AN ADAPTIVE ARRAY ANTENNA SDR BASE STATION FOR COMMERCIAL CELLULAR APPLICATIONS

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ABSTRACT

AirNet® Communications Corporation is now introducing the first commercially available, fully adaptive, smart antenna GSM base station. AirNet's AdaptaCell® Broadband, Software-Defined Base Station is the foundation for the software-centric realization of an adaptive array antenna system. This paper provides an overview of the AdaptaCell base station architecture, implementation of the adaptive antenna array and adaptive processing on the AdaptaCell base station, as well as discusses deployment considerations to support capacity improvements in a commercial cellular network.

1. ADAPTACELL BROADBAND, SOFTWARE-DEFINED BASE STATION ARCHITECTURE

In 1997, AirNet Communications Corporation introduced the first commercially available broadband, Software-Defined Radio (SDR) base station to the wireless industry. Capable of transmitting and receiving several different types of wireless standards, AirNet SDR base stations are currently deployed and operating using the worldwide GSM standard, processing voice and General Packet Radio Service (GPRS) data signals.

AirNet SDR base stations are software upgradeable to support EDGE (Enhanced Data for GSM Evolution) high-speed data waveforms and, in the future, may be configured for 3G UMTS CDMA. Using the revolutionary SDR product as the foundation, AirNet has developed a software-centric, fully adaptive smart antenna GSM base station.

2. THE CHALLENGES TO THE OPERATOR

GSM operators need to increase their network capacity and coverage, increase performance, and improve spectrum utilization, while reducing the cost of infrastructure and operations. Many have started to roll out high-speed data services, while others are cautious about data expansions due to network capacity/coverage limitations and expense.

Enhanced GPRS (EGPRS), employing EDGE technology, is the 3GPP standard for the next evolution of GPRS packet data capabilities. Several North American GSM operators have adopted EGPRS and have started deployment of this feature. However, existing cell sites using traditional radio equipment cannot provide the same coverage for high-speed data due to the much higher carrier-to-interference (C/I) requirements, demanding up to 5 times as many sites for the same coverage.

Adaptive beamforming can provide high capacity and coverage for high-speed data without requiring additional sites. Improved traffic handling capacity of up to 800% is possible via the ability to focus a signal beam on a specific user and to "null out" interferers. Narrowband systems cannot economically provide these needed capabilities. It is achievable only with broadband SDR technology.

3. ADAPTACELL SUPERCAPACITY BASE STATION

Based on broadband software-defined radio technology, AirNet has the only commercially deployed GSM base station that is evolvable to 2.5G and 3G, while offering superior performance in all of the GSM bands (850, 900, 1800, and 1900 MHz). The AdaptaCell base stations with "SuperCapacity" enhancements eliminate the need for new sites when supporting the higher C/I requirements of new 2.5G and 3G features, such as GPRS and EGPRS. The field proven AdaptaCell base station has integrated digital beamforming adaptive array software algorithms and, for the first time, this technology is cost effective and practical for commercial use.

3.1 The AdaptaCell Architecture

The AdaptaCell base station, based on the only commercial broadband SDR architecture, utilizes patented technologies in the areas of DSP (digital signal processing), A/D (analog-digital conversion), and multiprocessing. Figure 1 shows the architecture differences between legacy single-carrier systems and the revolutionary SDR-based AdaptaCell base station product.

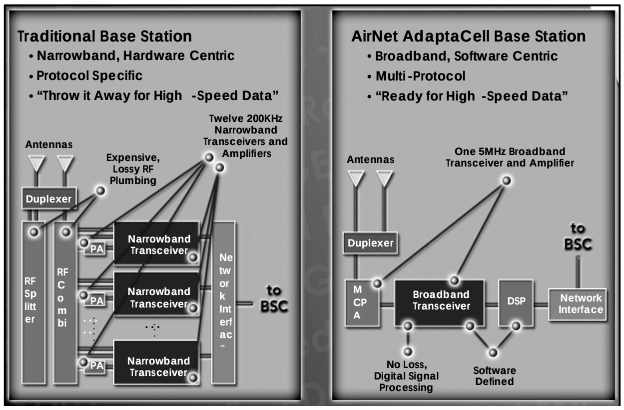

Figure 1 – AdaptaCell BTS Architecture

Traditional base station technology employs narrow-band hard-wired logic that has changed little over the past 20 years, resulting in feature and performance compromises in these legacy systems. Operators are forced to constantly tweak their networks to support the very high voice traffic at the major urban centers like Hong Kong, Beijing, and London. Most technology experts realize the limit of narrowband technology has been reached and the move to a wideband radio platform is necessary to support new data services and higher capacity.

