

MIMO and Smart Antennas for 3G and 4G Wireless Systems

Practical Aspects and Deployment Considerations

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1. INTRODUCTION AND EXECUTIVE SUMMARY

According to Chetan Sharma's analysis of the U.S. wireless market, wireless data traffic exceeded voice traffic in 2008 and grew by 193 percent in 2009 to over 400 petabytes (400 x 10^{15} Bytes), about 4.4 times the information content of the deep web. [1,2]

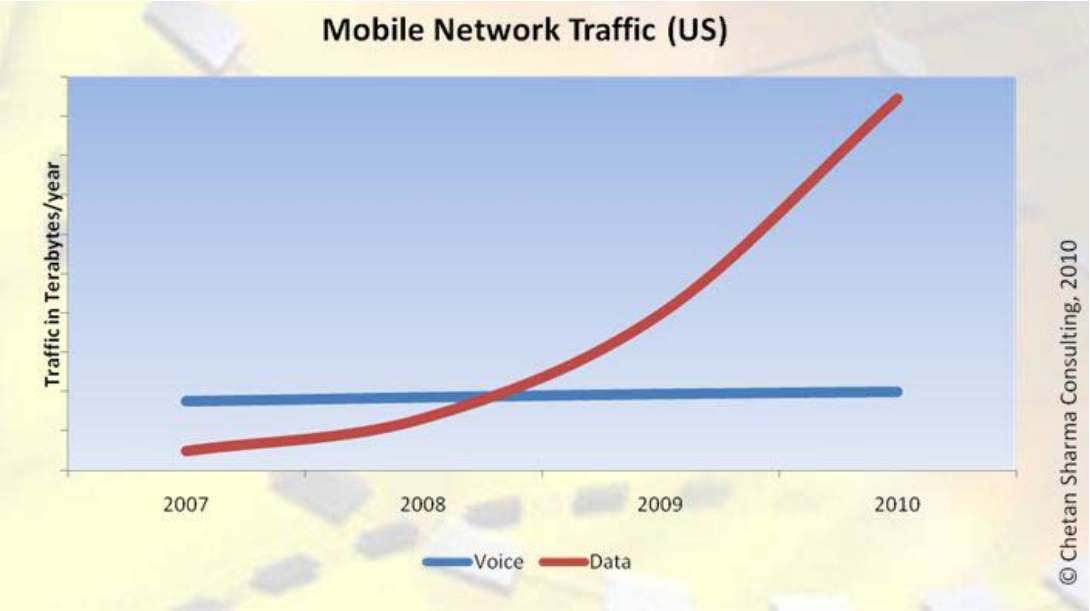


Figure 1. Comparison of voice and data traffic trends showing the recent upsurge in wireless data traffic (Chetan Sharma Consulting, March 2010)

With this rapid growth of wireless data traffic, now greatly exceeding voice traffic in many developed markets, operators are anxious to quickly expand the capacity of their wireless networks. To address these demands for increased capacity in a cost effective way, 3GPP standards have incorporated powerful techniques for using so-called "Smart Antennas." This paper outlines the considerable importance of various smart antenna schemes for improving the capacity (and coverage) of the emerging generations of wireless networks.

Several insightful papers have described in detail the processing gains feasible with smart antennas; notably the 3G Americas whitepaper entitled, "MIMO Transmission Schemes for LTE and HSPA Networks."[3] This paper concentrates on the practical aspects of antennas and their deployment for 3G and 4G wireless systems.

Growth in data traffic is putting immense strain on the operator's network. To increase capacity, operators have five primary tools at their disposal:

1) **Adding Cell Sites** is an effective but expensive approach to adding capacity. In general adding new real estate is time consuming and increasingly prohibitive. With median inter-site distances, dropping from 5 km to 2 km and recently to less than 200 m in dense urban areas the operator has less choice in selecting affordable property. Doubling the number of cell sites approximately doubles the network capacity and the throughput per user (assuming the user density stays constant), and greatly improves the peak user and the aggregate throughput per km^2.

2) **Adding sectors** such as changing from 3 sectors to 6 sectors is a useful way to approximate the introduction of new cells. However, this does not quite double the capacity as the "petals" of 6 sector coverage do not interleave as well as 3 sector coverage, and the fractional overlap of 6 sectors is greater. This also challenges handoff processing when near highways. This is a common approach in dense urban areas where rooftops are available. There is about a 70 percent increase in capacity in moving from 3 to 6 sectors in an environment with low angle spread (where the base station is located above the clutter).

3) **Adding Carriers** (or more accurately, **bandwidth**) directly adds to capacity. The LTE standard is particularly adept at utilizing increased bandwidth without increasing control channel overheads. In addition, in the U.S., the FCC permits increasing radiated power with the bandwidth in the PCS, AWS, and lower 700 MHz bands providing improved penetration and coverage.

4) **Improved air interface capabilities** such as in evolving from Release 99 UMTS to Release 5 HSDPA that provided well over four times the aggregate downlink capacity. However, in moving from Release 6 HSPA (1X2) to Release 7 (1X2) with 64QAM and 2X2 MIMO we see a more modest 10 percent to 20 percent improvement in the aggregate throughput. As has been observed before, improvements in air interface (while leaving everything else the same such as bandwidth and antenna configuration) is seeing diminishing returns on improvements. Something more than simply increasing modulation and coding rates is needed.

5) **Smart antennas** provide the next substantial increase in throughput. The peak data rates tend to be proportional to the number of send and receive antennas, so 4X4 MIMO is capable of twice the peak data rates as 2X2 MIMO systems. For another example, in upgrading from HSPA (1X2) to LTE (2X2) a gain of 1.6x is seen (Rysavy, 2009).

By "smart antennas" we here refer to adaptive antennas such as those with electrical tilt, beam width and azimuth control which can follow relatively slow-varying traffic patterns as well as so called intelligent antennas that can form beams aimed at particular users or steer nulls to reduce interference and finally Multiple-Input Multiple Output (MIMO) antenna schemes.

This paper focuses on the practical aspects of deploying smart antenna systems in existing Radio Access Systems (RAS). A substantial and growing body of theoretical and field experience is able to provide reliable guidance on the tradeoffs of various antenna configurations. Operational experience with WiMAX and TD-SCDMA systems that have utilized smart antennas for several years provides practical experience applicable to the upgrade to HSPA and LTE wireless systems. Many previous papers describe the theoretical capabilities of smart antennas and the mechanisms that provide for their support in the standards. The reader is referred to surveys such as those in [1,4,5,6] (3G Americas June 2009), and (BLTJ 2009[7]) for details on simulations and measured performance of various configurations. A summary of high-level results is also presented in Section 3.

This paper aims to address the practical tradeoffs of performance with the realistic constraints on the types of antennas that can be realistically installed, cognizant of zoning, wind loading, size, weight and cabling challenges and constraints from legacy terminals and other equipment. Constraints are, of course, present in both the base station and the terminal side of the air interface, where MIMO technology promises useful gains if multiple antennas, amplifiers, receivers and baseband processing resources can be made available in terminals.

Section 1 of this paper gives the background to the subject, defining terms and classifications of antenna schemes. In particular, it discusses the LTE downlink transmission modes in relation to practical antenna configurations.

Section 2 concisely covers the evolution of the base station antenna. Legacy antennas are described, as are antennas appropriate for multiband and multi-standard operation. Also described is a variety of advanced antenna

technologies used for receive and transmit diversity, beam steering and shaping, and MIMO. Active antennas are introduced as well. Subsequent subsections provide more in-depth discussions of the various advanced antenna technologies.

Section 3 discusses antennas used for MIMO and the suitability of dual-polarized antennas or spatially separated vertically polarized antennas for a 2X2 application. Also discussed is 4X2 and 4X4 MIMO implementation using horizontally separated dual-polarized antennas, and section 8.2 presents an analysis of the impact of different antenna spacings on both the spatial multiplexing and the diversity performance.

Section 4 presents the planar array antenna typically used for adaptive array beamforming. The architecture, application, calibration, and properties of these antennas is considered. The architecture implemented when planar arrays are used to radiate multiple fixed beams is also explained.

Section 5 covers reconfigurable beam antennas, which extend the concept of variable elevation beam tilt to beam control in the horizontal plane. The results of a radio planning simulation show benefits of optimizing both coverage and interference, as well as the benefits of load balancing.

Section 6 introduces active base station antennas where the active RF functionality of the radio is integrated into the antenna by distributing medium power transceivers directly behind each antenna element. This architecture and its plusses and minuses are described.

Section 7 discusses spectral efficiencies of various air-interfaces and presents the results of simulation and field trials on various MIMO antenna configurations.

Section 8 examines the typical deployment scenarios seen in current cellular networks.

Section 9 introduces various deployment issues including commercial restrictions on antenna and their use. The accelerated horizontal pattern distortion, which is the result of mechanically downtilting an electrical tilted antenna, is characterized. The topic of passive intermodulation (PIM) is explained as is its potential for interface in the RX path. The remote radio head architecture and feature set for MIMO is described as is a RRH feeder cable solution. The weight and windload advantages of a RRH installation as compared to a conventional coaxial feeder cable installation is analyzed. Co-siting solutions for multiple base stations and technologies is treated using typical spectrum and equipment scenarios. An overview of drive test equipment and the impact of multi-antenna technologies will have on this equipment is discussed. Finally, two types of relay implementations are compared for extending MIMO coverage indoors via a distributed antenna system.

Section 10 presents a study and its results relating realistic terminal antennas to the link budget and throughput that can be expected for MIMO implementation in LTE. Practical examples of how terminal antennas are implemented in hardware are presented.

2. BACKGROUND AND SCOPE OF WHITEPAPER

This white paper discusses downlink antenna techniques available in LTE Release 8. While additional techniques such as Multi-User MIMO (MU-MIMO) are available for the uplink, and new techniques have been and will be introduced in Release 9 and Release 10, they are beyond the scope of this paper.

Figure 2 below shows the taxonomy of antenna configurations supported in Release-8 of the LTE standard (as described in 3GPP Technical Specification 36.300). The LTE Release 8 standard supports one, two or four base station transmit antennas and two or four receive antennas in the User Equipment (UE), designated as: 1X2, 2X2, 4X4, where the first digit is the number of antennas per sector in the transmitter and the second number is the number of antennas in the receiver. The cases where the base station transmits from a single antenna or a single dedicated beam are shown in the left of the figure.

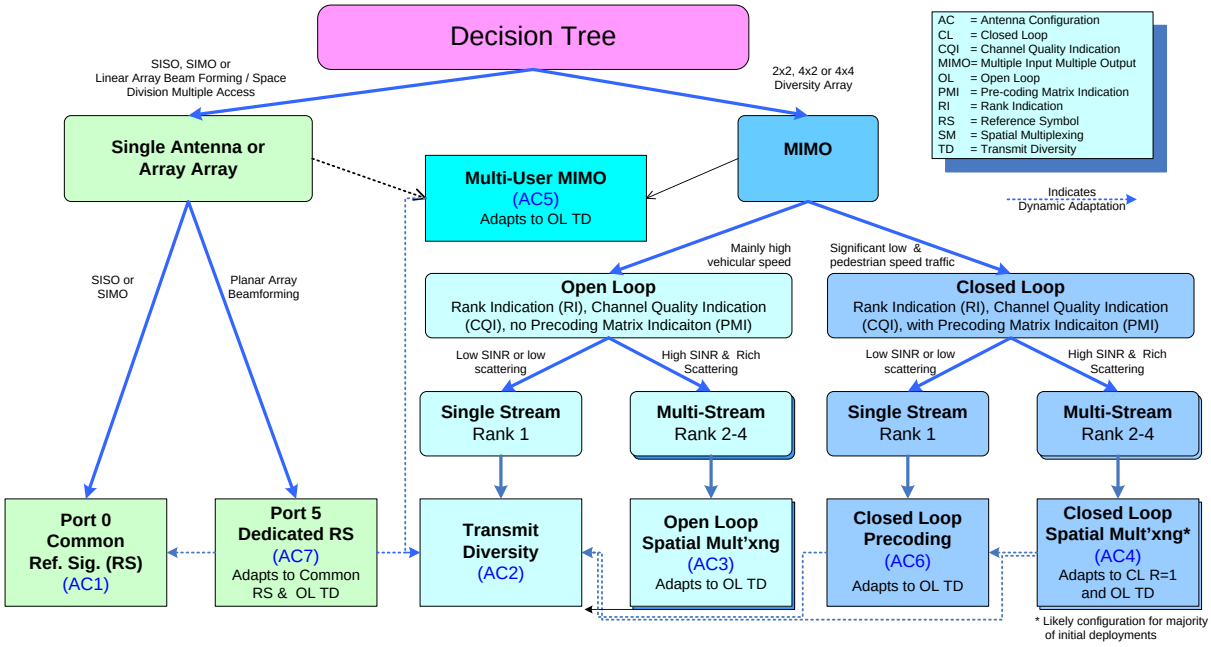


Figure 2. Taxonomy of smart antenna processing algorithms in Release 8 of the LTE standard.

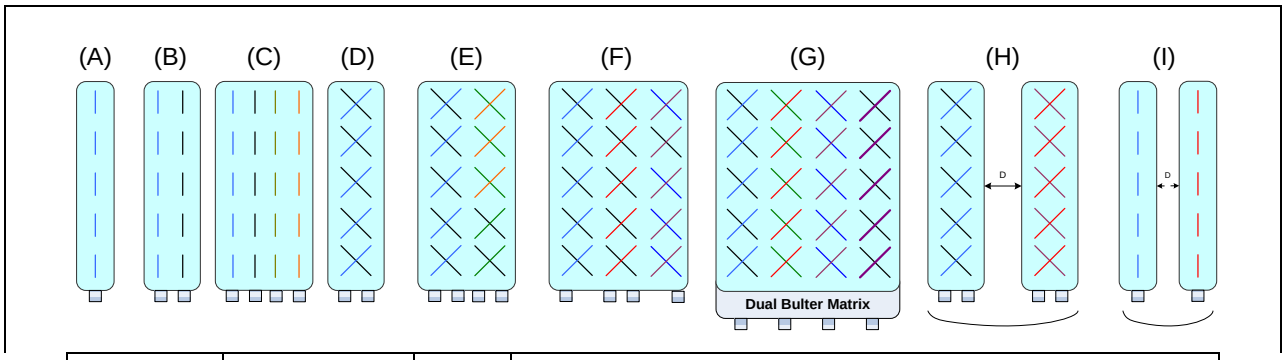
Beyond the single antenna or beamforming array cases diagramed above in Figure 2, Release 8 of the LTE standard supports MIMO antenna configurations. This includes Single-User (SU-MIMO) protocols using either Open Loop or Closed-Loop modes as well as Transmit Diversity and MU-MIMO. In the Closed-Loop MIMO mode, the terminals provide channel feedback to the eNodeB with Channel Quality Information through CQI, Rank Indications (RI) and Precoder Matrix Indications (PMI), which supports the highest peak data rates, and is likely to be the most commonly used scheme in early deployments. However, this scheme provides the best performance only when the channel information is accurate and when there is a rich multipath environment. So Closed-Loop MIMO is appropriate in low mobility environments such as with fixed terminals or those used at pedestrian speeds.

In case of high vehicular speeds, Open Loop MIMO may be used, but because the channel state information is not timely, the PMI is not considered reliable and is not used. Note that in TDD networks, the channel is reciprocal and thus the DL channel can be more accurately known based on the uplink transmissions from the terminal (the forward link's multipath channel signature is the same as the reverse link's – both paths use the same frequency block), so MIMO can potentially improve TDD networks under more conditions than in FDD networks.

One may visualize spatial multiplexing MIMO operation as subtracting the strongest received stream from the total received signal so that the next strongest signal can be decoded and then the next strongest, somewhat like a multi-user detection scheme. However, to solve these simultaneous equations for multiple unknowns, the MIMO algorithms must have relatively large Signal to Interference plus Noise ratios (SINR), say 15 dB or better. With many users active in a base station's coverage area, and multiple base stations contributing interference to adjacent cells, the SINR is often in the realm of a few dB. This is particularly true for reuse 1 systems, where only users very close to the cell site experience SINRs high enough to benefit from spatial multiplexing SU-MIMO. Consequently, SU-MIMO works to serve the single user (or few users) very well, and is primarily used to increase the peak data rates rather than the aggregate data rate in a network operating at full capacity.

Angle of arrival beamforming schemes form beams which work well when the base station is well above the clutter and when the angular spread of the angle of arrival is small, corresponding to users that are well localized in the field of view of the sector, in rural areas, for example. To form a beam, however, one must have antenna elements spaced less than a wavelength apart, while the spatial diversity required of MIMO requires either cross-polarized antenna columns or else it requires that the columns be far apart. The farther apart, the more path diversity they will have. This is often about 10 wavelengths (1.5 m or 5 ft. at 2 GHz).

These physical antennas are categorized below in Figure 3. The short lines correspond to individual antenna elements, typically arranged in columns. Such columns are able to form the fan beam required to properly illuminate a cell sector and which is a characteristic of base station antennas. The antenna elements in each column are interconnected and share a common RF connector shown below the columns. These correspond to the individual RF cables that connect the radios and their amplifiers. The configurations shown are restricted to no more than 4 cables per sector, corresponding to the 4X4 limit in the Release 8 standard.



Antenna Algorithms	Antenna Configuration	Figure	Description
AC1	1V	(A)	1 Column with vertical polarization (V-Pol)
AC7	ULA – 2V	(B)	2 Closely spaced V-pol columns
AC5, AC7	ULA-4V	(C)	4 V-pol columns
AC2-4, AC6	DIV 1X	(D)	1 Column with dual-slant-45 polarization (X-pol)
AC2-6	CLA-2X	(E)	2 Closely spaced X-pol columns (Quad Port)
AC2-6	CLA-3X	(F)	1 X-pol center column between two closely spaced x-pol columns
AC2-7	BM-4X (aka CLA-4X)	(G)	4 X-pol columns with dual Butler Matrix
AC2-6	DIV-2X	(H)	2 Widely spaced X-Polarized columns
AC2-6	TX-DIV	(I)	2 Widely spaced V-pol columns

Figure 3. Antenna configurations (from endnote [6]) with the constraint of no more than four antenna cables per sector for a total of 12 cables for a three-sector system.

The Butler matrix in antenna (G) is used to distribute properly phase and amplitude weighted contributions of the 4 RF connectors to the eight columns to form four separate beams (two for each polarization, each half as narrow a beamwidth as antenna (E)).

No one antenna configuration is applicable to all environments, for example in rural systems, where the eNodeB antennas are located above the clutter, antennas that can form beams such as (C) and (G) are best. In urban macrocellular antennas (E) (G) or (H) are expected to be best. Urban microcellular base stations that are embedded in the clutter and the angle of arrival spread is large then antenna (H) is expected to be good at providing the greatest path diversity, but as seen in Section 3 and in Figure 39, we see that the closer the columns of antenna (H) are, the

better the user data rates will be for downlink data, although different antenna spacings may be beneficial in different environments or for different data types, etc.

