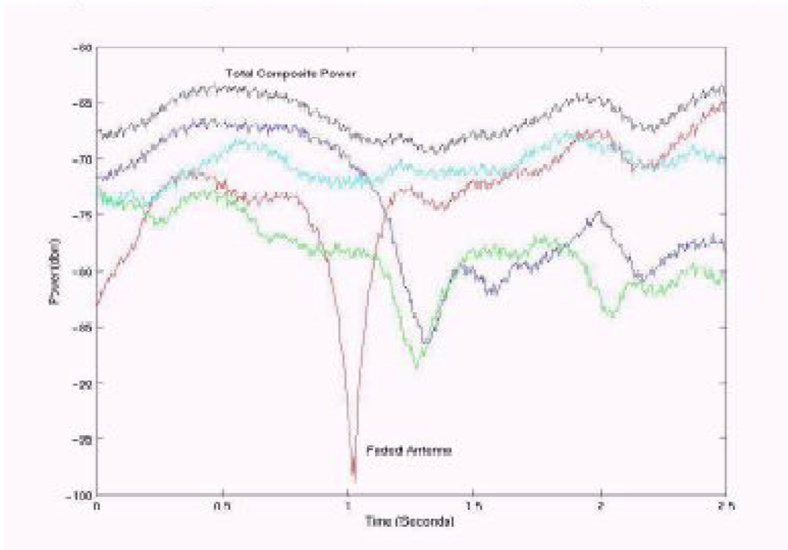
In contrast to the uplink gain of 10log10(M), the downlink gain is, therefore, 10log10(M2) = 20log10(M). As mentioned before, a significant issue in forming the downlink weights is obtaining knowledge of the downlink signature. In the uplink, the base station can employ any number of passive techniques such as using training sequences to obtain the uplink signature. In the downlink, however, the methods are highly dependent on the type of communication system employed. TDD systems have a reciprocal property in that the downlink signature is more or less proportional to the uplink signature. In FDD systems, the relation between uplink and downlink is not so simple, and a complex nonlinear mapping between the two along with other techniques based on direction of arrival or feedback from the handset is often necessary.

Finally, another important complication arises because the signals received by the base station and transmitted by the base station flow through different electronic circuitry. In the simplest case, this induces a simple multiplicative transformation on spatial signatures, and in the worst case, this induces a linear or even nonlinear transformation on the signatures. Correcting for this effect is known as "calibration," and techniques for calibration are important elements of the techniques in IntelliCell.

6.3 Selective Uplink And Downlink Gain: Diversity

All wireless systems suffer some degree of "fading," which is the unavoidable consequence of reflections with short time lags constructively and destructively interfering at the receiving antenna. Since the environment is dynamic, the fades themselves are time varying. The consequence for wireless system designers is that the air interface must be robust to sudden outages (for example, using interleaving of symbols), and margins against fading must be introduced into link budgets and cell planning, which reduces coverage. The reduction in the needed margin against fading, is

Figure 5 Signals Across a 4-Antenna Array. One antenna undergoes a large fade, while the other antenna show slight variation. Though individual antennas fade in and out, the total composite signal is far more stabl



often referred to as a “diversity gain.” The calculation of this gain depends on the targeted outage probability, the detailed assumptions regarding the fading process and the number of antennas. Under a large class of assumptions, the averaging provided by the array yields reductions in the equivalent margin of 13-17 dB.It is important to note that this diversity gain is in addition to the standard 10log10(m) gain:

Both the conventional, single-antenna system and the multiple-antenna system require a fading margin, but the multi-antenna system requires a much lower margin.