While the industry's approach is to replace entire networks with wideband CDMA technology, similar data and capacity capabilities can be achieved via software upgrades to the digital signal processors (DSP) within the AirNet SDR base station shown in Figure 2.

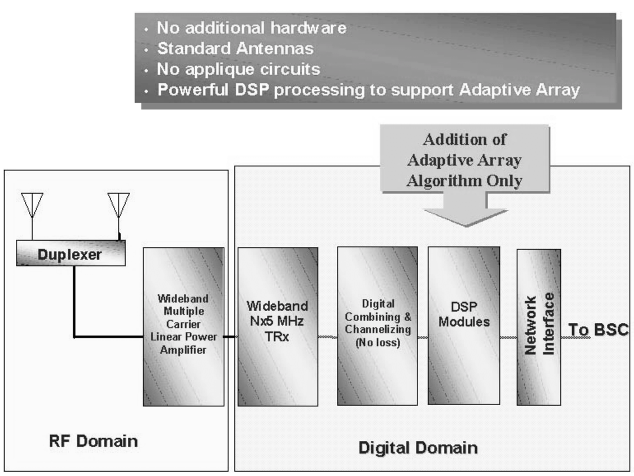

Figure 2 – Software Upgrade for Adaptive Array

3.2 Beamforming Adaptive Array

Cellular systems are prone to interference and poor voice quality due to wasteful wide area RF transmission of cellular signals. In traditional systems, this method is necessary because the user's location is unknown. Considerable radiated power is sent in every direction-- making radio planning difficult and costly. In contrast, adaptive array systems determine the location of the user and interferers to focus transmission and receive energy only on the intended user.

The notion of a more intelligent cell that uses multiple antenna elements and innovative signal processing has existed for many years. Varying degrees of costly smart antenna systems have already been applied in defense and commercial systems. Until recently, cost barriers have prevented adaptive array use in commercial mobile networks. The advent of low-cost digital signal processing and innovative algorithms has made smart antenna systems practical on a broadband platform at a time where spectrally efficient solutions are imperative. AirNet offers the only broadband multicarrier GSM/GPRS/EDGE base station platform.

3.3 Adaptive Array C/I Gains

By adjusting to the RF environment as it changes, adaptive array technology can dynamically alter the signal patterns to optimize the performance of the wireless system, delivering dramatic increases in both capacity and coverage. The adaptive approach utilizes sophisticated signal processing algorithms to continuously distinguish between desired signals, multipath, and interfering signals, calculating their directions of arrival for each frequency and user.

The adaptive approach continuously updates its beam pattern based on changes in both the desired and interfering signal locations-- smoothly tracking the users with main lobes and interferers with deep nulls, constantly optimizing the link budget C/I ratio without micro-sectors or pre-defined patterns.

Figure 3 shows one beam pattern used to communicate with the user on the left, while a second pattern is used to communicate with the user on the right. Using real-time adaptive array signal processing, the base station generates dynamic peaks towards the desired user (focusing gain), while generating deep RF nulls towards potential co-channel interferences.

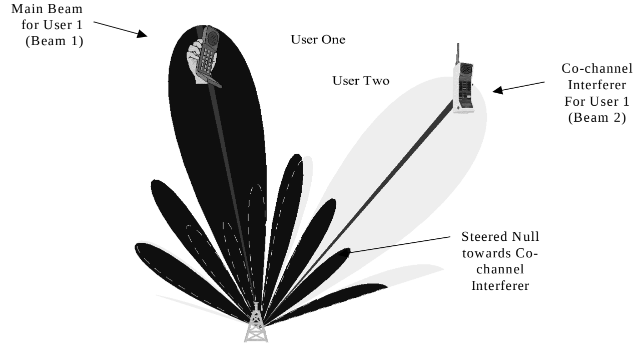

Figure 3 – Adaptive Array Principles

As shown in Figure 4, the Adaptive Array C/I gain is a combination of the main loop focusing gain and the reduction of interference. The net effect of focus gain plus interference nulling is (C2-C1) + (I1-I2). Since downlink spatial and amplitude information is derived from analysis of uplink information, the relative C/I gains for the uplink typically exceed those for the downlink.