Vocabulary

A word about vocabulary is in order. LTE is bringing with it a usage of the term "cell" that is more common among the Europeans than that used in the Americas; namely, "cell" references the sector rather than the base station. Where it has been common in the U.S. to refer to a "3-sectored cell," it is becoming more appropriate not to use the term "sector", but to refer to the 3 "cells" associated with a single base station or Node-B. (One may also have other than three cells associated with a single base station, four or six, for example.) In this document, we use the words "cell" and "sector" interchangeably, and try to be clear in referring to base stations as a fixed site, such as a tower or rooftop, where multiple antennas are located.

This is illustrated below in Figure 4 which shows how base stations are typically considered located at the vertices of three cells (sectors). The interlaced "petals" of adjacent cells is such that the approximate beamwidth of the antennas located at these base station sites are 60 degrees as illustrated in the bottom right part of the figure. These interlacing petals work well for 3 sector base stations and show why antennas tend to be narrower in beamwidth than the 120 degrees one might otherwise assume from thinking of a base station located in the center of a cell.

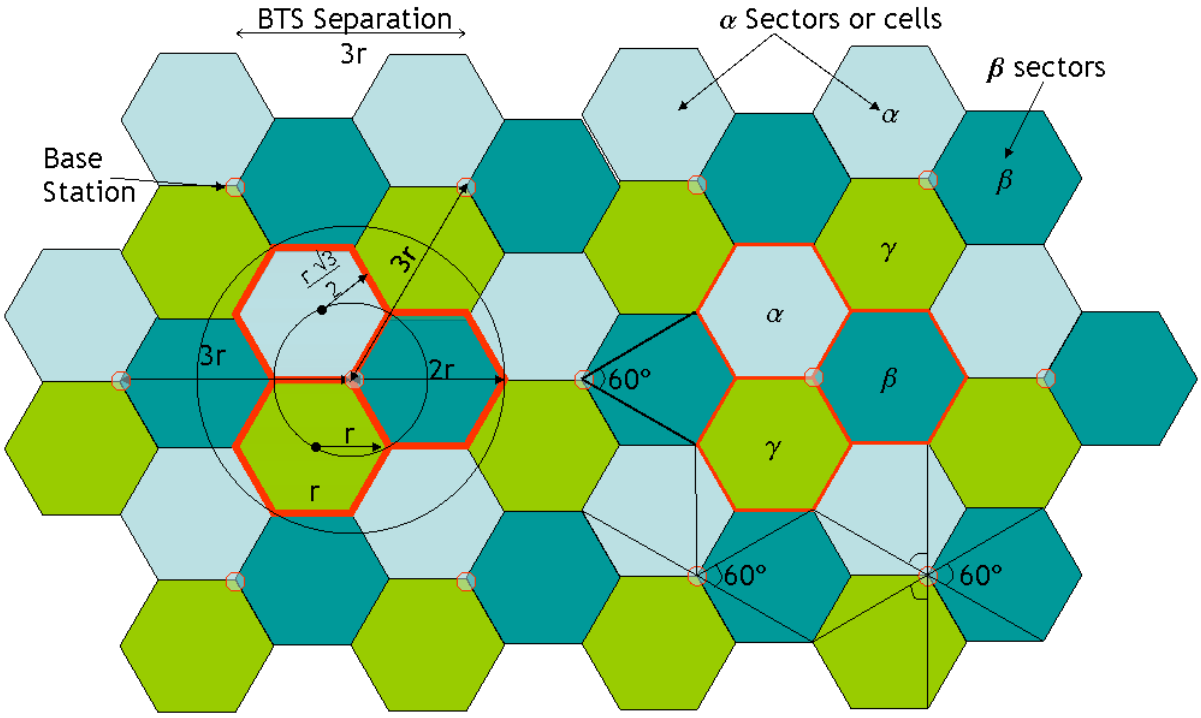


Figure 4. Illustration of the terminology of base stations and cells.

The previous vocabulary will be increasingly strained as the industry deploys remote antennas further from the base station, so we will refer to the area covered by common control signals (PCFICH, PDCCH, PHICH) as a cell.

We further refine our vocabulary by pointing out that a radome can contain multiple antennas, typically in columns (though that is not the case with some active array antennas). These columns share a common RF connector with the same RF signal. So a radome might consist of pair of cross polarized antennas one at -45 degrees, the other at 45 degrees polarization (from the vertical) and each with a distinct, RF connector that is fed with a distinct RF signal having a separate Reference Signals (RS) while serving the same cell (sector). This is distinct from some references

that consider multiple antennas within a single radome to be part of one antenna. Both uses of the term antenna are common on the cellular industry and this is common can lead to some confusion.

Some radomes serve multiple frequency bands with common RF connectors. These permit sharing of expensive coaxial feeders and effectively have internal duplexers that split the different frequency bands and distribute the signals to separate antenna columns. In this way, one can have a single coax and a single RF connector on the base of a radome serving a multiple bands, with two or more antennas internal to the radome. The different bands might be separately down-tilted and steered.

In the following section, we describe in detail the evolution and variety of antenna designs commercially available and in development.

3. BASE STATION ANTENNA EVOLUTION

Base station antenna technology has progressed in response to industry requirements and trends. The key drivers have been the continuing addition of cellular frequency bands, the integration of more functionality into single radome housing, and antenna techniques that contribute additional capacity to cellular networks. The following figures concisely describe the development of the base station antenna including advanced antenna technologies in use and emerging today.

3.1. EARLY TECHNOLOGY

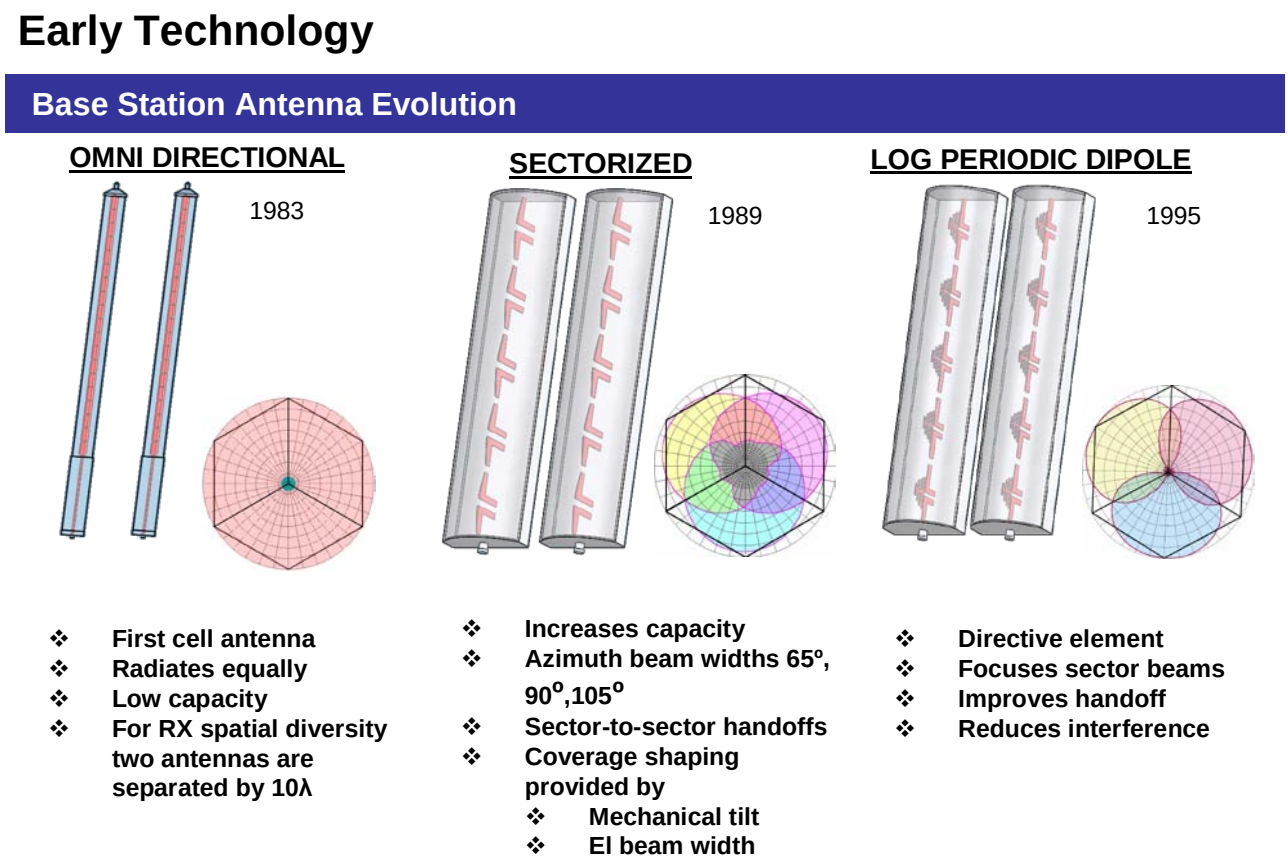


Figure 5. Early base station antenna technology.

3.2. CURRENT TECHNOLOGY

3.2.1. EXTENSIVE USAGE

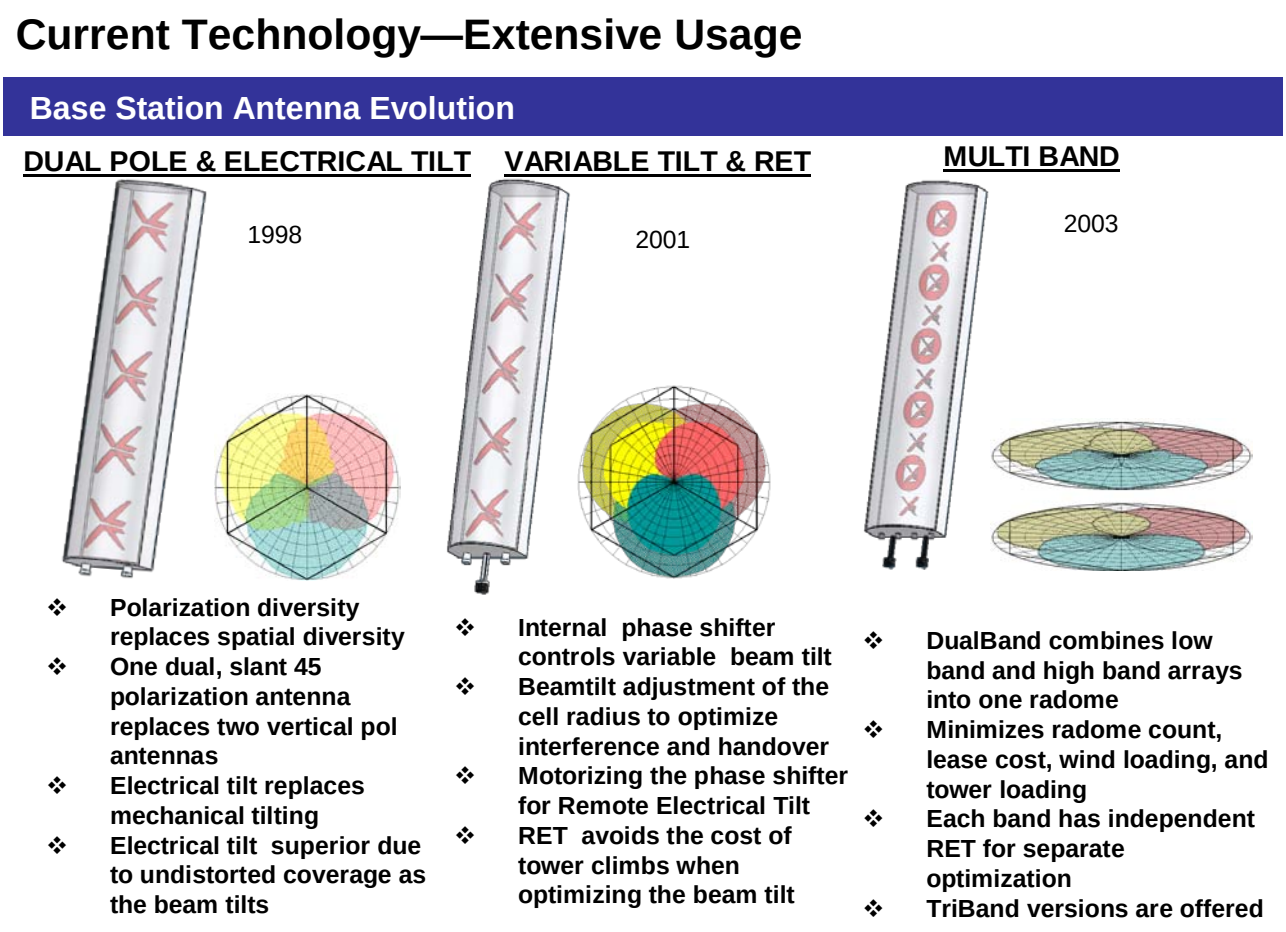
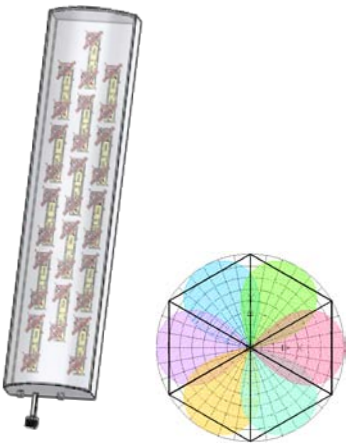


Figure 6. Current base station antenna technology -- extensive use.

Current Technology—Moderate Usage

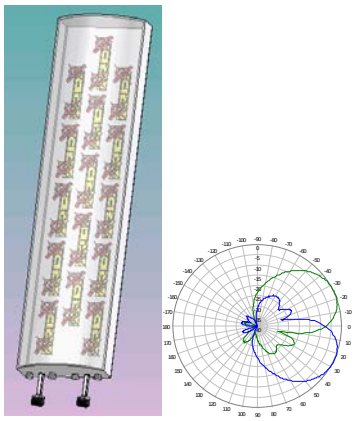
Base Station Antenna Evolution

6 SECTOR



- Additional sectorization increases capacity
- 33º and 45º beam widths
- Multiple antenna columns creates the narrow beam
- DualBands available but not common
- RET

MULTIBEAM ANTENNA



- Multi-beams from a single array –butler matrix feed
- Separate ports for each beam
- Independent tilt for each beam
- Reduces the number of antennas for a six sector site from six to three

CONCEALMENT & INTEGRATION



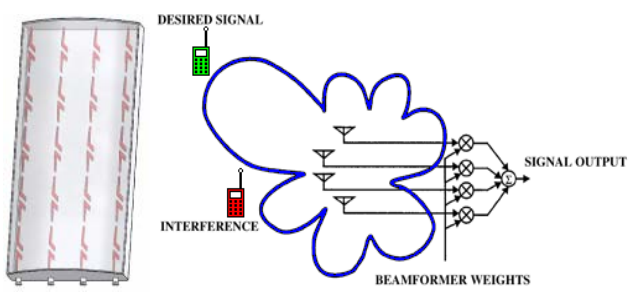
- 3-sectors in one radome
- Improved aesthetics and concealment
- TMAs can also be integrated

Figure 7. Latest base station antenna trends -- moderate usage.

Advanced Antenna Technology

Base Station Antenna Evolution

ADAPTIVE ARRAY (AA)





- Planar Array – multiple columns of radiators
- External DSP controls the horizontal antenna pattern
- A unique beam tracks each mobile
- Pattern nulls mitigate interfering signals
- Increased S/N generates capacity improvements
- 4,6, & 8 column v-pol used for WiMax and TD_SCDMA
- 4 column dual-pols are now also used – 8 ports
- λ /2 spacing between columns is required as coherence is needed to form beams (correlation)
- Calibration is needed to eliminate phase and amplitude variation in feeder cables
- Often tower top electronics are used with AA
- AA is best suited for TDD and LOS applications

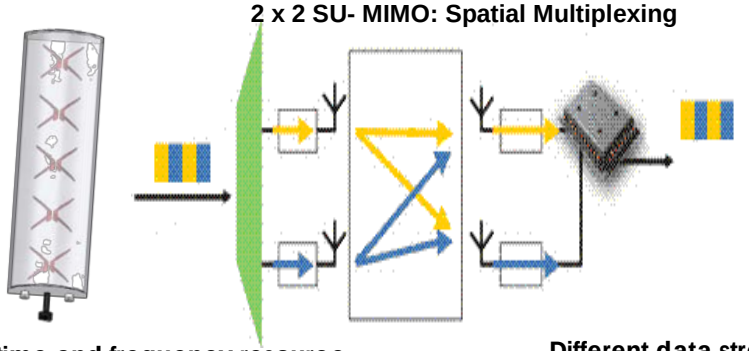
Figure 8. Advanced Antenna Technology.

Advanced Antenna Technology

Base Station Antenna Evolution

MIMO SYSTEMS

2 x 2 SU- MIMO: Spatial Multiplexing



Same time and frequency resource

Different data streams

- Multiple Input Multiple Output
- Capacity gains due to multiple antennas at both ends of the link
- Multipath provides additional channel using DSP
- LTE supports 1x2,2x2,4x2,4x4
- Spatial Multiplexing requires a multi-path environment

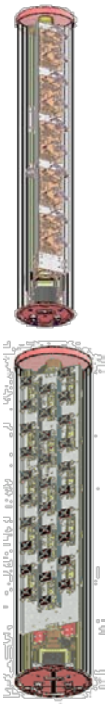
- Space Time Block Coding is a transmit diversity mode used when S/N cannot support Spatial multiplexing
- Decorrelation between antennas and propagation paths required for Spatial multiplexing
- A Dual polarized BSA for 2x2 MIMO; two separated for 4x2 or 4x4 MIMO
- Alternatively vertically polarized antennas can be used with spatial separation

Figure 9. MIMO Systems.

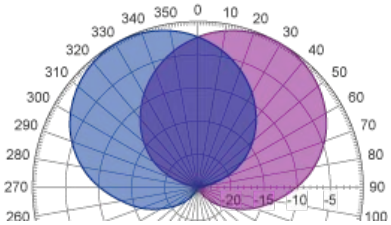
Advanced Antenna Technology

Base Station Antenna Evolution

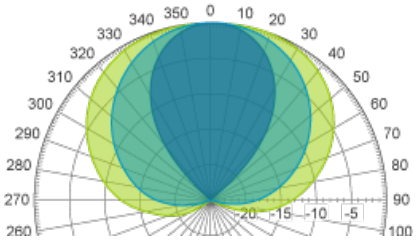
RECONFIGURABLE BEAM ANTENNA



Beam Panning



Beam Fanning



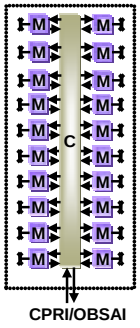
- **Passive beam control**
- **1-way: standard RET antenna**
- **2-way: adds beam panning – horizontal beam steering**
- **3-way: adds beam fanning – horizontal beam width adjustment**
- **Capacity improvements:**
- **- network optimization**
- **- load balancing**
- **Dynamic coverage adjustments can be made in response to changes in traffic distribution - SON**

Figure 10. Reconfigurable Beam Antenna.