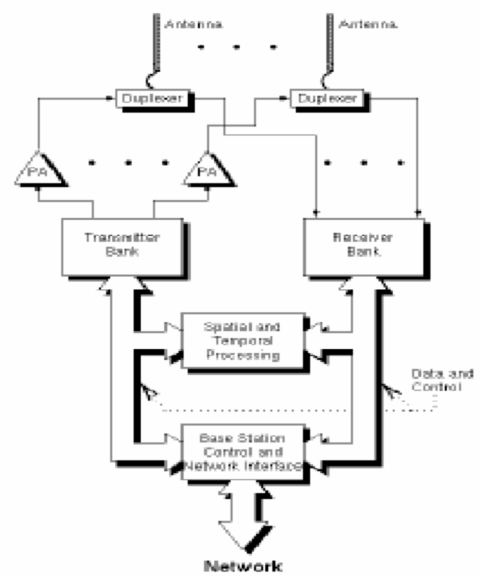
Figure 5 shows real data collected from a 4-antenna array in a suburban environment. The horizontal axis denotes a 2.5-second interval, while the vertical axis indicates the power level. Each of the lower curves shows the power levels for each antenna, respectively, while the upper curve denotes the composite power.

A conventional single-antenna system would need provisions and margins against the deeper fades exhibited by a single antenna, while an IntelliCell system requires a far smaller margin.

6.4 Uplink And Downlink Interference Mitigation

The uplink and downlink interference mitigation provided by IntelliCell processing is perhaps the most remarkable of the system benefits. In practical implementations, uplink interference can be suppressed between 30 to 50 dB. In the downlink direction, practical issues often mean that the ability to “null” or mitigate transmitted interference is less than can be achieved in the uplink. As before, the performance in the downlink direction is dependent on the particular communication system. In a TDD system, practical issues limit the nulling performance to between 30 and 40 dB. It should be noted that within the fully adaptive approach of IntelliCell, the weighting and the receive and transmit interference suppression and mitigation are performed continuously and dynamically in very short time frames.

Figure 6 Typical IntelliCell Base Station Architecture



6.5 Higher Spectral Efficiency

The reduction in interference due to IntelliCell allows an increase either in the number of subscribers utilizing the spectrum or in the overall signal quality, which enables higher data throughput. The upshot of the reduction in interference network-wide is, in either case, an increase in spectral efficiency. The order-of-magnitude increases possible are in the range of 20-40X versus non-IntelliCell implementations.

7. Intellicell Architecture

IntelliCell systems employ a highly integrated approach in base station design, with the smart antenna architecture incorporated from the outset. Figure 6 shows the block diagram of such an architecture.

IntelliCell systems make use of ordinary, off-the-shelf antennas. Received radio signals are digitized and accumulated by the receiver bank. This received data is then packaged and processed in the spatial temporal processing block. This block is the heart of the IntelliCell system and typically involves the use of high-performance digital signal processors and ASICs. This block extracts and demodulates the various signals of interest and appropriately packages the results for transport through the network interface

and on into the network. At the same time, data is being received from the network bound for subscribers. The spatial temporal processing block communicates with the transmitter bank to indicate how the data is to be weighted across the different antennas. Finally, the modulated data is routed through power amplifiers (PAs), one for each antenna, and transmitted across the array.

8. Conclusion

IntelliCell technology uses sophisticated signal processing techniques in combination with small arrays of standard, off-the-shelf antennas to manipulate signals at the base station and dynamically control transmission and reception. Conventional radio systems indiscriminately broadcast energy, creating interference for other users. Using IntelliCell processing, base stations optimize radio transmission and reception by selectively amplifying signals to / from users of interest and rejecting unwanted signals. This substantially increases the signal quality and suppresses and mitigates interference on both the uplink and downlink radio channels, resulting in increased coverage and spectral efficiency. The conventional techniques used to increase coverage and spectral efficiency have been exploited over the past 20 years to the point that gains from these techniques are incrementally small. Despite these efforts, the spectral efficiency of commercial air interfaces is typically only about 0.1-0.2 bits/sec/Hz/cell, independent of the technologies used. This performance is well short of what is needed to deliver broadband wireless data services economically.

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