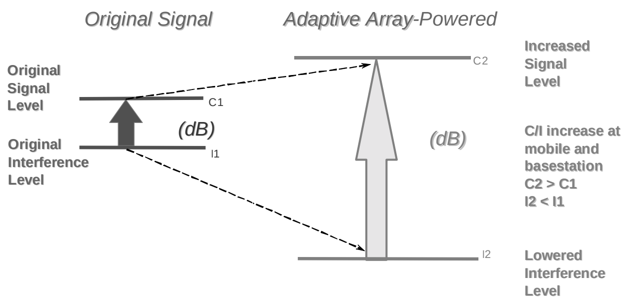

Figure 4 – Adaptive C/I gains

In actual trials conducted in Melbourne, Florida during August and December of 2002 and January of 2003, dynamic C/I gains up to 31dB (uplink) and 25 dB (downlink) were repeatedly achieved. Most of the gain is from interference rejection, while the remaining is focusing gain. While other systems have primarily relied on just focusing gains, the adaptive array technology adds the benefits of active interference rejection. Interference is the primary performance limitation in high capacity networks.

3.4 Switched Beam or Appliqué Systems

Compared to the integrated architecture of AirNet's broadband solution, traditional narrowband systems require external adaptive antenna appliqués and processing circuits, multiple narrowband base stations, and combiners to support such functions. Numerous trials with narrowband technology have demonstrated the economic and technical disadvantages using this approach.

Shown in Figure 5, legacy systems implementing switched beam functionality require off-board processing systems, RF circuitry, and other costly elements. The net effect is high capital costs, high operating costs, and disappointing performance. The integrated broadband SDR approach requires only a software upgrade to enable the adaptive array feature.

Table 1 demonstrates that roughly 9 times the number of physical components is necessary for a traditional narrowband approach to implement an adaptive array relative to the broadband integrated method. This is obviously impractical in terms of cost and size.

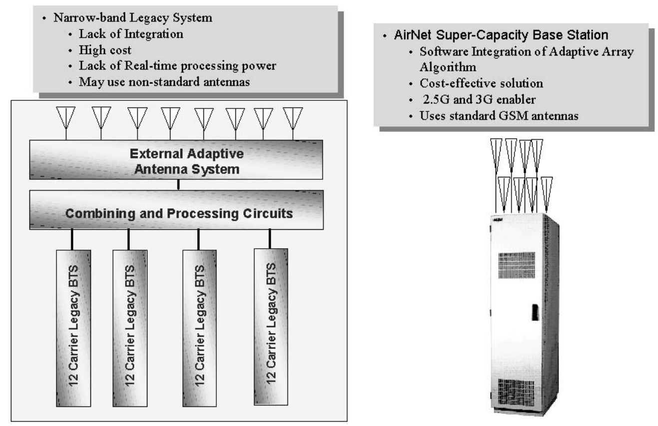

Figure 5 – Comparison with Legacy Systems

Table 1 – Comparison with Legacy Systems

Hardware	Narrowband Legacy Systems	AdaptaCell Super-Capacity BTS
Transceivers	4 x 12 = 48	4
HPAs	4 x 12 =48	4
Combiners	4	0
Splitters	4	0
Digital Channelizer/Combiner	0	4
Adaptive Antenna Applique and Processing Circuits	4	0
Total Count	**108**	**12**

3.5 Adaptive Array Capacity Advantages

With the significant improvement in C/I for the adaptive array system, coupled with the broadband SDR architecture, much higher capacity can be supported compared to legacy systems. In 5 MHz of spectrum (5 MHz uplink and 5 MHz downlink), a traditional capacity network would consist of S4/4/4 base stations with frequency hopping, deployed a 1/3 frequency re-use plan. However, this network would typically perform with marginal voice quality and low data throughput.

Adaptive array technology can *fundamentally* improve the C/I of every subscriber of every cell achieving C/I as much as 31 dB on uplink and 25 dB on downlink without the need for complex RF planning and optimization. Coupled with adaptive multi-rate (AMR) voice codecs and other techniques, an adaptive array base station can support much tighter frequency re-use, achieving true N=1 loading, which is not possible using traditional methods. Given that most urban networks are C/I limited, this technology allows operators to support considerably more subscribers within the same spectrum or in even smaller spectrum space than currently used, allowing growth of voice traffic and increases in data usage.