Advanced Antenna Technology

Base Station Antenna Evolution

Active Antenna System (AAS)





- **Radio-embedded BSA**
- **Functionality of a Remote Radio Head integrated and distributed into the antenna**
- **Same size as a standard passive BSA**
- **Standard azimuth beam**
- **RX/TX Transceiver feeds each element directly**
- **Loss of a transceiver does not cause a complete failure of the sector – graceful degradation with self-healing**

- **Input to BSA is via fiber and CPRI or OBSAI radio interface standard**
- **Electrical tilt beam control done digitally**
- **Electronic elevation beam control features that can provide capacity benefits:**
  - **Vertical sectorization**
  - **Tilt by service or carrier**
  - **Separate TX-RX tilt**

Figure 11. Active Antenna System (AAS).

3.3. COMPARISON TABLE—ANTENNA TYPES SUPPLIED – ONE VENDOR

The following is a table comparing the distribution of antenna types recently supplied by one global vendor.

Table 1. Antenna Types Supplied -- One Vendor.

Antenna Type	%	Comments
Vertically polarized (V-pol)	10	80% of these are Omni; the rest are high gain sector antennas for rural deployment
Dual polarized (X-pol)	90	

Antenna Type	%	Comments
Variable tilt	60-70	
Fixed Tilt	30-40	

Antenna Type	%	Comments
RET	15-20	RET market share is increasing
Non-RET	80-85	

Antenna Type	%	Comments
Single band	60-70	40% of these are quad port
Multiband	30-40	Multiband market share is increasing

Antenna Type--Elevation Beamwidth 800/900 MHz		
Degrees	%	Comment
16	45	Nominal height is 1.4M
10	20	Nominal height is 2.0M
8	35	Nominal height is 2.6M
4	0	N/A
Antenna Type--Elevation Beam Width 1800/1900/2100 MHz		
Degrees	%	Comment
16	10	Nominal height is 0.7M
10	5	Nominal height is 1.0M
8	65	Nominal height is 1.4M
4	20	Nominal height is 2.0M
Antenna Type--Azimuth Beam Width		
Azimuth (Degrees)	%	Comment
90	15	Typically Rural
65	75	Urban/Suburban/Rural
33 and 45	20	Six Sector

3.4. ANTENNAS FOR MIMO

MIMO systems place the same requirements on the RF link as do the receive diversity systems that are in place for current cellular networks, that is, there must be de-correlation between the channels received at the antenna. This de-correlation is provided by space diversity when achieved by the separation of the antennas, or by the use of polarization diversity when implemented by the use of orthogonal antenna elements.

Early cellular systems employed spatial diversity and typically used two vertically polarized antennas separated by a distance of 10 wavelengths, or greater, at the frequency of operation. Most cellular providers have switched to polarization diversity, utilizing dual polarized antennas, which have been shown to provide equivalent if not better diversity gain as it does for spatial diversity.[8] Dual polarized antennas have the added benefit of integrating two antenna arrays into one radome housing while maintaining the same size.

Most antenna properties, and their associated specifications, influence the illuminated coverage of the cell site topography and the link budget between the base station and handset. However, for dual-pol antennas, cross-polar discrimination and port-to-port isolations can affect the diversity or MIMO performance of the system by introducing correlation between the channels. Studies have shown that the standard specifications that meet the requirements for

effective receive diversity performance,[9] also provide adequate de-correlation for effective MIMO system performance.[10]

In summary, a standard dual-pol antennas work well for 2X2 MIMO, as do two spatially separated dual-pol antenna for 4X2 or 4X4 MIMO. A quad antenna, which packages two dual polarized arrays into one radome, provides effective 4X2, or 4X4 MIMO performance in a compact width radome.[10] Spatial separation of 1λ between dual-polarized arrays is the norm for quad antennas. Studies presented in section 6.2 of this paper indicated that quad antennas that have a spatial separation of less than 1λ can provide throughput gains for closed-loop, spatial multiplexing, pre-coded beamforming (LTE transmission mode AC4) albeit at the possible expense of degraded diversity performance and some compromise in antenna performance.

4. ADAPTATIVE ARRAY (AA) BEAMFORMING ANTENNAS

4.1. INTRODUCTION

An adaptive beamforming multi-column array antenna can be considered an advanced multiple antenna technique that will provide an improvement in the overall communication link between the base station and mobile. The basic architecture of an adaptive beam-forming antenna consists of multiple columns of radiating elements that are driven by separate transceiver networks. Each transceiver path has the ability to adjust the amplitude and phase of the transmit (downlink) and receive (uplink) signals.

Figure 12 below shows typical planar array architectures that are currently deployed in wireless networks. Three different antenna array architectures are shown:

- Eight columns of vertically polarized radiating elements
- Four columns of vertically polarized radiating elements
- Four columns of dual-polarized radiating elements

There has been a significant trend to migrate towards dual-polarized arrays as the resulting physical size of the antenna has been reduced by 50 percent as compared to a vertically polarized array.

It is important to note that the beamforming that we are referring to takes place in the azimuth plane of the beam. This will be discussed further when we review various beamforming azimuth patterns.

As shown in Figure 12, the separation between the columns for a beamforming array is on the order of 0.5 wavelengths. It is not unusual to further increase the spacing to as much as 0.7 wavelengths, but there will be some resulting degradation in the beamforming characteristics under various scanning conditions. By maintaining a fixed column spacing of 0.5 wavelengths, grating lobes will be completely suppressed as the beam scans across the sector.

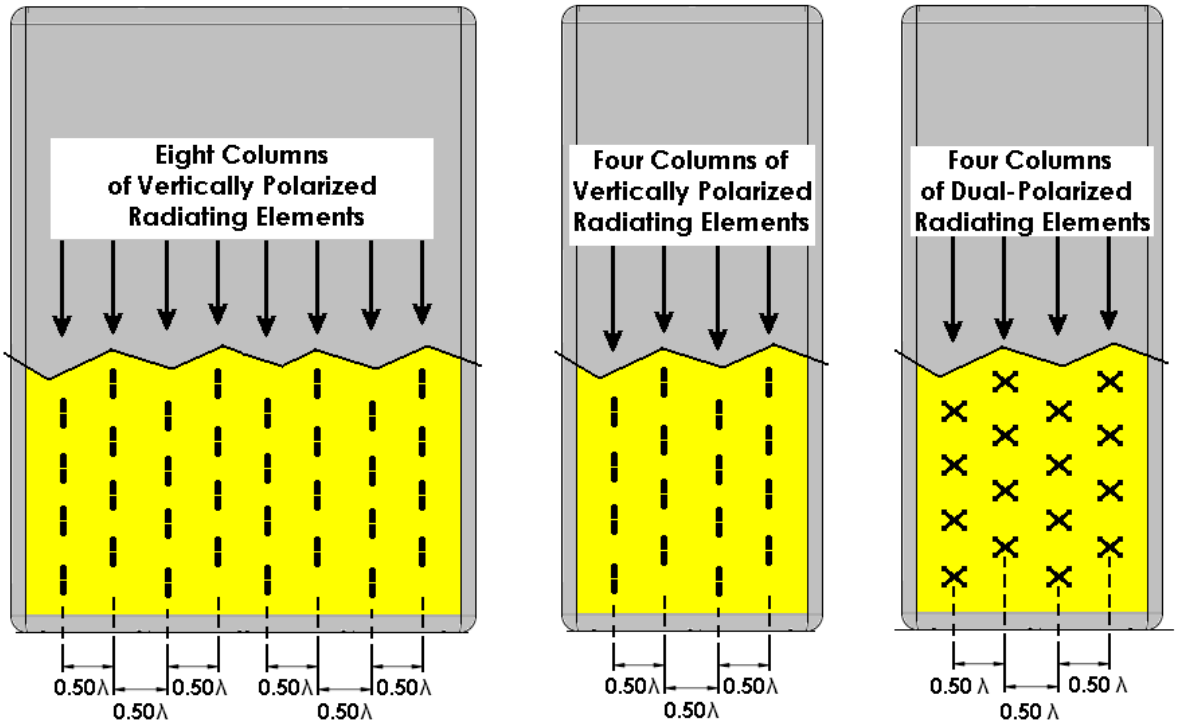


Figure 12. Typical Multi-Column Planar Array Architecture.

Figure 13 below shows a comparison of another type of antenna topology that is often confused with a beamforming type of antenna. Effective implementation of MIMO techniques requires that the signals on any ports not be highly correlated. For the beamforming antenna shown below with 0.5 wavelength column separation, the signals between adjacent columns would be highly correlated in low angle spread environments. The two-column antenna shown on the right has a column separation on the order of 1.2 wavelengths. This type of antenna would be suitable for a 4X4 MIMO scheme, as the signals between any two sets of cross polarized ports would not be highly correlated even in environments with relatively low angle spread. This two-column antenna could support a 2X2 MIMO scheme as well. Conversely, the two-column antenna with 1.2 wavelength separation would be a poor choice for a beamforming antenna.

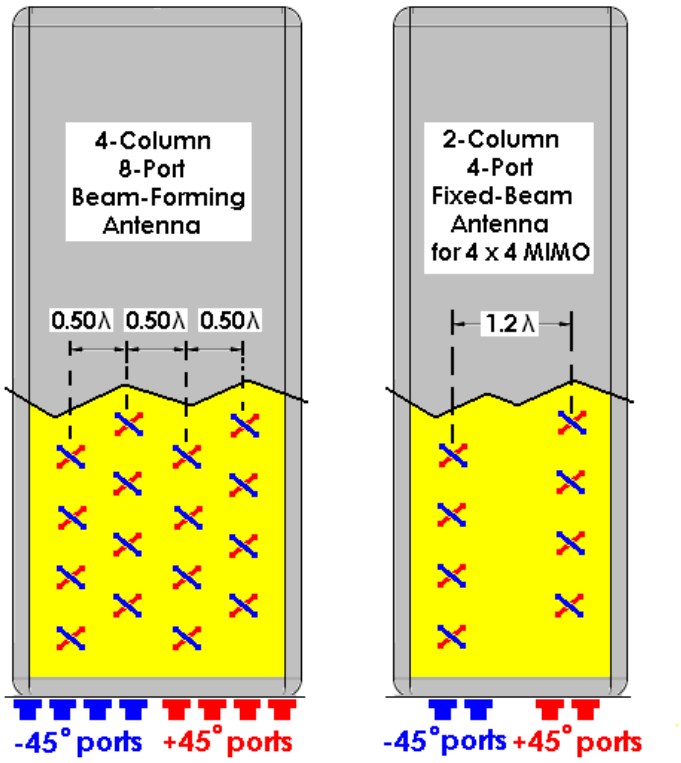


Figure 13. Beamforming antenna and fixed beam quad-port antenna.

4.1.1. INDIVIDUAL ANTENNA COLUMN CHARACTERISTICS

Each of the individual columns of a multi-column beamforming array are comprised of radiating elements, a low-loss power combining corporate feed network and an input port to provide access for a discrete transceiver. Figure 14 shows the topology of a single column of vertically polarized elements.

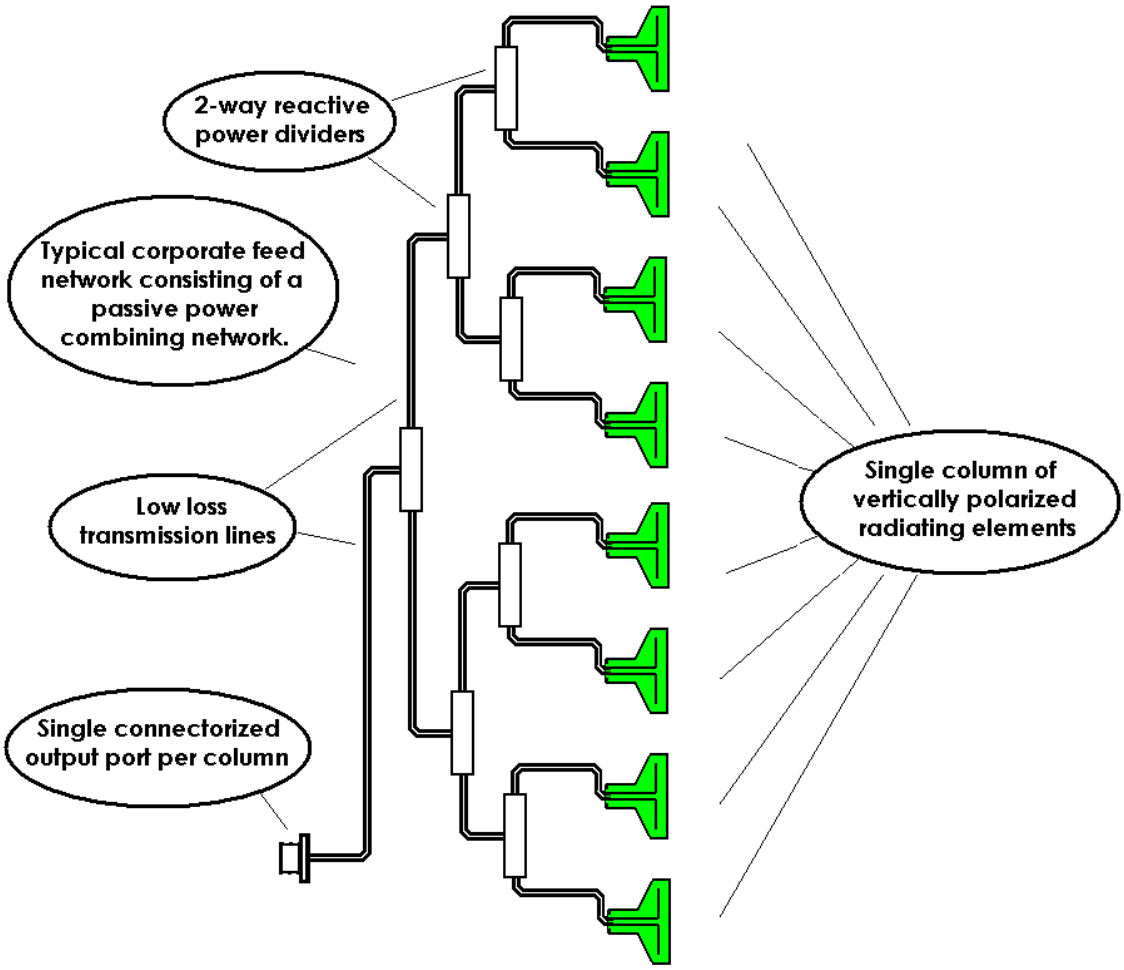


Figure 14. Topology of a single column of radiating elements.

Multi-column, adaptive, beamforming array antennas will therefore have a single output port for each corporate feed network. For a vertically polarized antenna array, this will result in a single port for each column. For a dual-polarized antenna array, each column will require two ports as a corporate feed network is dedicated for each polarization. Figure 15 depicts a typical connector scheme for a four column vertically polarized antenna with four ports as compared to a four column dual-polarized array that requires eight ports.

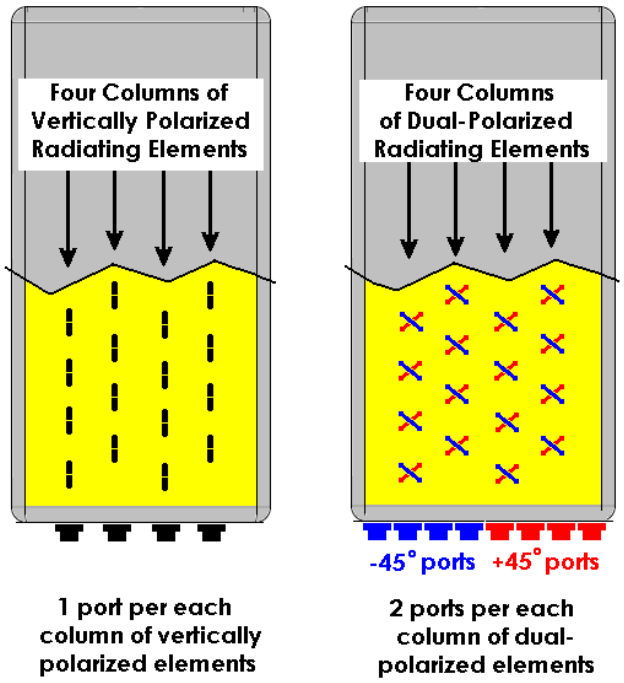


Figure 15. Connector ports for vertical and dual-polarized arrays.

The typical azimuth and elevation patterns of a **single antenna column** are shown below in Figure 16. The important characteristics of the azimuth and elevation patterns are highlighted. Many of the characteristics are similar to those of a traditional single column sector antenna used in non-beamforming systems.

The azimuth pattern is characterized to have a 65-degree half-power beam width and a good front-to-back ratio of 30 dB. It is also common to have a broader half power beam width of 90 degrees. However, there may be more unwanted interaction between the antenna columns when the azimuth beam width is 90 degrees as the spacing between the columns is only 0.5 wavelengths. While the 0.5 wavelength column spacing is preferred for good beamforming characteristics, it is not unusual to increase the separation between the columns to 0.6 or 0.7 wavelengths. The increased separation reduces the mutual coupling between the adjacent columns and provides more favorable and predictable individual column azimuth patterns.

For many of the beamforming planar array antennas deployed today, it is common to physically mount the radio electronics (remote radio heads) directly to the back of the antenna structure. It is important to characterize the azimuth antenna performance with the electronics present in the actual deployed condition. Certain parameters such as the front-to-back ratio or front-to-side ratio may be influenced as compared to a stand-alone antenna.

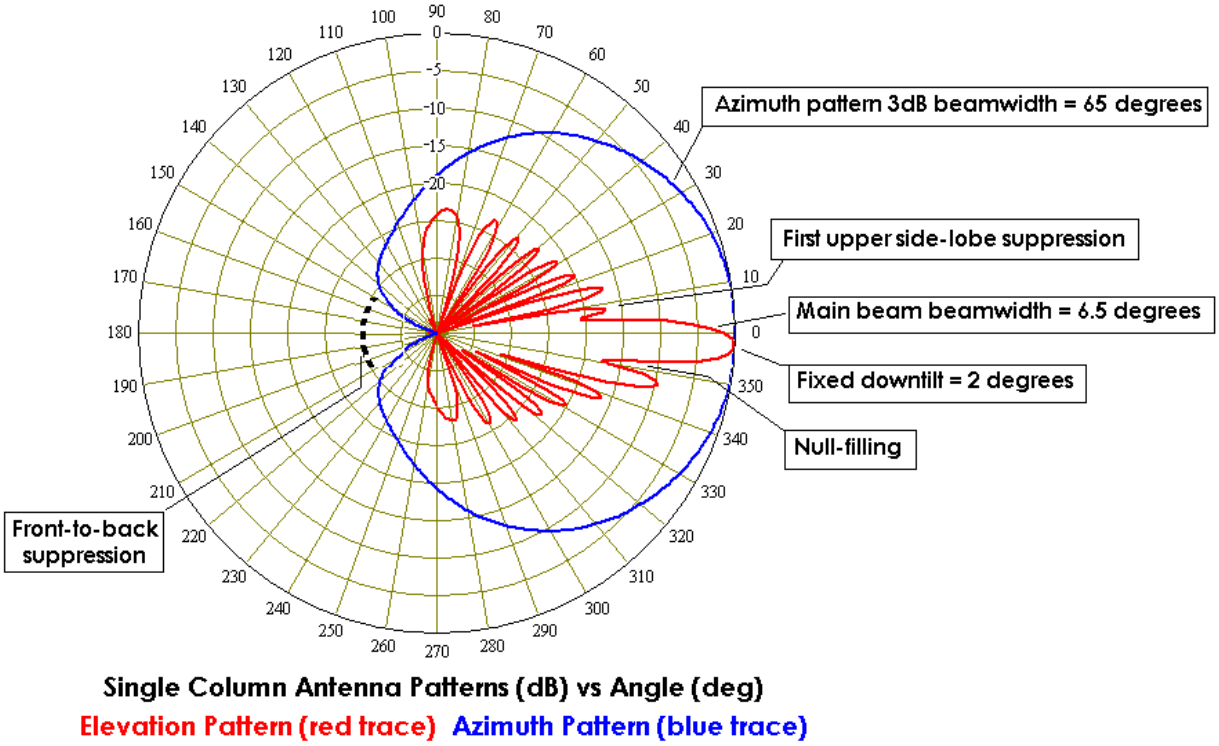


Figure 16. Typical antenna patterns for a single column of elements.

To emphasize the importance of reducing interference from adjacent cell sites, first upper side lobe suppression is typically specified to be a minimum of 17 dB to 18 dB. Fixed elevation beam down-tilt requirements will often be specified at approximately 2 degrees below the horizon. Many engineers have now expressed interest in implementing remote electrical down-tilt (RET) capability for individual columns to gain the advantages of proven RET technology. It is also common to include some null filling for the main beam below the horizon. However, null-filling values must be judiciously selected as excessive null filling may degrade the gain.

The elevation half-power beam width will typically be within the range of 6 to 7 degrees. The elevation beam width is strongly related to the overall height (vertical dimension) of the individual columns. The size limitation of the antenna therefore may result in a significant trade-off in elevation beam width. There is also the obvious frequency dependence of the antenna size on frequency. Figure 17 shows the relative physical sizes of three different antennas at the common operating frequency ranges of 850 MHz, 1900 MHz and 2500 MHz. Each of the antennas shown has an approximate elevation beam width of 6.5 degrees to provide a relative comparison. It is apparent from figure 6 that at the lower frequency range of 850 MHz, a multi-column beamforming antenna may become unacceptably large and require some compromise in elevation beam width.

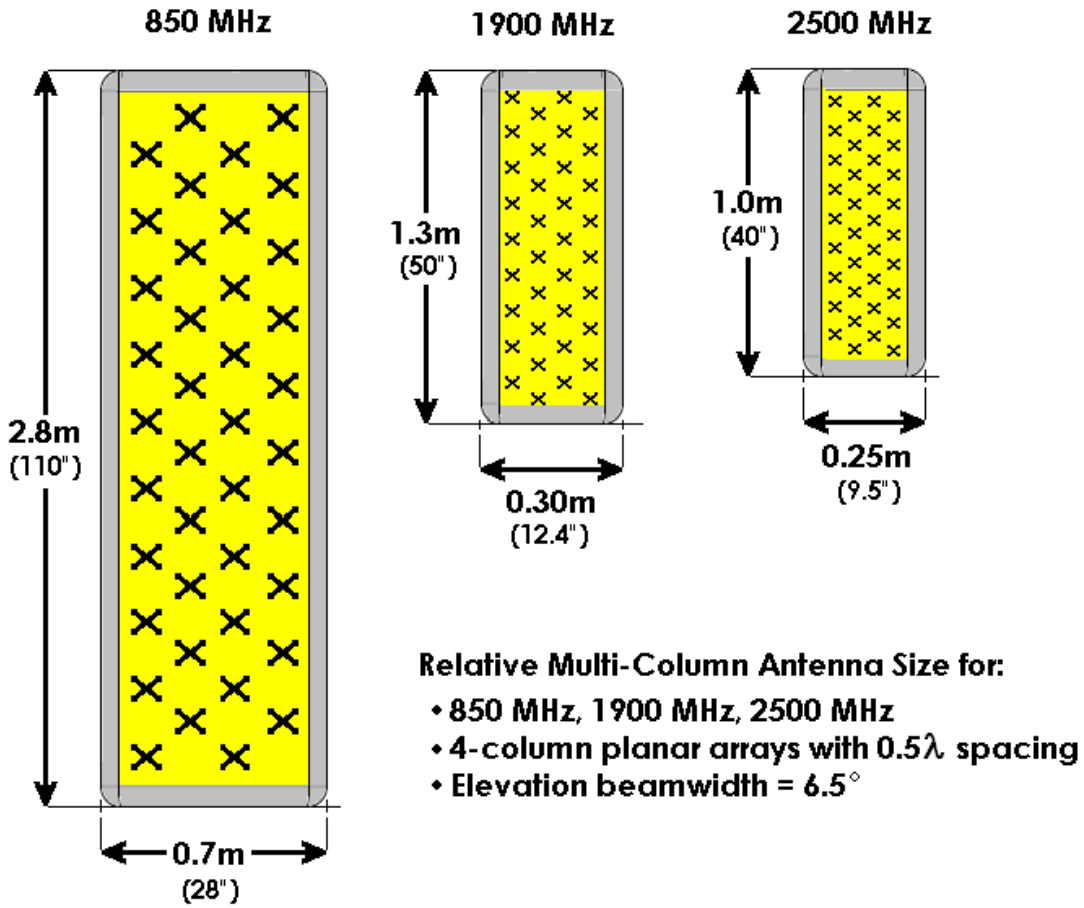


Figure 17. Typical and relative antenna size for multi-column arrays at various frequencies.

There are typically well-defined requirements for port-to-port isolation, return loss and passive inter-modulation performance. The minimum isolation between any two columns of the antenna array is typically a well-defined requirement that is derived from system level performance. Typical specifications for isolation between any two columns may be on the order of 25 dB. For a vertically polarized antenna with 0.5 wavelength spacing between adjacent arrays, the coupling can be significant and may have a relaxed requirement of 20 dB.

There is also an isolation requirement between the +45-degree and -45-degree polarizations of any single column for a dual-polarized antenna array. Typically, this isolation requirement will also be on the order of 25 dB to 30 dB.

The return loss performance of the individual antenna columns must be carefully evaluated over the various scanning conditions that will be used to synthesize patterns. As the amplitude and phase values of the individual columns are varied, the return loss will also vary and may degrade to unacceptable levels. By judiciously designing the radiating elements, these return loss degradation scenarios can be avoided.

4.2. BEAMFORMING

Figure 18 and Figure 19 below show some basic azimuth pattern beamforming scenarios for a four-column array. Figure 18 depicts the resulting antenna pattern for the case of all four transceiver modules generating identical signals. This is the case of a uniform amplitude and uniform phase distribution that will result with a main beam in the direction of bore-sight.

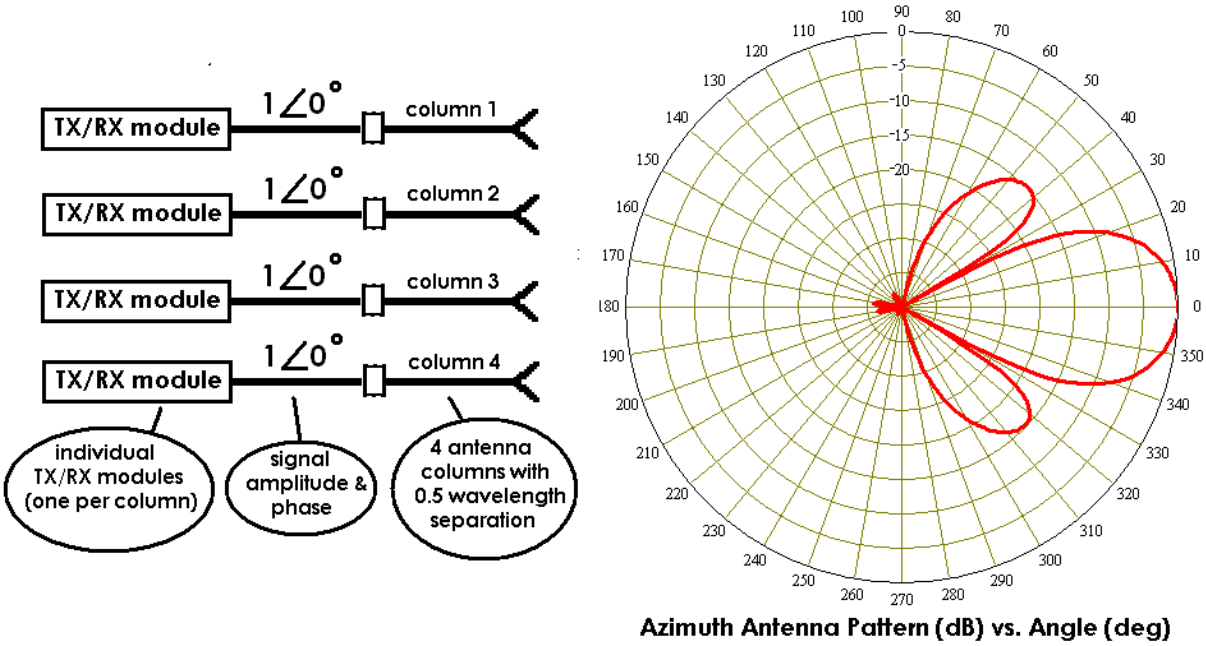


Figure 18. Azimuth Pattern Beamforming.

Figure 19 shows the resulting antenna pattern for the case of the four-transceiver modules generating equal amplitude signals but with a progressive phase variation of 68 degrees. The resulting pattern shows how the main beam is effectively scanned 20 degrees in the azimuth plane as a result of the progressive phase of the signals.

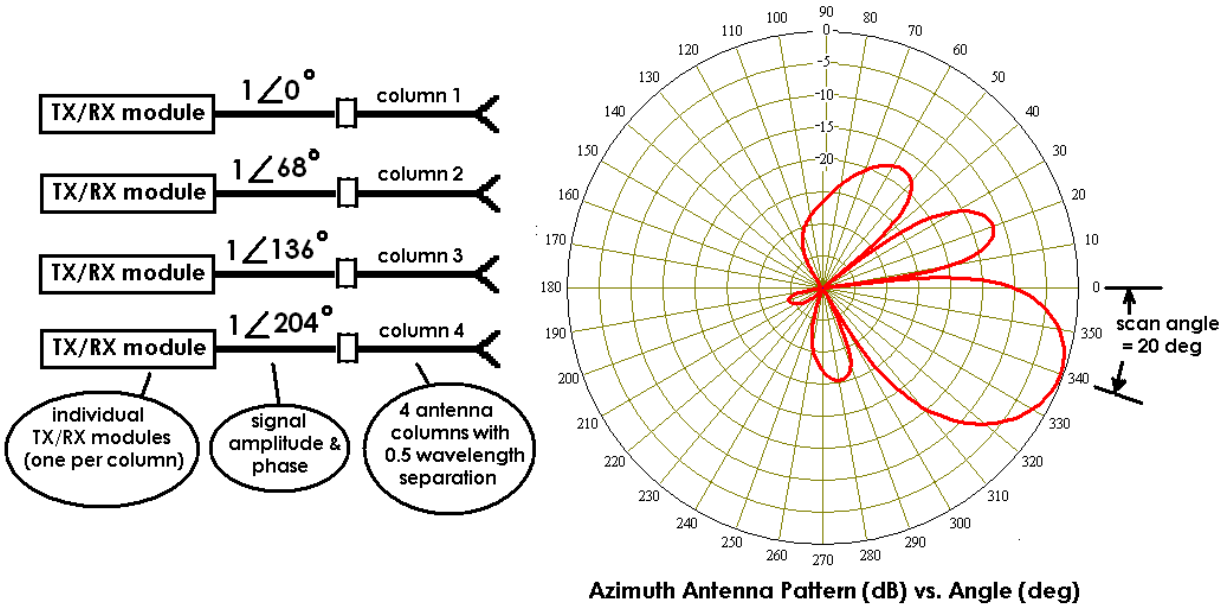


Figure 19. Azimuth pattern beamforming with a scan angle of 20 degrees.

The patterns shown in Figure 18 and Figure 19 are also typical patterns that an antenna supplier would be required to demonstrate compliance. As can be seen from Figure 19, side lobes can rise and beam widths can increase as beams are scanned away from broadside. Therefore, compliance is typically specified using multiple scan angles.

By adjusting the beamforming vector value (in both amplitude and phase) of the individual signals presented to the elements, a beam can be synthesized and scanned across the sector. By intelligently controlling the amplitude and phase values, a variety of different pattern shapes can be generated.

In any case, the fundamental objective of an adaptive beamforming antenna is to provide significant enhancement in the uplink and downlink communication streams:

- For the downlink case (when transmitting a signal), the objective of the beamforming array is to increase the signal strength in the desired direction (while reducing interference to the undesired directions if possible).
- For the uplink case (when receiving a signal), the objective of the beamforming array is to improve the receiver sensitivity in the direction of the desired signal (while reducing interference from the undesired directions if possible).

Figure 20 below shows an example of a synthesized azimuth antenna pattern for an eight-column array. The pattern shown has been created by applying judiciously selected amplitude and phase values to the individual transmit/receive paths. The resulting pattern shows several main-lobes that are directed in desirable locations. The pattern also shows how nulls are generated in the directions of interference.

The processing requirements for beamforming such patterns can be quite sophisticated. Typical requirements may require amplitude and phase beam weight values to be updated on the order of 10 milliseconds. Complex algorithms are used to support the pattern synthesis and may be further impacted by the complexity of the channel and the number of subscribers. However-, useful information regarding the channel is available from the uplink reference signals generated by the TD-LTE or WiMAX subscribers.

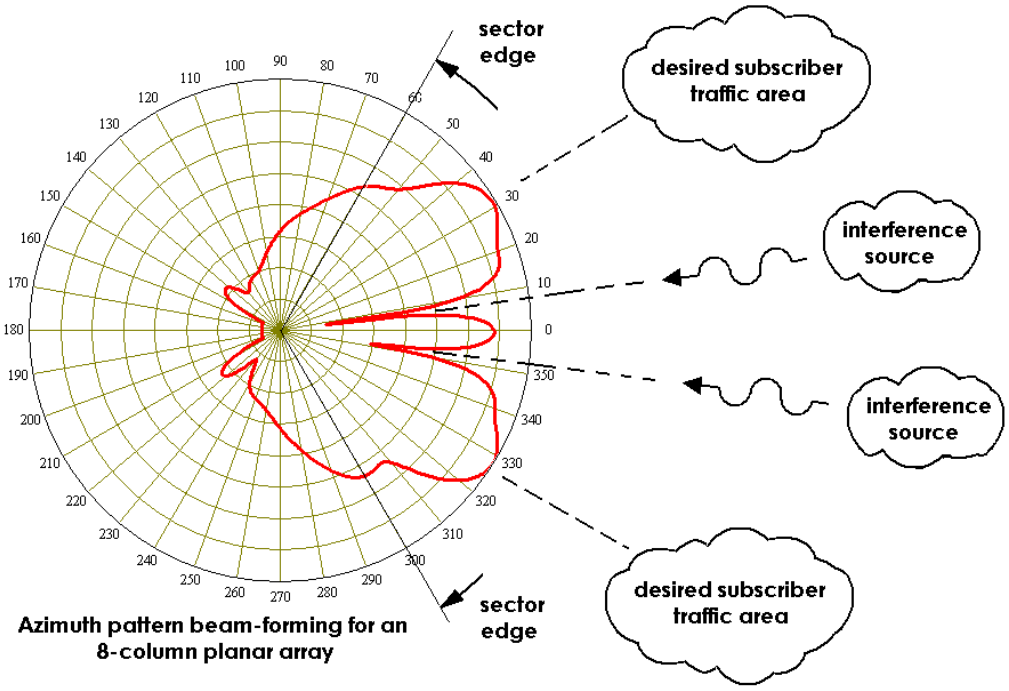


Figure 20. Null-forming and beam steering for optimizing sector performance.

The number of elements in the beamforming array will also affect the complexity of the beamforming patterns. In other words, an antenna array consisting of eight elements will allow for a higher degree of pattern shaping as compared to a four-element array. Obviously, an eight-element array would result in a larger overall antenna and would require eight transceivers resulting in a significant increase in cost and complexity. Figure 21 below shows the difference between a scanned beam for an eight-column array as compared to a four-column array. The eight-column array provides a sharper higher resolution main beam. The eight-column array also demonstrates the ability to generate more nulls. The eight-column array would require more complex algorithms, would have a larger overall form factor and higher cost. These are obvious considerations that would need to be evaluated by the system designer.

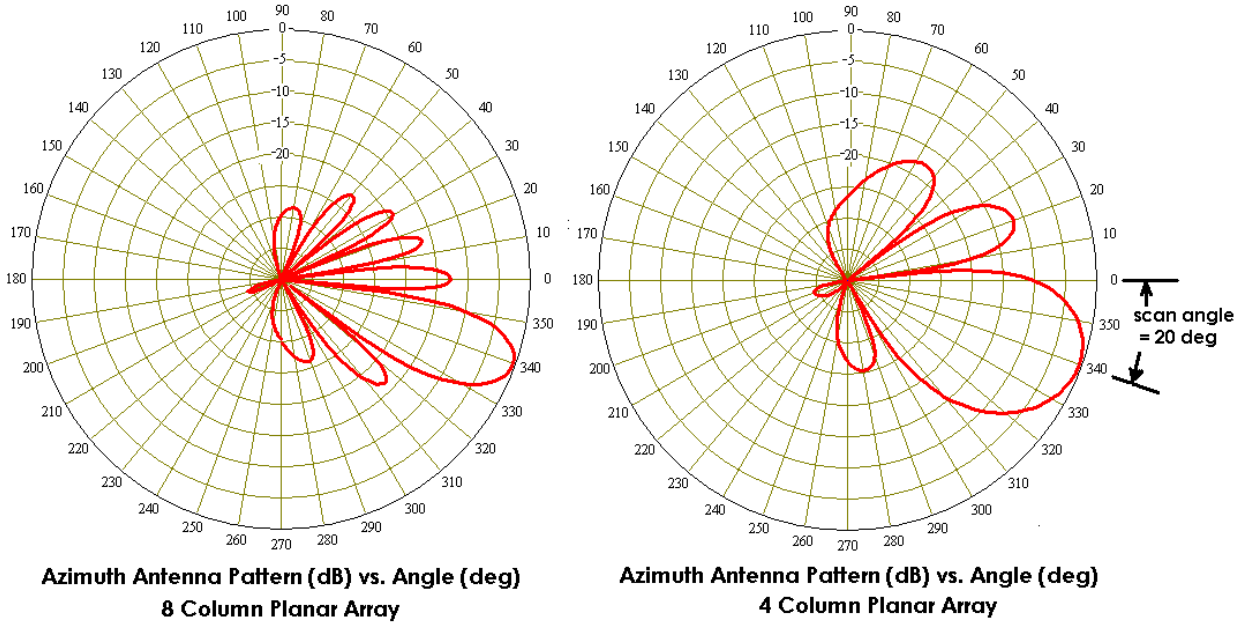


Figure 21. Azimuth pattern beamforming comparisons of eight elements vs. four elements.