Figure 6 shows that a typical legacy S4/4/4 site without frequency hopping will support about 33 Erlangs in an ideal situation within 5 MHz. Using this 33 Erlangs as a baseline, a comparison with figures for adaptive array systems is made.

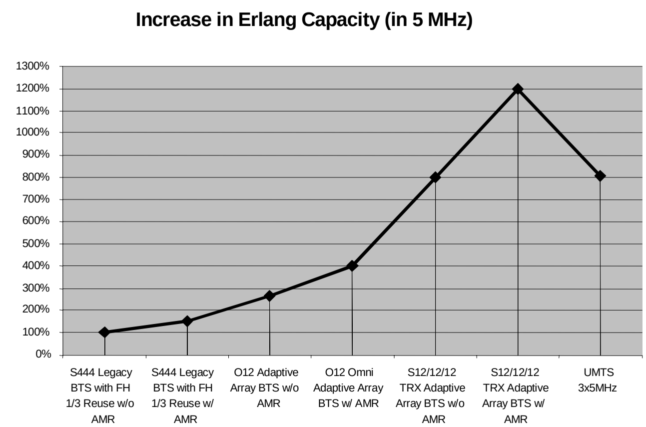

Figure 6 – Adaptive Array Capacity Comparison

Assuming 50% improvement with AMR, then the corresponding figures are also compared. A 12-carrier omni-directional adaptive array base station can provide up to 250% capacity above the baseline, whereas a 36-carrier, 3-sector adaptive array system can provide up to 800% capacity. The S12/12/12 adaptive array base station with AMR will provide up to 12x improvement, which compares well with the initial phase of UMTS, thus further extending the useful life of GSM networks by at least another decade.

By comparison, it could take 8 times the number of legacy S4/4/4 sites to equal the Erlang capacity of a single S12/12/12 adaptive array base station within the same 5 MHz band.

This capacity growth curve allows operators to support their ever increasing subscriber and traffic levels and support new traffic intensive services such as in-building business applications. The need for cell splitting is eliminated, as is the use of expensive, less effective micro-cell and pico-cell architectures. Operators may postpone the investment into new frequency bands or UMTS. They may continue to enjoy the best GSM infrastructure and handset cost curves, maximizing their investment returns.

3.6 Adaptive Array Data Application

The mid-2000 release of GPRS and EDGE specifications convey the importance of C/I performance to high-speed packet data. Table 2 illustrates the improvement of data throughput of the enhanced coding schemes within EDGE over that of GPRS. A simple calculation of the number of additional base stations needed using traditional infrastructure equipment to provide 2.5G services shows the substantial expense high-speed data implementation will be for most operators. Video streaming and multimedia services will generally require data rates at a minimum of 384 kbps (corresponding to EDGE MCS-7), which will require the operator to increase sites by at least 4 times in urban centers. For MCS-9, the operator will need at least 10 times more sites to provide the same coverage as the existing voice coverage.

Table 2 – C/I Requirements of Packet Data

Modulation	Coding	Data Rate/ts (kbps)	Data Rate/carrier (kbps)	Required Co-Channel C/I (dB)	Deficit from GSM 9dB C/I	Dense Urban Coverage Area (x GSM) [1]	Suburban Coverage Area (x GSM) [2]	Dense Urban Sites (x GSM)	Suburban Sites (x GSM)
GSM	CSD	9.6	57.6	9	0	100.0%	100.0%	100%	100%
GPRS	CS-1	9.05	72.4	13	4	65.2%	61.9%	153%	162%
GPRS	CS-2	13.4	107.2	15	6	52.7%	48.7%	190%	205%
GPRS	CS-3	15.6	124.8	16	7	47.3%	43.2%	211%	231%
GPRS	CS-4	21.4	171.2	19	10	34.4%	30.1%	291%	332%
EDGE	MCS-1	8.8	70.4	8	0	100.0%	100.0%	100%	100%
EDGE	MCS-2	11.2	89.6	10	1	89.9%	88.7%	111%	113%
EDGE	MCS-3	14.8	118.4	15	6	52.7%	48.7%	190%	205%
EDGE	MCS-4	17.6	140.8	20	11	30.9%	26.7%	324%	375%
EDGE	MCS-5	27.2	217.6	14	5	58.6%	54.9%	171%	182%
EDGE	MCS-6	29.6	236.8	17	8	42.5%	38.3%	235%	261%
EDGE	MCS-7	44.8	358.4	23	14	22.4%	18.7%	446%	535%
EDGE	MCS-8	54.4	435.2	28	19	13.1%	10.2%	763%	980%
EDGE	MCS-9	59.2	473.6	31	22	9.5%	7.1%	1053%	1408%