4.2.1. BEAMFORMING ANTENNA CALIBRATION REQUIREMENTS

Beamforming quality in the azimuth plane depends on the relative accuracy of the amplitude and phase values of each transceiver. As with all multi-column beamforming antenna systems, there is some degree of error due to undesirable variations between each transmit and receive path. Some type of calibration method must be implemented to minimize the amplitude and phase errors between transceivers and antenna columns. Figure 22 below shows the comparison of a beam synthesized without any amplitude or phase errors as compared to a beam synthesized with random amplitude and phase errors. For this particular example, random amplitude errors of +/-0.5 dB and random phase errors of +/-20 degrees were applied simultaneous to each transceiver of an eight-column beamforming antenna array.

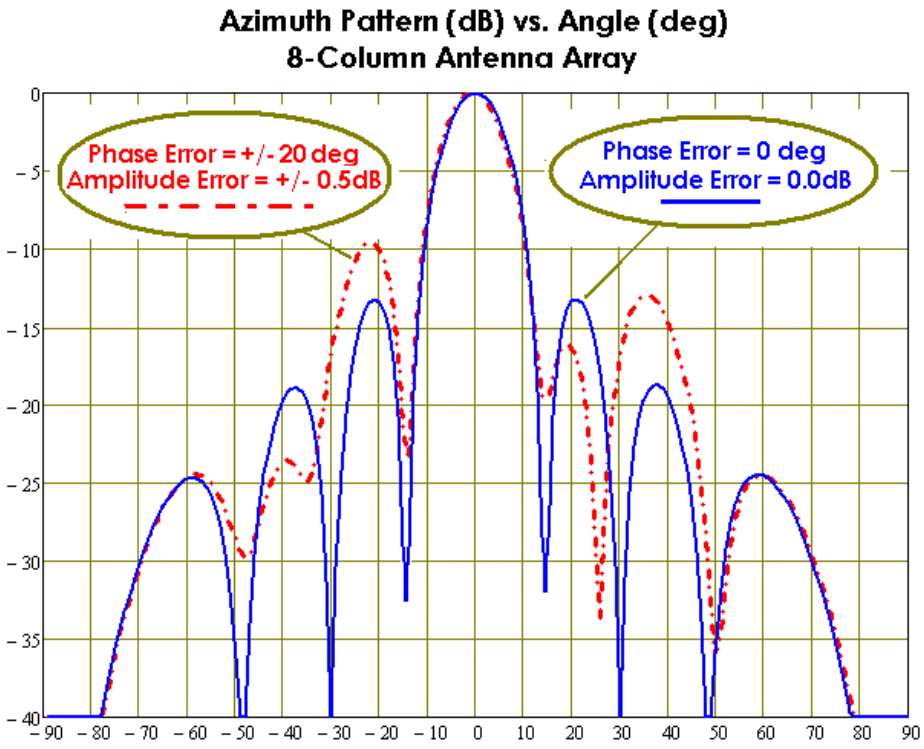


Figure 22. Beamforming degradation due to amplitude and phase errors.

As can be seen in the patterns in Figure 22, phase and amplitude errors can result in significant beamforming degradation. The degraded patterns may result in undesirably high side-lobe levels, squinting of the main beam, degradation in gain as well as losing the ability to accurately position nulls. Typical beamforming systems deployed today require that amplitude variations be limited to +/- 0.5 dB, while phase variations are limited to no more than +/- 5 degrees.

Calibration networks for beamforming antennas can be implemented by integrating directional couplers on individual antenna paths. The coupled outputs are then combined and connect to a dedicated calibration transceiver. A typical calibration network block diagram for a four-column beamforming antenna array is shown below in Figure 23. By selectively powering up individual transceivers, the amplitude and phase characterization of each antenna path can be achieved.

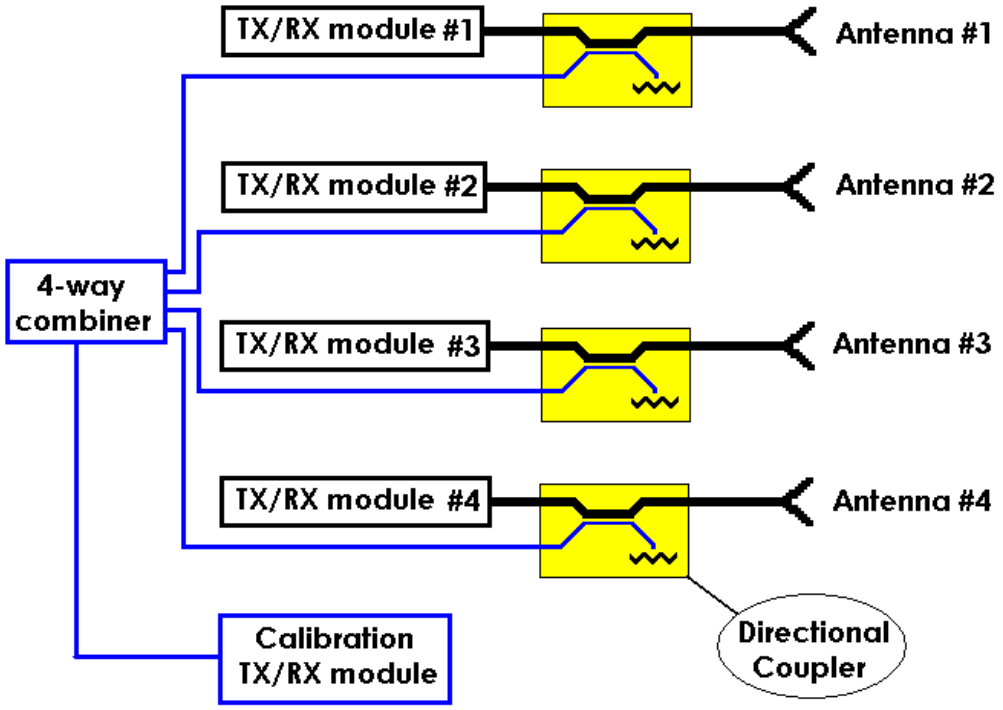


Figure 23. Calibration network block diagram for a four-column beamforming array.

The calibration network shown in Figure 23 allows for periodic automated calibrations. Typically, these calibrations would take place at periods of low traffic usage, but essentially can be performed at any time. It is important to note that the power divider network and directional couplers must be carefully designed and calibrated such that they do not contribute additional amplitude and phase errors. These types of networks require careful s-parameter characterization at the factory level to ensure that adequate performance levels are achieved.

For beamforming antennas with additional columns, there will be an obvious increase in cost and complexity of the calibration networks. Some lower cost calibration networks have eliminated the need for couplers, combiners and dedicated calibration transceivers. These lower cost calibration networks exploit the strong mutual coupling of the adjacent antenna columns to establish phase relationships between columns. A separate calibration transceiver is not required, but instead, the main transceivers are used for calibration activity. While these types of calibration networks are lower cost and lower complexity, they do require more complex algorithms for extracting the calibration data.

It is important to note that the amplitude and phase errors are proportional to the operating frequency. Beamforming antenna systems operating at 2.5 GHz and 3.5 GHz will observe phase variation significantly higher than for a system operating at 850 MHz. These increased errors are due to the natural tolerance variations of the transmission line paths at higher frequencies.

4.3. FIXED MULTI-BEAM ARRAY ANTENNAS

Introduction

To address the need of increasing capacity in high-density macro-cell sites, fixed multi-beam antennas can provide an effective solution using multiple fixed beams.

An example of fixed twin-beam antenna patterns is shown below in Figure 24. On the left, we see a typical 65-degree sector azimuth (horizontal) antenna pattern. The patterns on the right show the paired asymmetrical azimuth beams created by a twin beam antenna.

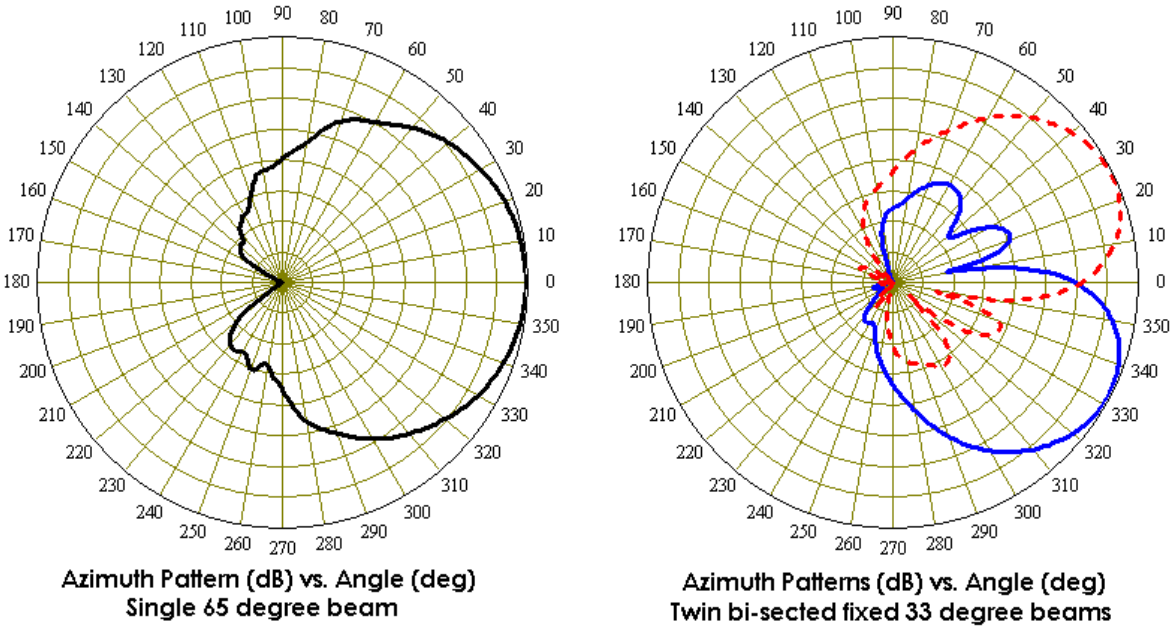


Figure 24. Single 65-degree antenna and twin fixed 33-degree beams.

For the patterns shown in Figure 24, a passive butler matrix type power-splitting network creates the fixed beamforming. The power-splitting network can be designed to accommodate relatively broad bandwidths. Fixed twin-beam antennas are commercially available today that operate from 1710 MHz to 2180 MHz, and with the beams individually capable of variable electrical down tilt and RET. Figure 25 below shows the basic architecture of fixed twin beam antennas for vertically polarized and dual-polarized four column antennas.

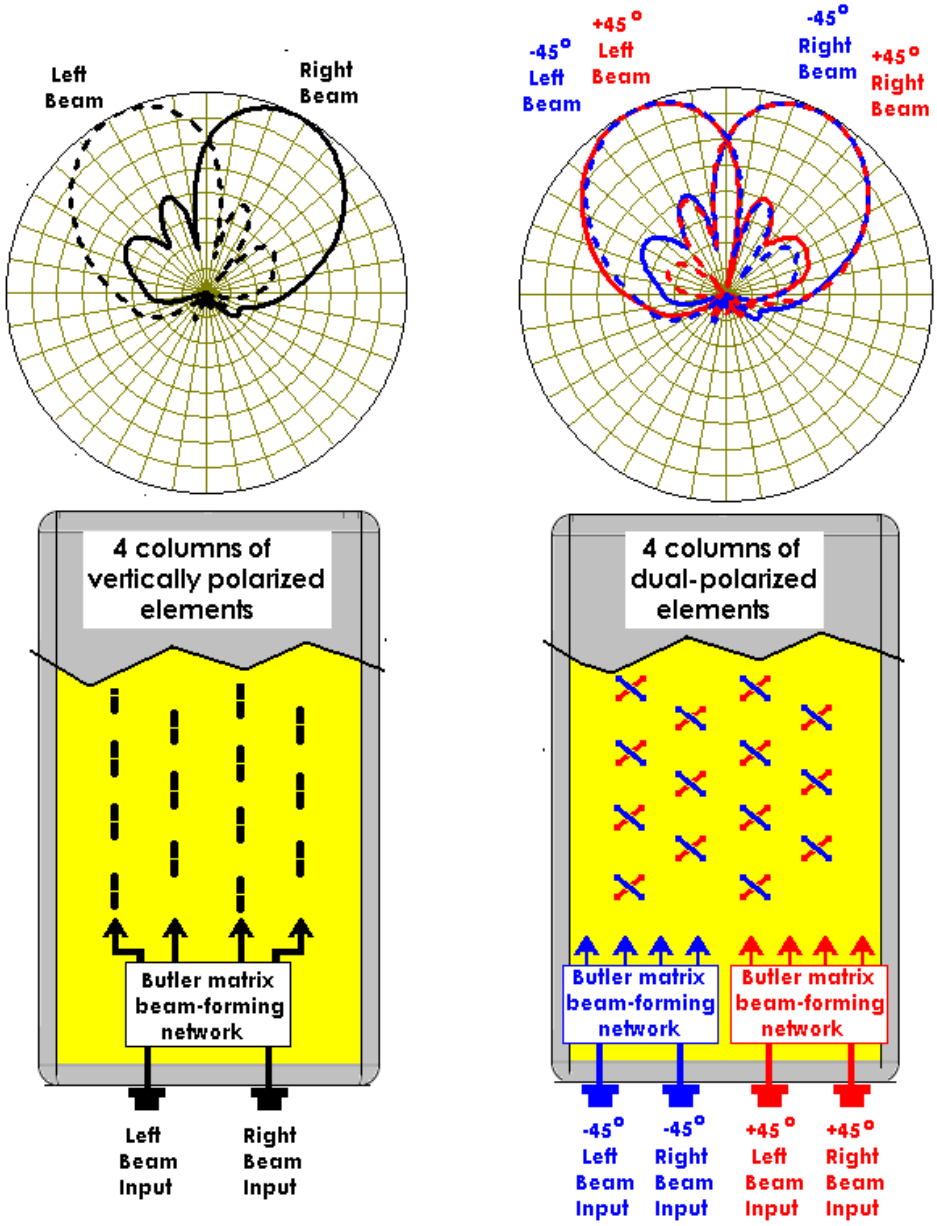


Figure 25. Fixed twin-beam antenna architectures.

The fixed twin-beam antenna has many advantages over the conventional approach of using two discrete antennas for sector splitting:

- The fixed twin-beam antenna provides pre-set alignment of the main beams while providing the optimal overlap. For the patterns shown above, the main beam pointing angles are perfectly fixed at -27 degrees and +27 degrees.

- The pattern shaping is optimized for sector splitting as well as preserving the footprint of the original 65-degree coverage. This optimization can be observed in the sector edge roll-off characteristics and azimuth pattern side-lobe suppression.

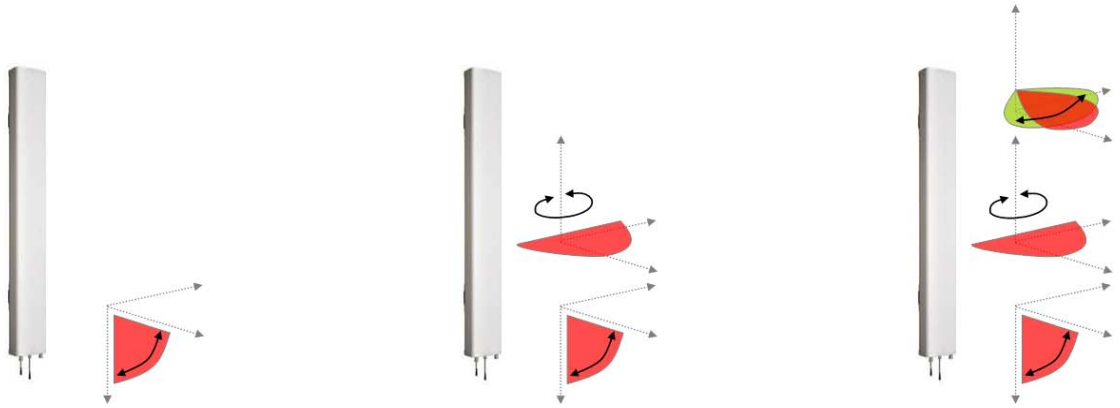
- Three antenna enclosures provide six sectors of coverage resulting in reduced tower loading and favorable aesthetic appearance. The reduced antenna count minimizes cap-ex and op-ex costs.

It is important to note that the azimuth patterns are fixed as compared to the multi-column beamforming antennas previously discussed. However, the fixed-azimuth-beam antennas commercially available today incorporate remote electrical down-tilt for adjusting of the elevation patterns. The electrical down-tilt is implemented such that each of the antennas can be independently controlled for greater flexibility in network optimization.

5. RECONFIGURABLE BEAM ANTENNAS

5.1. HOW RECONFIGURABLE BEAM ANTENNAS WORK

Reconfigurable beam antennas extend the range of remote beam changes from a single dimension for elevation beam steering (Remote Electrical Tilt, RET) to multiple dimensions. These antennas include the possibility to change the boresight or azimuth direction (panning), as well as the beam width of the antenna (fanning) remotely (see Figure 26). Figure 26 includes additional terminology associated with the beam control functionality of these antennas (1D, 2D, 3D and RET, RAB, RAZ).



1D Reconfigurable beam (RET) [tilting]

2D Reconfigurable beam (RET and Remote Antenna Azimuth (RAS)) [tilting + panning]

3D Reconfigurable beam (RET, RAS, and Remote Antenna Beam Width (RAB)) [tilting + panning + fanning]

Figure 26. Comparison of the different degrees of freedom for the reconfigurable beam antenna family.

5.2. USE CASES OF RECONFIGURABLE BEAM ANTENNAS IN 3G NETWORKS

Reconfigurable beam antennas can be used for multiple purposes, including coverage, quality, and capacity improvements. Several use cases are explored with a focus on load balancing capabilities.

To gain better insight into the real value of reconfigurable beam antenna technology, a radio planning analysis was conducted. Data was used from a 129 site, 3G UMTS radio network in Brussels, Belgium. The study utilized a commonly used radio network planning tool, including the planning data from the configuration data base that is geo data, operational target values, and traffic distribution statistics.

All base station and link budget-related parameters (power levels, operating frequencies, mobile service requirements, transmit and receive properties of the base station, as well as the mobile equipment, etc.) are based on typical examples used by operators to plan and optimize their UMTS radio network.

In general, radio networks can be limited by coverage, interference, or radio resources. Networks in the first phase of their life cycle (and deployment cycle) are typically limited by coverage or bad interference design.

In contrast, mature radio networks are typically limited by capacity and radio resources. A description of these is depicted in Figure 27. The maximum traffic load is indicated by the red line at the 100 percent mark. Since different base stations may use different radio equipment, and hence have different absolute capabilities for maximum traffic, relative numbers are shown.

Phase 1 shows the network where traffic demand due to mobile users in the network is very low. Networks are typically designed and deployed based on land usage information (clutter), as indicated in the color-coded clutter map on the top left-hand side in Figure 27. The loading of individual sectors is also well below the maximum traffic that can be handled in such cases. The network is typically limited by coverage and interference rather than capacity.

Phase 2 describes a more mature network where higher traffic demands occur. Once the number of subscribers and the data rates for the individual services increase, the cell utilization increases. This is shown on the bottom right-hand side of Figure 27. The traffic distribution in such cases is typically highly inhomogeneous within a network, which is indicated by the top right-hand side, color-coded traffic density map. This results in many cells with a low load, while other cells are overloaded, i.e., exceed the nominal limit of 100 percent maximum traffic load. An increasing number of blocked and dropped calls are the consequence, leading to significant additional infrastructure investments to handle the offered traffic.

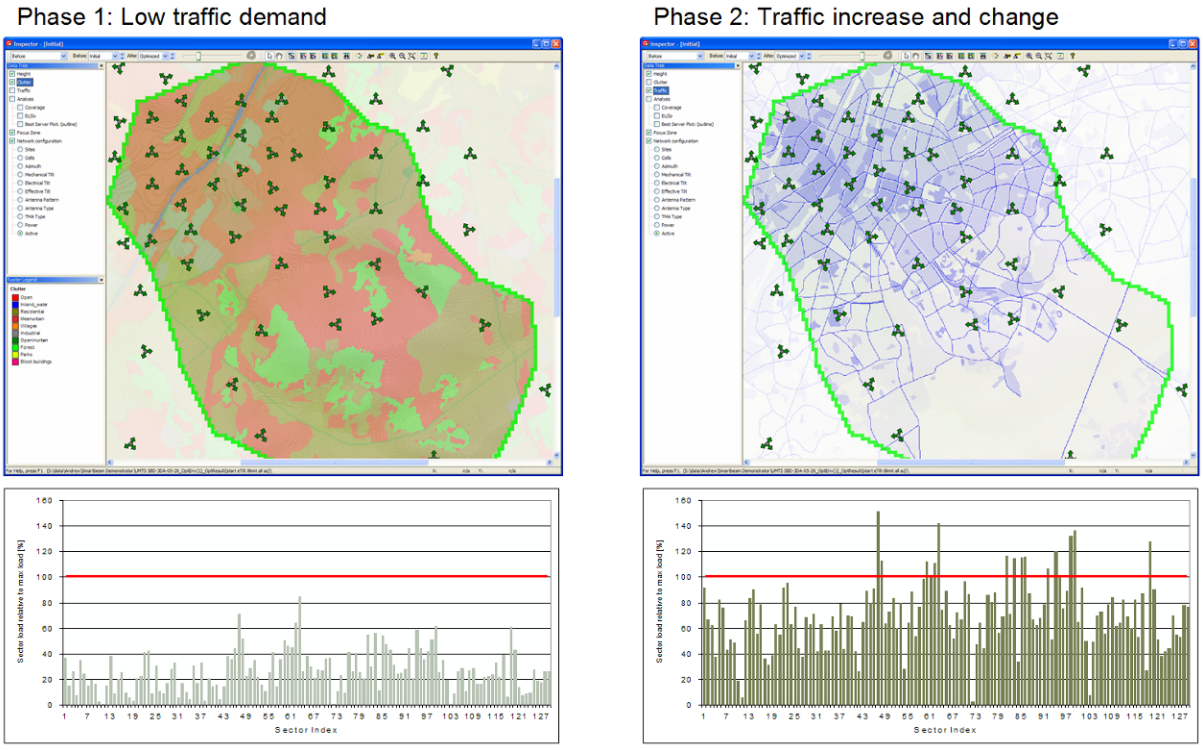


Figure 27. Life-cycle of a wireless network.

Therefore, one of the key questions to be answered by the study is whether reconfigurable beam antennas can help balance the load between different cells, leading to a combination of coverage, interference, and capacity improvements.

5.3. COMPARISON OF RET, 2D, AND 3D RECONFIGURABLE BEAM ANTENNAS

To investigate the impact of Reconfigurable beam antennas on load balancing, we compared its performance with conventional antenna technologies, including RET antennas using the network and traffic scenario as shown in Figure 27, phase 2 as the starting position.

This is a 3G UMTS network with 65-degree antennas. The mechanical tilts are used from the underlying 2G network. The initial electrical tilts were set to 2 degrees. This is a typical deployment coverage approach for a 3G overlay on an existing 2G network. Comparing three different reconfigurable beam antenna types and the range of parameters used for this simulation:

- **RET antenna:** Fixed 65-degree horizontal pattern, elevation range of the remote tilt [0 degrees to 10 degrees], no azimuth changes; → *Tilting only.*
- **2D Reconfigurable beam antenna:** Fixed 65-degree horizontal pattern, elevation range of 0 degrees to 10 degrees, remote azimuth changes in the range of [–30 degrees to +30 degrees]; → *Tilting* + *Panning.*
- **3D Reconfigurable beam antenna:** Elevation range of [0 degrees to 10 degrees], remote azimuth changes in the range of [–30 degrees to +30 degrees], flexible antenna beam width in the range of [33 degrees to 120 degrees]; → *Tilting* + *Panning* + *Fanning*.

5.3.1. MEASUREMENT OF COVERAGE, INTERFERENCE, AND LOAD BALANCING WITH RECONFIGURABLE BEAM ANTENNAS

Reconfigurable beam antennas can provide multi-dimensional improvements in coverage, interference, and load balancing.

- Coverage Measurement
    - Pilot coverage: Sufficient signal coverage on the pilot (also called common control or broadcast signal) is the basis for all wireless communications systems. The received signal strength of the pilot tone at the mobile has to exceed the receiver sensitivity to ensure that a mobile can connect to the network. Reconfigurable beam antennas can significantly help to increase the basic network coverage.
    - Service coverage: Different services may require different received signal levels so that a successful service connection (a voice call or any data transmission) can be established between the mobile and the network. These service coverage requirements depend upon the received signal level and the received signal-to-interference ratio.
- Interference Measurements
    - Improvements in C/I (Ec/Io): Interference is one of the key limiting factors in wireless systems. In order to work properly, every data transmission requires a minimum signal to interference ratio. This is usually expressed in terms of carrier to interference ratio (C/I), or Ec/Io[1].

[1]Ec/Io = Average energy per chip over the total received power spectral density, including signal and interference in a CDMA system.

Improvements in the C/I (Ec/Io) result in better service coverage, services with higher data rate throughputs, and improved service quality in general. Improving the C/I (Ec/Io) also means that lower transmit power levels per connection are required for the same service, leading to significant improvements in the overall network capacity.

- Reduction in the cell overlap or "Soft Handover": Cell overlap in CDMA type systems is required for a smooth handover for a user moving from one service cell to another, also called "Soft Handover." As mobile devices in Soft Handover mode receive the same, hence redundant, information from multiple base station transmitters simultaneously, a large cell overlap leads to significant capacity reduction. Cell overlap should therefore be kept as low as possible, but necessary as required by soft handover.

Reconfigurable beam antennas can be used to control both interference, as well as cell overlap in a highly effective manner.

- Load Balancing Measurements

As shown in Figure 27 on the right-hand side, the distribution of the sector load is typically highly inhomogeneous within the network. While some sectors experience very high traffic loads, the utilization of the majority of the sectors is well below the maximum load.

- Measurement in sector utilization: In an ideal network, the maximum system capacity can be achieved by equally balancing load between individual sectors. This means that load from highly loaded sectors should be shifted to those that can easily handle additional traffic.

- Reduction of the number of overloaded sectors: The key benefit of load balancing is to increase sector utilization, which reduces the number of overloaded sectors. This leads to significantly improved overall network performance and increased capacity utilization without additional radio channels, sectors, or cell sites there by reducing or delaying CAPEX.

It will be shown that reconfigurable beam antennas enable flexible, cost-effective balancing of individual sector loads by allowing remote tilting, remote panning and remote fanning.

5.3.2. NETWORK OPTIMIZATION VERSUS LOAD BALANCING

Although various improvements can be achieved simultaneously, the performance improvements that are achievable depend upon the available degrees of freedom of the reconfigurable beam system.

Coverage and interference improvements can be considered as classical optimization tasks. The tradeoff of capacity and coverage or coverage and Interference levels has been considered for use in dynamic optimization.[11] The results for these tasks are shown in Figure 28 below. The results for these tasks are shown in Figure 29A and include:

- Coverage improvement
- Reduction in cell overlap
- Relative C/I (Ec/Io) improvements

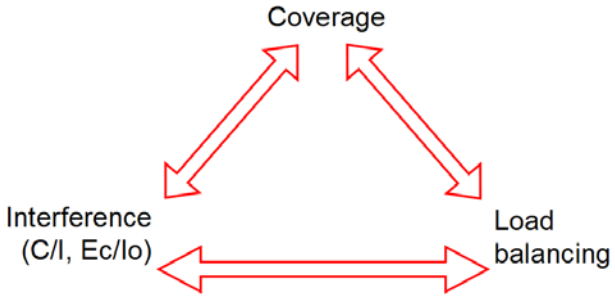
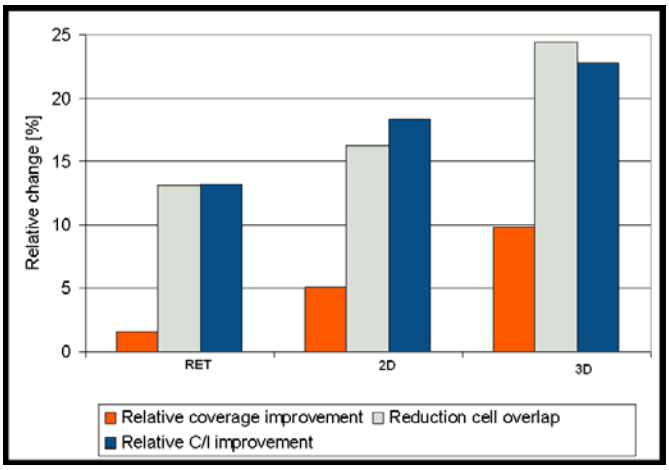


Figure 28. Compromise between coverage, interference, and load balancing effects in radio networks.

The results of load balancing are shown in Figure 29B, and include:

- Increase in sector utilization
- Reduction of overloaded cells



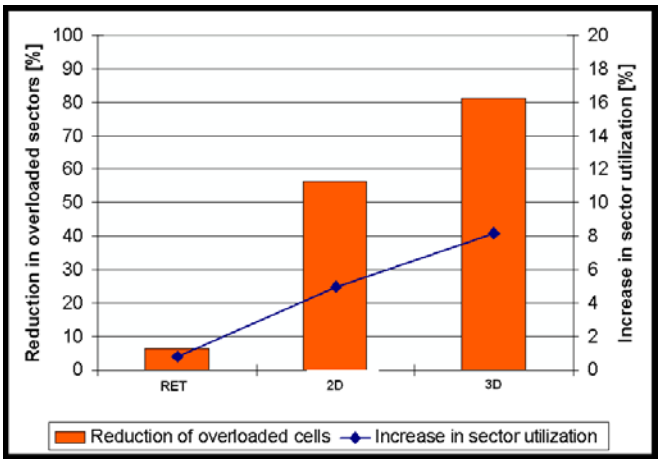


Figure 29A	Figure 29B

Figure 29. Simultaneous improvements achieved by RET, 2D reconfigurable beam, and 3D reconfigurable beam antennas.

In Figure 29A, the relative improvements in coverage, C/I (Ec/Io), and reduction in the cell overlap are shown. In Figure 29B, the relative increase in sector utilization and reduction of overloaded cells are shown as compared to the initial scenario. While RET antennas are good for interference optimization and cell overlap reduction, their benefit for coverage improvements and load balancing are limited as compared to 2D and 3D Reconfigurable beam antennas.

Starting from the initial settings, different antenna technologies have been used for both network optimization and load balancing, simultaneously. Improvements quantified by this study of a particular network and its associated environment and traffic pattern are summarized below:

- **Improvements by 1D RET antennas**

    - Optimization gains: It can be observed that the key strength of RET antennas is the optimization of C/I (Ec/Io) performance in a network (see Figure 29A). Cell overlap can be controlled similarly to the interference in the network. However, in this case RET antennas have shown a limited ability to improve the coverage of the network.
    - Load balancing gains: As Figure 29B shows, RET antennas were not as effective for load balancing as were panning and fanning antennas. In this case, modifying tilt was obviously not sufficient to move traffic effectively from one sector to another. This resulted in a small relative improvement of cell utilization. As a result, the number of overloaded cells was only reduced slightly, see Figure 29B.

- **Improvements with 2D Reconfigurable beam Antennas**

    - Optimization gains: In cases where 2D reconfigurable beam antennas were used, all optimization objectives were improved when compared to the RET situation. C/I (Ec/Io) and cell overlap performance have been improved, and the relative coverage improvement has more than doubled compared to the RET case. See Figure 29A.

    - Load balancing gains: Since 2D reconfigurable beam antennas have the additional degree of freedom for remote changes of the boresight direction (panning), it is shown that the offered traffic can be shifted more effectively between the individual cells. This resulted in better load balancing, and higher cell utilization, hence the ability to reduce the number of overloaded cells significantly, as shown in Figure 29B.

- **Improvements with 3D Reconfigurable beam Antennas**

    - Optimization gains: In addition to 2D reconfigurable beam antenna cases, the beam width of the antenna can be modified remotely (fanning). All of the performance indicators related to optimization were significantly improved compared to the 2D reconfigurable beam case. C/I and coverage were further improved. In this analysis, compared to RET antennas, C/I improvements were almost doubled.

    - Load balancing gains: Since 3D reconfigurable beam antennas have the highest flexibility to balance the load between sectors, i.e., to shift traffic among the cells, the study indicated that the increase in the average cell utilization was boosted. This lead to a dramatic reduction in the number of overloaded cells, as shown in Figure 29B.

5.3.3. ANTENNA BEAM WIDTH DISTRIBUTION

Most existing wireless networks use a fixed choice for antenna beam width, that is, the 65-degree antenna which is the most widely used antenna pattern worldwide. In contrast, this analysis shows that significant gains can be achieved with the flexible beam width provided by the 3D reconfigurable beam antenna.

To give insight into the most appropriate antenna beam width, Figure 30 shows the statistical distribution of the antenna beam width using the 3D reconfigurable beam antenna from the cases in the previous sections. Two beam width distributions are shown for different traffic scenarios. The traffic scenarios are taken from different network cases in the morning and late afternoon, respectively.

From the first look, it can be seen that the “65-degree pattern fits all” maxim is no longer valid. It has already been shown from the results of the 3D reconfigurable beam antenna in Figure 30 that significant improvements of

coverage, C/I (Ec/Io), as well as a large reduction in the number of overloaded cells, were achieved by the use of a flexible beam width.

A narrow antenna beam width results in a higher antenna gain in the main lobe direction, as compared to a wider antenna beam width with a significantly lower main lobe gain. This is one reason why a mixture of different antenna beam widths provides the best performance.

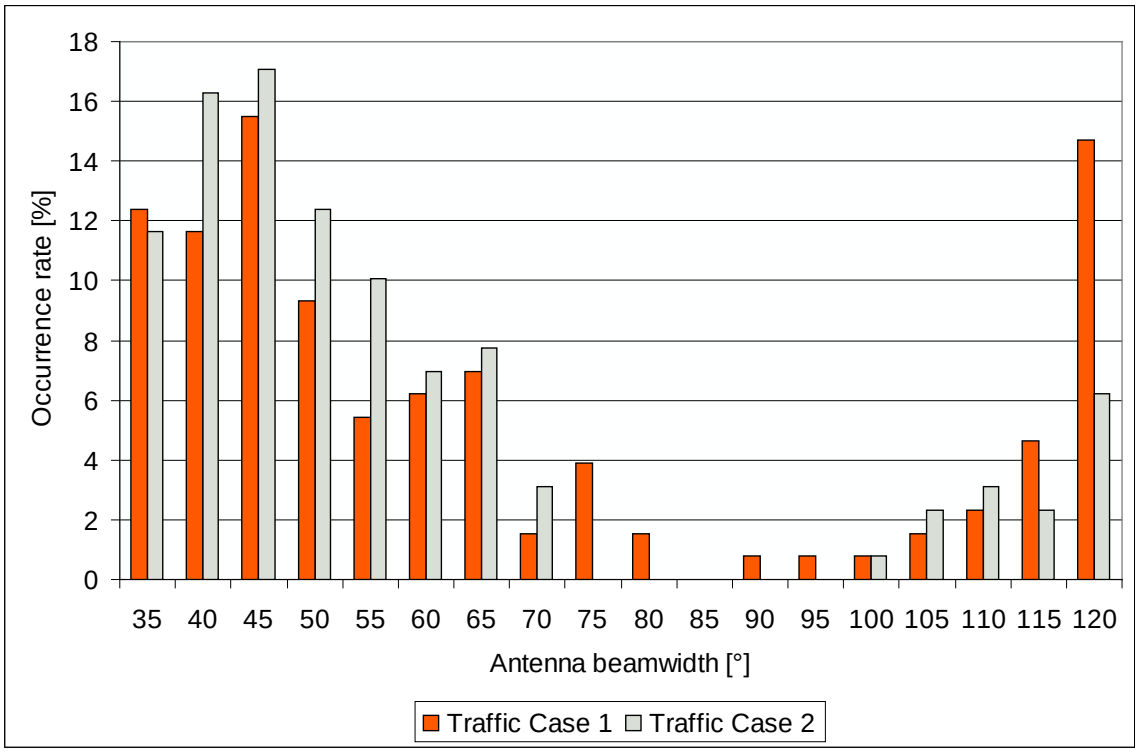


Figure 30. Distribution of the antenna beam width after the optimization. case 1 is morning and case 2 is afternoon.

Distribution of the antenna beam width shown in Figure 30 shows some clusters around 45 degrees and at the upper end above 100 degrees. The distribution depends on various input parameters, such as the scenario itself, the traffic distribution, as well as the desired focus on the optimization objective, as indicated in Figure 28. Compromise between coverage, interference, and load balancing effects in radio networks**.**

It is possible that wide beam width pattern will cause higher sector-to-sector interference. The results in Figure 29A show a different picture: The actual sector-to-sector interference was not significantly reduced by the use of variable beam width. This can be attributed to the fact that it is not just the beam width, but the combination of beam width and azimuth changes that provides substantial improvements.