* GSM900 Dense Urban and Suburban In-building models used
* Derived from ETSI SMG2 Studies

GSM voice networks are typically designed for a minimum of 9 dB C/I at cell edge. Since most urban networks are already C/I-limited, the additional C/I requirements of high-speed packet data even further impact the network performance.

The higher C/I requirement degrades the link budget of the legacy base stations to the point that the operator must reduce the RF output power dramatically to not flood the RF network with more interference. The net effect is that data rates will vary according to the distance from the antenna tower. RF optimization is much more critical without adaptive array technology. Frequency hopping cannot be used effectively with data due to relatively high bit error rates, so adaptive array technology is an excellent solution.

Typical urban operators will require up to five times the number of cell sites than currently deployed for voice coverage. The financial impact of deploying and supporting so many new sites is so prohibitive that it severely limits most operators' plans for wireless Internet.

Figure 7 compares the data throughput performance of adaptive array versus traditional deployment of base stations. With the up to 31 dB (uplink) and up to 25 dB (downlink) of C/I achievable, the adaptive array system will typically sustain more than 400 kbps per carrier performance up to the voice coverage cell edge, thereby achieving symmetry in voice and data coverage.

In comparison, traditionally planned networks will see a six-fold deterioration in data throughput at 470 kbps within 15% of the cell center area to 70 kbps at the voice cell edge. In urban areas, subscribers expect uniform coverage for voice and data, so operators must plan the RF network for cell edge performance. Therefore, a network operators' alternative to deploying adaptive array is to cell split by at least 5 times to achieve more than 400 kbps data rates. Even lower data rates would still require substantial cell splitting.

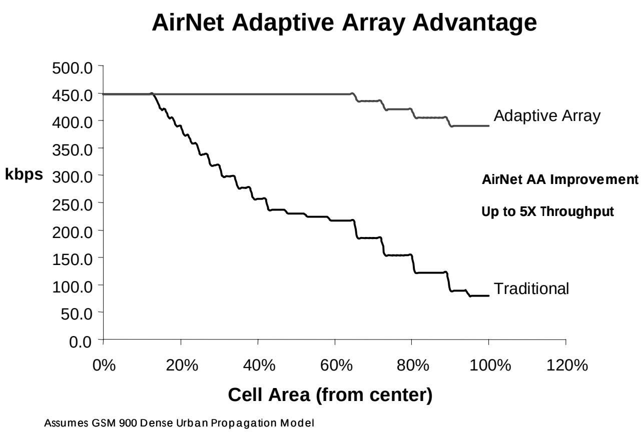

Figure 7 – Adaptive Array Data Throughput

4. IMPLEMENTATION ISSUES

In the past, other manufacturers have implemented switched beam equipment, which suffer from performance issues (less than 6 dB of gain improvement), complex antenna grids, complex feeder cabling, calibration issues, separate OMC, incompatibility with existing RF plan and network, etc. These issues have falsely generalized the opinion that adaptive array technology has a long way to go.

AirNet has demonstrated that all of these issues are resolved to provide much higher performance levels of C/I in the uplink and downlink without the many handicaps typical of appliqué systems. For example, AirNet adaptive array systems utilize standard omni or sectored GSM antennas arranged in a defined geometry for optimal performance. The feeder cables are not required to be of precise lengths, since calibration is performed automatically by the system without manual intervention. The adaptive array software is completely integrated within the BSS system.

The adaptive array system is also completely compatible with existing networks, since the adaptive array will always improve the performance even at cell junctions with existing networks. Operators can decide to expand the adaptive array cell coverage at their own pace, while enjoying immediate benefits to core problem areas.

4.1. RF Amplitude and Phase Drift

In adaptive array systems, the amplitude and phase offsets between multiple transmit paths must be very stable and calibrated to allow proper beam and null pointing. The amplitude and phase offsets between multiple receive paths must also be very stable and calibrated. Phase coherence in the RF hardware is achieved through a number of design considerations.