5.4. RECONFIGURABLE BEAM ANTENNAS--CYCLICAL TRAFFIC PATTERN MANAGEMENT

Measurements in wireless networks show a clear daily cyclical behavior. An example for the traffic pattern of a single sector, over a 24-hour, 7-days a week period is shown in Figure 31. It can be observed that the traffic pattern repeats over time.

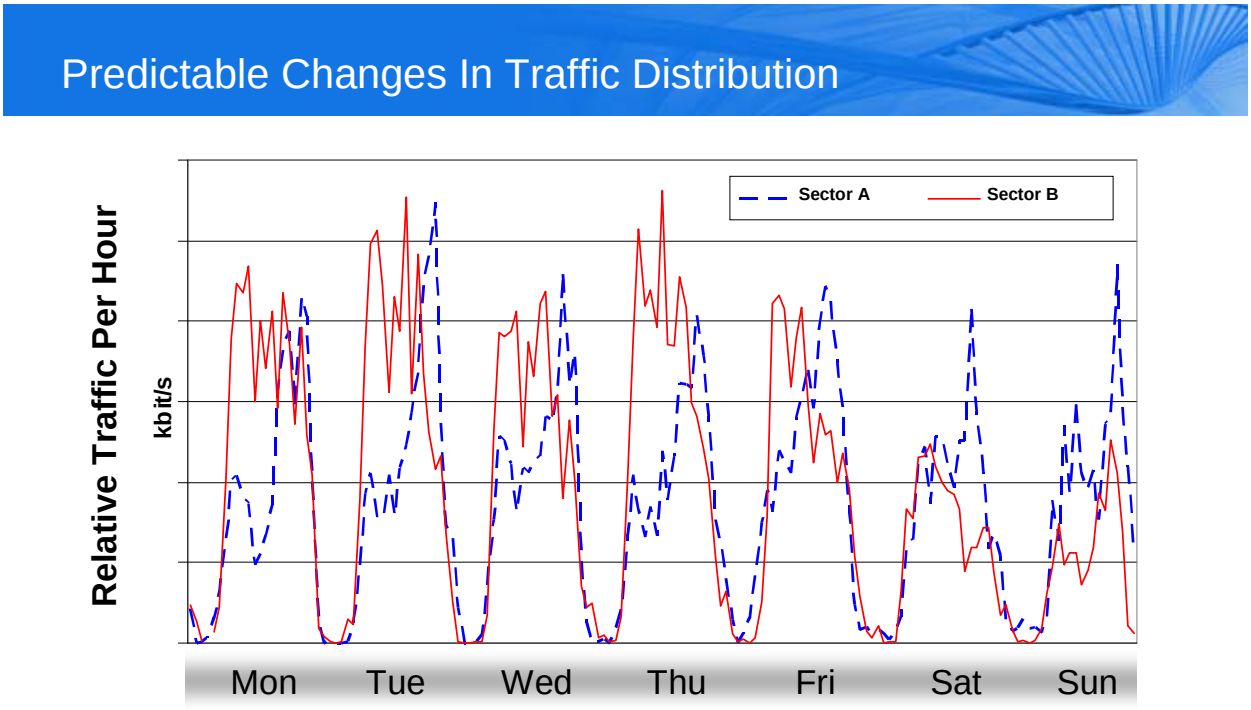


Figure 31. Predictable changes in traffic distribution.

Keeping in mind that the overall traffic will grow over time, in general, the total traffic will be a combination of a cyclical pattern combined with an increasing average value.

By using smart RF technologies, such as SON, with reconfigurable beam antennas, wireless networks can remotely adapt to these continuously changing traffic situations. This adaptive, agile beam control technology has the potential for a positive impact on both CAPEX and OPEX for networks operators.

5.5. RECONFIGURABLE BEAM ANTENNA SUMMARY

Reconfigurable beam antennas have been shown to be a benefit for flexible wireless network management.

The following conclusions can be drawn from the specific network analysis case presented.

- RET antennas had a significant impact on the improvement of C/I and Ec/Io in CDMA based 3G radio networks.

- 2D reconfigurable beam antennas showed significant improvements in all performance indicators when compared to the Brussels network optimized with RET antennas. This includes coverage and C/I (Ec/Io) improvements, as well as higher cell utilization.
- Higher cell utilization allowed 2D reconfigurable beam antennas to shift traffic from overloaded sectors to those that can carry extra load, in this case, reducing the number of overloaded cells by up to 50 percent.
- 3D reconfigurable beam antennas generated the highest performance gains of all the reconfigurable beam antenna types. This was the case for coverage and C/I (Ec/Io) objectives, as well as for cell utilization and the balance of cell loads.
- In the case of load balancing capability and improvements, for this typical example, 3D reconfigurable beam antennas outperformed RET antennas by more than a factor of five.
- The optimal distribution of the antenna beam width indicated that the singular use of a 65-degree pattern maybe far from ideal for wireless networks.
- In this case, reconfigurable beam antennas reduced the number of overloaded cells by approximately 80 percent. Higher utilization of existing sites, enabled by reconfigurable beam antennas, could reduce or delay future CAPEX and OPEX expenses for an operator.
- 3D reconfigurable beam antennas allow highly increased flexibility. With cyclically changing traffic patterns, a scheduled network adaptation, has the potential to impact the quality and cost and cost of cellular network operation. Reconfigurable beam antennas, in combination with the network management systems are well suited for this application.

References of interest on reconfigurable beam antennas can be found in the endnotes.[12,13]

6. ACTIVE ANTENNA ARRAYS

A most general approach to DSP controlled smart antennas that permits both the typical horizontal beamforming but also vertical beamforming, is made possible by active antenna arrays as shown in Figure 32. This scheme permits amplitude and phase variation to be applied to vertically stacked antenna elements, such as the 16 elements shown below. In contrast to standard passive base station antennas, where a coaxial cable distribution network divides and feeds power to each element, individual transceivers, composed of radio modems, amplifiers, and filters are located directly next to the radiating antenna elements.

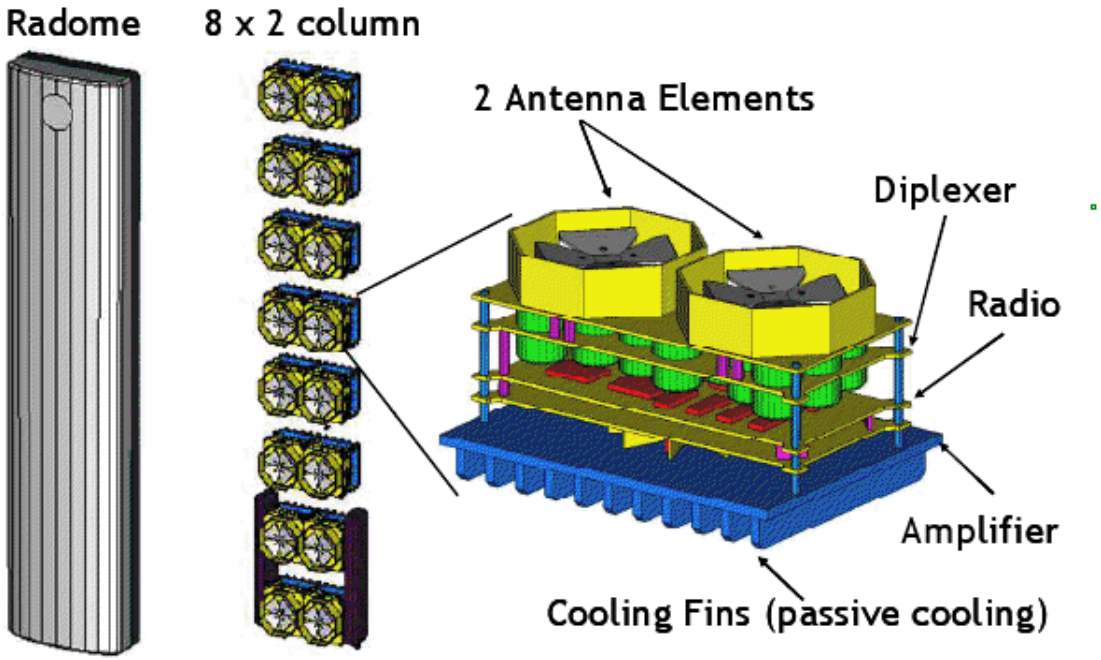


Figure 32. Active antenna array concept with a column array (left) and single antenna module (right).

This technology has the added benefit of eliminating power losses in the RF feeder cables, much like Remote Radio Heads. With the radios integrated directly into the radome housing, and with replacement of a small number of large amplifiers with many small amplifiers, the heat is spread over the larger antenna structure as opposed to the smaller RRH or amplifier shelf, permitting larger total RF transmit powers without the use of fans or other active cooling. Alternatively, the use of many lower power amplifiers, operating at cooler temperatures, can increase the reliability of the radio system.

By integrating the remote radio head functionality into the antenna, the aesthetics of the site can be improved, windload reduced, and potentially, some leasing costs avoided. See Figure 33.

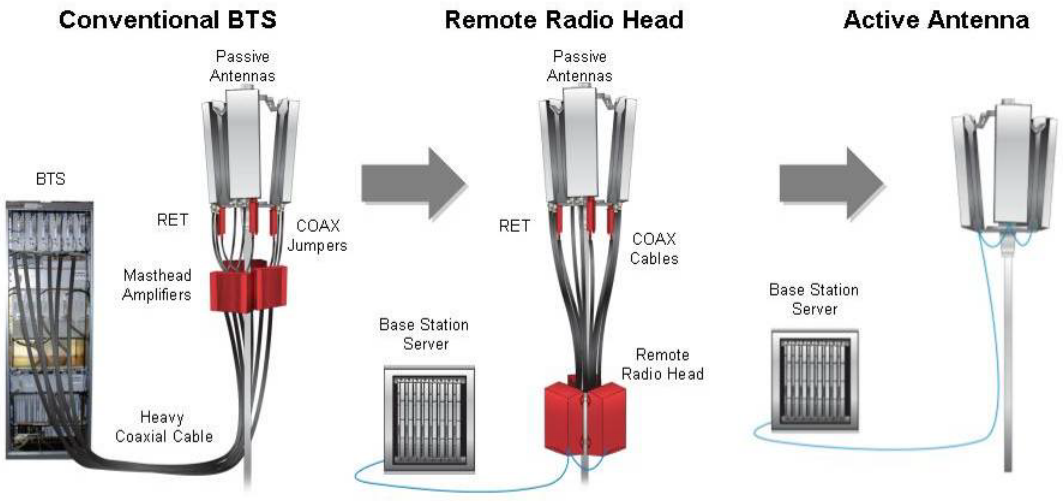


Figure 33. Radio Integration Trend.

Research and development activities on active antenna systems for cellular applications have been conducted by various organizations over the last decade,[14,15] and recently field trials have been completed.[16] Figure 34 presents an active antenna used in a 900 MHz field trial.



Figure 34. 900 MHz Active Antenna.

One architecture for an active antenna is depicted in Figure 35. In this architecture the distributed transceivers, or micro-radios, are fed digitally from a central digital processing controller and are composed primarily of three custom IC building blocks and a duplexer.

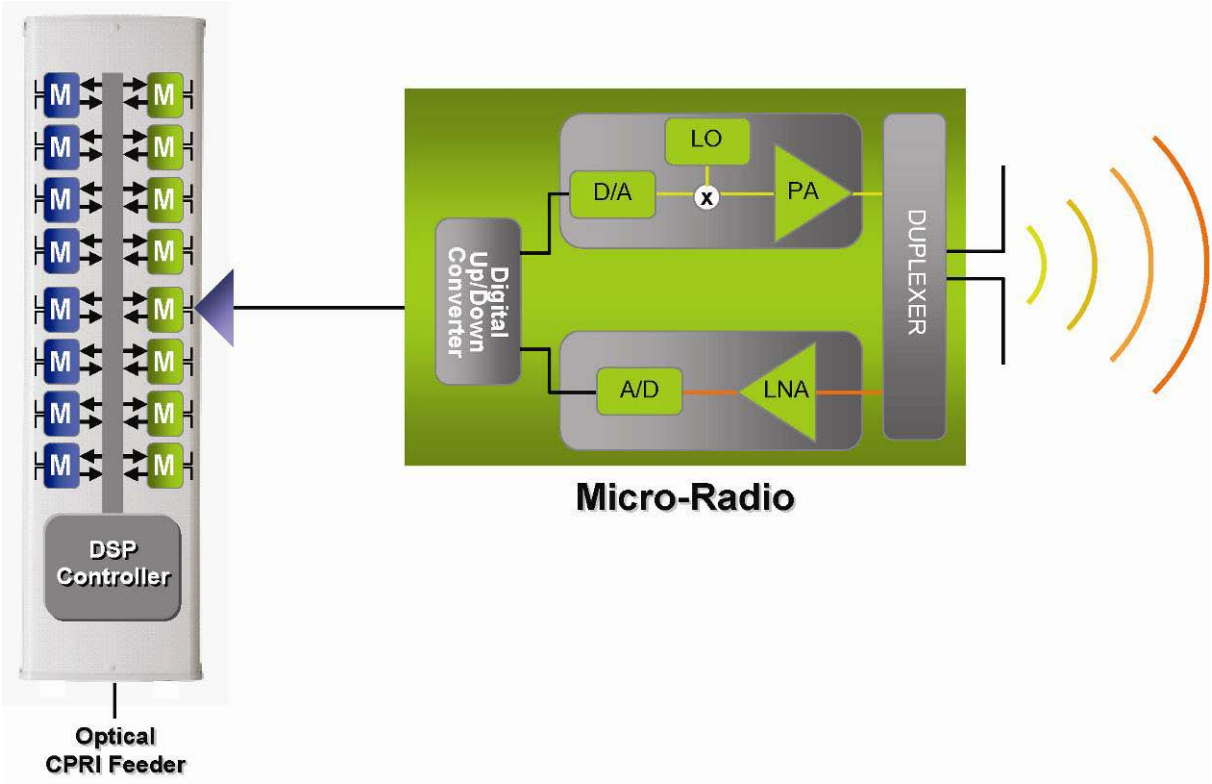


Figure 35. Typical active antenna architecture.

Another critical benefit of an AAS is the unique ability to electronically tilt elevation beams by having independent base band control of the phase and amplitude on each element. This supports multi-mode systems where different carriers in the same frequency band, with different air interfaces, may require different orientations. For example, legacy GSM/GPRS/EDGE or UMTS carriers may provide adequate coverage, but when a newly introduced LTE carrier is used for hot spot coverage or is used to span a more sparsely deployed area, LTE may be down-tilted differently than the legacy carriers. With a two-column active array, the LTE carrier may also be directed toward different azimuths directions than are the legacy carriers. The electronic tilt capability also allows for the separate beam tilting and optimization of the TX and RX paths and of the vertical sectorization of a cell (see Figure 36). Vertical sectorization of an LTE sector has been shown in simulation to provide significant capacity benefits.[17]

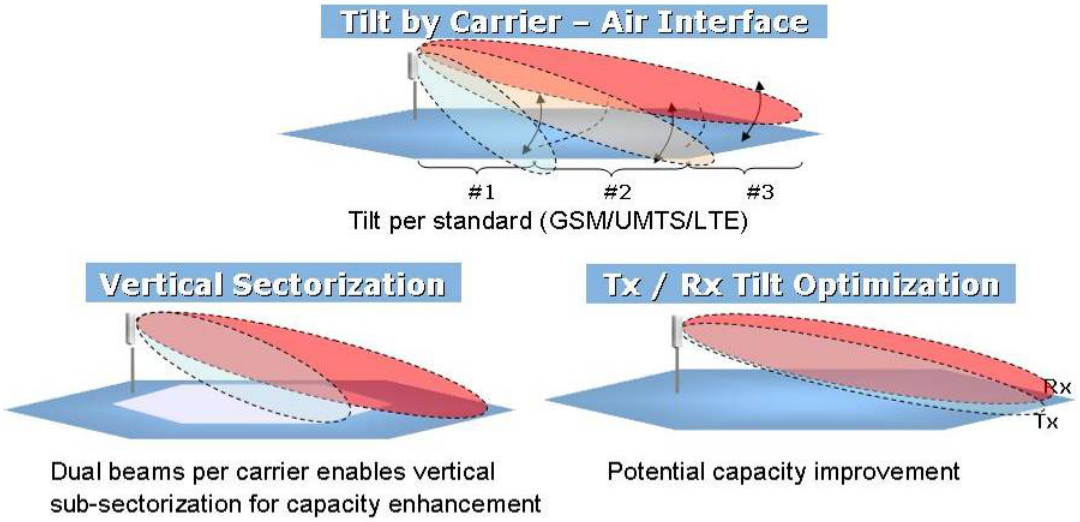


Figure 36. Electronic tilt applications.

The distributed and redundant architecture of the AAS, where each antenna element has its own transceiver, provides reliability benefits as the failure of one micro-radio does not cause the catastrophic failure of the sector. Of course, some loss of both EIRP and received signal level is experienced, but this may be tolerable for a period of time while the AAS awaits repair. Since the system is intelligent, and can sense a transceiver failure, the amplitude and phases on the remaining elements can be adjusted to compensate for the elevation beam distortion and the reduction of EIRP on the horizon (see Figure 37).

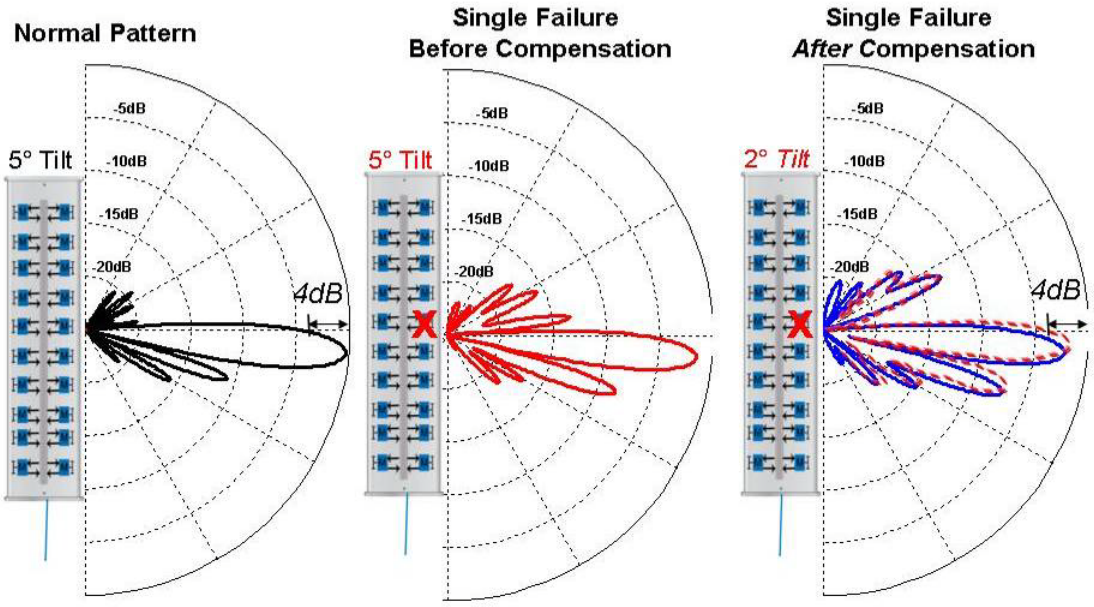


Figure 37. Self-healing capacity.