The local oscillators (LO) in each transceiver within the base station are all actively phase locked to one common low phase noise GPS-steered frequency reference. This includes tunable RF LOs, fixed IF LOs, and fixed digital sample clocks for the A/D and D/A converters. Each synthesizer design is carefully optimized for low phase noise and minimum jitter.

Coherence is maintained between all channels in the transmit paths and in the receive paths by limiting both short-term and long-term phase and amplitude drift. The RF designs are done using components with wideband responses that vary little over time and temperature. Some components, such as surface acoustic wave (SAW) filters, have significant phase delay variation over temperature but become more stable after warm-up. These components tend to drive the calibration requirements. Careful voltage regulation is incorporated for all components that are susceptible to amplitude or phase shift with voltage.

4.2. Uplink (Receive) Calibration

In a receive-only system, if the absolute direction of arrival is not required, then calibration of the receive paths is unnecessary. If the absolute direction of arrival is needed, then the receive paths must be accurately calibrated. When the adaptive array base station optimizes its downlink transmit signal based on the information derived from the uplink receive signal, then both signal paths must be calibrated-- as is the case of the AirNet Adaptive Array system.

Coherence is maintained between up to 8 receive paths through periodic calibration of the relative phase and amplitude offsets of each path after warm-up and during operation. Fixed delay differences in the RX signal path, such as cable lengths or SAW filter delays, as well as fixed phase offsets between local oscillators are calibrated and digitally removed.

The receive calibration is performed by receiving a transmission from a transponder that is connected to a calibration antenna located in the near-field of the antenna array at a known angle. Unoccupied signal channels on different frequencies are used and each path's relative amplitude and phase offsets are derived. The entire receive chain for all 6-8 receive paths from the antennas to the DSP are calibrated to less than 5 degrees and 0.1 dB of accuracy.

4.3. Downlink (Transmit) Calibration

Since the adaptive array base station optimizes its downlink transmit signal beam and nulls based on the information derived from the uplink receive signal, then the 4 transmit paths are also fully calibrated to within 5 degrees and 0.1 dB.

After warm-up and during operation, the fixed amplitude and phase differences in the TX signal path, such as cable lengths or SAW filter delays, as well as fixed phase offsets between local oscillators are calibrated and digitally removed in the DSP.

The calibration of the transmit path is done by alternatively forming transmit nulls at the calibration antenna located in the near-field of the antenna array at a known angle using different combinations of transmit antennas. The calibration antenna is connected to a transponder that receives the downlink transmit signals in unoccupied GSM channels on different frequencies and then communicates back to the base station via a corresponding uplink channel.

5. SUMMARY – AIRNET ADAPTACELL SUPER-CAPACITY BASE STATION

The AirNet implementation is the only viable and proven solution for GSM adaptive array beamforming technology. It is the key enabler for high capacity voice and packet data services, which is fundamental to success for GSM operators. AirNet has the only proven broadband software-defined radio platform that will support a seamless integration of adaptive array technology.

The AirNet AdaptaCell base station, upgraded with adaptive array software, has the following benefits:

- Improvement of dynamic C/I on a per subscriber basis, achieving a C/I up to 31 dB on the uplink and 25 dB on the downlink,
- Improved quality throughout the network,
- Improved spectrum utilization and Erlang capacity by 8x for urban voice applications versus traditional technology,
- Up to 5x higher data throughput for GPRS and EGPRS,
- Overall cost reductions in both capital and operations,
- Extending the GSM network's viability indefinitely, and
- Alternative to expensive and uncertain 3G plans.

6. AIRNET OVERVIEW

AirNet Communications Corporation first deployed the AdaptaCell Base Station for commercial GSM applications in 1997, achieving major market successes both in North America and internationally. During the GSM Association conference in Cannes, France in February 1998, AirNet was honored to become the only GSM infrastructure manufacturer to be chosen to receive the coveted "Best Technical Innovation" Award based on the innovative broadband software-defined AdaptaCell and the Backhaul-free AirSite Base Station products.

During the PCS'99 exhibition in September 1999, AirNet further announced that the AdaptaCell base station would support the smooth migration from 2G GSM voice & data applications to GRPS, 2.5G (EDGE) and 3G (WCDMA) services on the same platform. This migration requires only minimal hardware modifications-- not the "forklift upgrade" required by most other operators. Powerful digital beamforming processing for adaptive array antennas can be added simply by upgrading the software.

AIRNET™