These newly proposed active array antennas are only now in trials and have not yet proven their reliability, the acceptability of weight and their ability to economically linearize amplifiers sufficiently to make multi-channel emission specifications without channel-wide filters. The power consumption of many low-power radio amplifier modules versus

a small number of large power amplifiers is also not yet clearly proven. However, similar active antenna arrays have been used in military RADARs for many decades and have advantages for versatility and performance.[18]

7. ADDITIONAL SIMULATIONS AND COMPARISONS OF LTE TRANSMISSION SCHEMES / ANTENNA CONFIGURATIONS

7.1. COMPARABLE DOWNLINK SPECTRAL EFFICIENCY

Previous measurements, simulations and estimations of the relative spectral efficiency of various air interface technologies and antenna schemes are summarized in Figure 38.

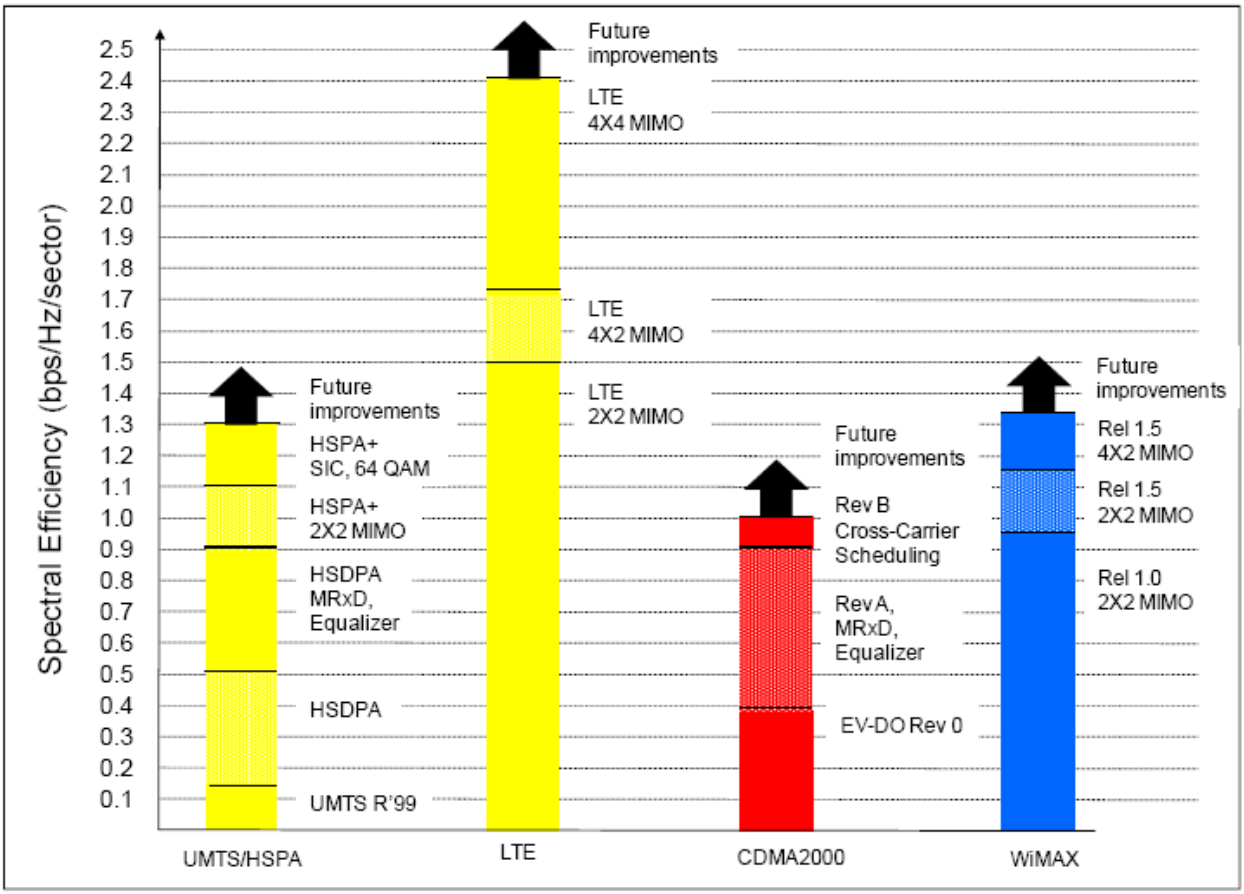


Figure 38. Summary of downlink spectral efficiencies for various air interfaces and antenna schemes (3G Americas & Rysavy Research, September 2009)

These values are from a joint analysis by 3G Americas' members based upon 5+5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz DL/UL=29:18 TDD for WiMAX, and assuming a mix of mobile and stationary users.

This figure clearly shows the relative performance of HSPA vis-à-vis LTE where HSPA with type 3 terminals implementing Mobile Receive Diversity (MRxD) effectively double HSPA's spectral efficiency from 0.5 bps/Hz/sector to 0.9 bps/Hz/sector while LTE with 2X2 MIMO provides 1.5 bps/Hz/sector. The 2X2 MIMO gives HSPA a 20 percent increase over MRxD, but 64 QAM capable terminals and Successive Interference Cancellation (SIC) can raise HSPA efficiency to 1.3 bps/Hz/sector. Further improvements can be obtained in Release 9 HSPA with dual-carrier operation with MIMO. Note that the upgrade to 64QAM can be implemented with a software upgrade in most base stations while

MIMO requires a change in antennas, though the contribution of 64QAM modulation is slight, due to the rarity with which it can be expected to be available in typical cellular network operation.

It is important to note, that the gain of 2X2 MIMO in the case of HSPA+ assumes that all terminals have two receive antennas. In a deployment where there are legacy terminals without 2 receiver and MIMO capability, the multi-stream transmissions from the base stations transmitting SU-MIMO signals will contribute multi-path interference to older terminals and actually degrade the overall throughput in proportion to the percentage of terminals that do not support MIMO.

The LTE values show 2X2 MIMO with 1.5 bps/Hz/sector moving to 1.73 with SIC or general interference cancellation and 4X2 MIMO. This 4X2 operation uses a simplified switched-beam approach standardized in Release 8. Downloadable codebooks, which are being discussed in 3GPP for future releases of the standard, have potential for future improvements beyond the 2.4 bps/Hz/sector with 4X4 MIMO, although the implementation of these types of adaptive antenna and beamforming algorithms are based on proprietary algorithms so the gains are implementation dependant and may evolve with field experience.

7.2. AN ANALYSIS OF ANTENNA CONFIGURATIONS FOR 4X2 AND 4X4 MIMO

An attractive base station antenna solution for LTE supporting up to four layers in the downlink is to use two horizontally separated dual-polarized antennas. This enables a compact antenna design that can utilize both the spatial and polarization dimensions. The amount of separation between the two antennas will have different impacts on the potential gains of beamforming, diversity, and spatial multiplexing. Realizing these gains put conflicting demands on the antenna separation and different choices of antenna separation will result in different system performance profiles. The antenna size is also an important parameter from a site installation point of view. It influences various aspects, e.g., visual footprint, wind load, and site rental cost.

Results from a study on the impact of antenna separation on LTE system performance are presented.[19] By means of system simulations, evaluations are performed to aid the understanding of the antenna separation trade-off. In addition, empirical support to the simulation results is provided by means of comparison to results from a measurement campaign.[20]

The simulations were performed with a detailed dynamic system simulator that includes models of, e.g., adaptive coding and modulation, UE mobility, and delays in channel quality reports. It also contains an implementation of the 3GPP spatial channel model (SCM)[21] and the mutual information based link-to-system interface described in, “A Fading-Insensitive Performance Metric for a Unified Link Quality Model.”[22]

A simulation scenario similar to the defined 3GPP case 1[23] was evaluated for different configurations with dual-polarized antennas at the BS using the closed-loop spatial multiplexing transmission mode. 3GPP case 1 refers to a macro-cell reference system deployment type with the 3GPP SCM used for channel modeling. The network consisted of 19 sites separated 500 m with three cells per site and an average traffic load of 4 UEs per cell. Each antenna port of the BS antenna was modeled according to the BS antenna model[21] regardless of antenna separation. The notation N_{tx}_x N_{rx} will be used for an antenna configuration with N_{tx}transmit- and N_{rx} receive antenna elements. For downlink (DL), 4X4, 4X2, and 2X2 configurations, comprising one or two dual-polarized antennas at the UE and BS, are investigated. For uplink (UL), 1X4 and 1X2 configurations comprising one vertically polarized antenna at the UE and one or two dual-polarized antennas at the BS. (The E-UTRA standard for LTE assumes the use of at least two antennas in the UE, at least as a baseline.[24])

Next we consider the performance impact of changing the separation of two columns of base station antennas, such as (H) in Figure 3.

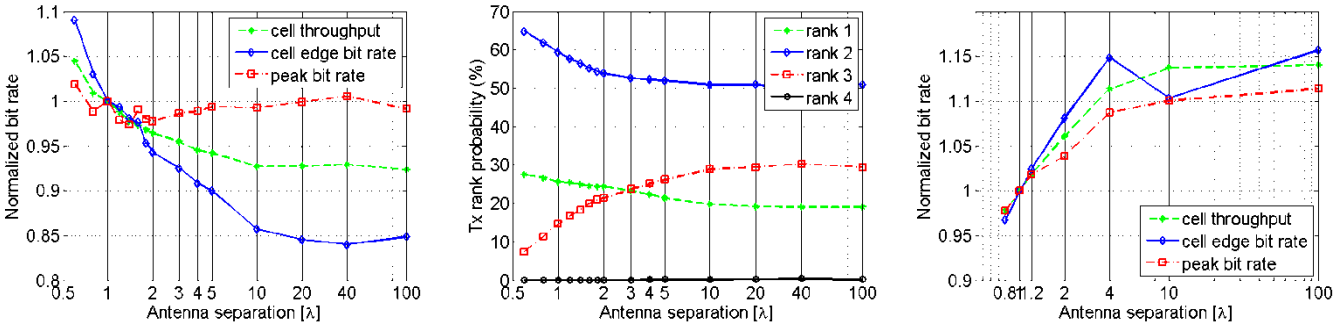


Figure 39. Downlink bit rate (left), downlink transmission rank probability (middle), and uplink bit rate (right) as a function of the two dual bs antennas separation for the 4X4 and 1X4 antenna configuration in the DL and UL, respectively.

The left plot Figure 39 shows normalized downlink (DL) bit rate for the 4X4 antenna configuration as a function of the separation, given in wavelengths λ, between the two BS antennas. Three different metrics are shown: cell throughput and the 5- and 95-percentile of the CDF of the active radio link bit rate (ARLBR), respectively. The ARLBR is the user bit rate averaged over the time a user has been assigned resources. The bit rates have been normalized in such a way that it is one at 1λ separation between the dual-polarized BS antennas for each percentile curve. The middle plot shows results from the 4X4 antenna configuration of the probability of a certain transmission rank as a function of the two dual-polarized antennas separation. The results in the left plot show that the cell throughput and cell edge bit rate decrease as the base station's antenna separation increases, while it is essentially constant for peak rate. There is a benefit of a small antenna separation in this scenario since it is interference limited; hence, beamforming gains are more important than spatial multiplexing gains. The rank statistics in the middle plot show that rank 1 and 2 are most probable for small antenna separation. As the separation increases, the probability of rank 3 transmission increases. Almost no rank 4 transmissions occur, since the Signal-to-Interference-and-Noise Ratio (SINR) is too low in this scenario. Corresponding UL results for a 1X4 configuration are shown in the right plot in Figure 39. The results show that in this case the bit rate increases (except for the cell edge bit rate at 10λ). The results show that in this case the bit rate increases (except for the cell edge bit rate at 10λ-polarized antennas separation. The results in the left pl

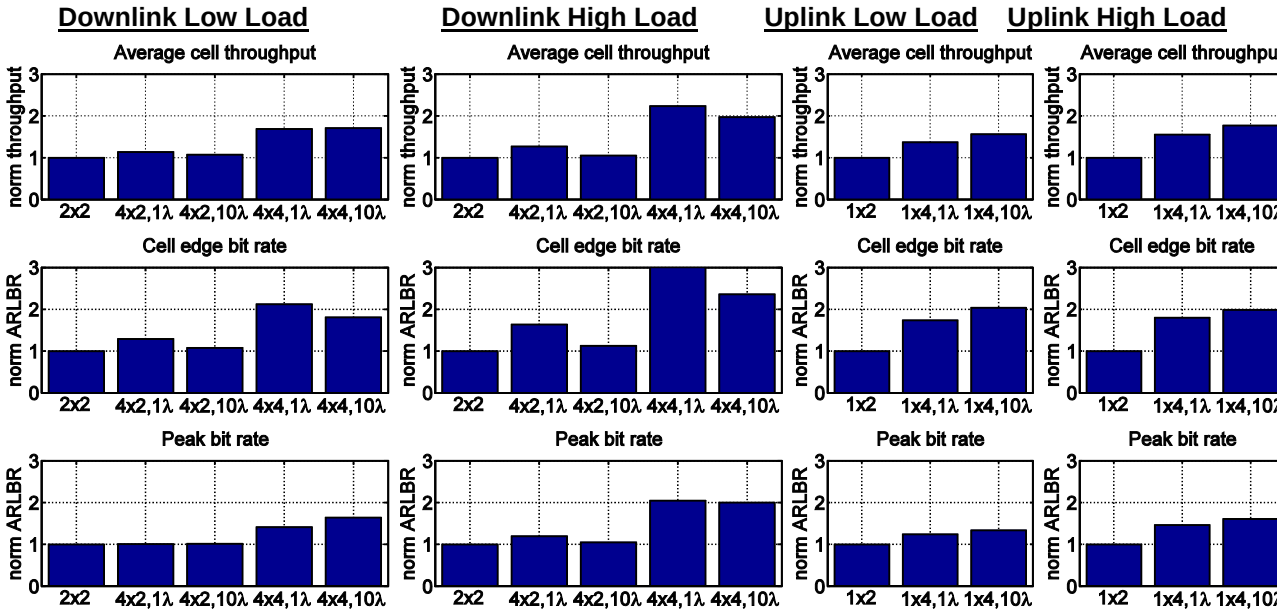


Figure 40. Performance summary of different antenna configurations for DL and UL for networks in high or low load conditions.

Figure 40 shows a summary of the performance with different configurations for DL and UL in networks with high load as well as in networks with low load. The bit rates have been normalized so that it is one for corresponding 2X2 and 1X2 results for DL and UL, respectively. Two different antenna separation are compared: 1λ and 10λ, representing small and large separation, respectively. In the low load network scenarios shown, there are on average 0.1 UEs/cell. The results show that for DL, a small antenna separation gives highest performance for all cases except for peak throughput at low load. For UL, large antenna separation gives highest performance in all cases. However, most of the UL gain in going from two to four antennas is achieved also with 1λ separation.

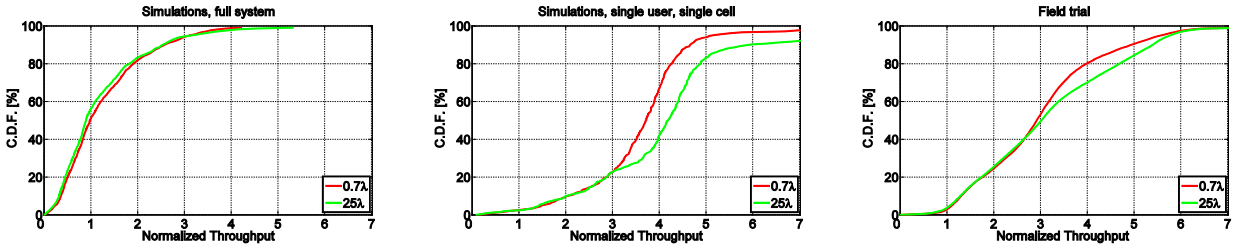


Figure 41. Results from full system simulation (left), single cell, single user simulation (middle) and field trial (right) for downlink 4X4 antenna configuration.

In order to allow comparison to measurement results, Figure 41 shows throughput CDFs for a full system simulation with an average of 4 UEs/cell, simulation of a single UE single cell (SUSC) scenario, and for the SUSC field trial results, respectively. These results are for 4X4 configurations and each plot shows CDFs for two antenna separations; 0.7λ and 25λ. The results are normalized to the median of the full system simulation CDF for the antenna separation of 0.7λ. The measurements were performed using a single UE in a single cell scenario and only downlink performance was addressed.[20] In order to simulate a SUSC scenario, all intercell interference was turned off in the simulator. In these simulations somewhat different parameter settings were used to better reflect the trial scenario,

e.g., getting a similar signal-to-noise ratio (SNR) range in simulations and trials. The purpose of the comparison is not to reach an accurate agreement in terms of absolute performance numbers, but rather to illustrate that the relative performance between different configurations show similar behavior.

Similar to previous results, the full system simulation shows that a small antenna separation gives the highest throughput. In the SUSC simulation and the field trial the configuration with large antenna separation gives higher throughput for UE positions with good channel quality. In these cases, the SNR is sufficiently high to benefit from the additional spatial multiplexing gains offered by the uncorrelated antennas.

8. DEPLOYMENT SCENARIOS

Planning for future deployments of various smart antenna schemes requires an appreciation of the currently deployed legacy cell sites as does discussions of general deployment issues affecting operators.

8.1. TYPICAL CELL SITE ARCHITECTURE

A typical Cell Site consists of the components diagramed in Figure 42 below. This includes the power main and any wired backhaul facilities to the site, an AC to DC power rectifier and battery supply, and the eNodeB cabinets. These cabinets may be located in a shelter for weather protection or they may be outdoor units mounted on cement plinths. Backup diesel generators or other power sources may provide backup of one or more operators' AC supplies. The eNodeB base station cabinet may contain the RF modulators, RF Power Amplifiers, duplexing filters and lightning arrestors and serve antennas through long coaxial feeder cables as shown on the left tower, or it may distribute the RF components to positions next to the antennas as shown on the right figure with the use of the Remote Radio Heads (RRHs). In this case, the eNodeB has a pair of fiber optic cables and power line connecting to the RRH that has the radio modem, the power amplifier and filters for a sector as shown on the right tower below where one sector's equipment is shown.

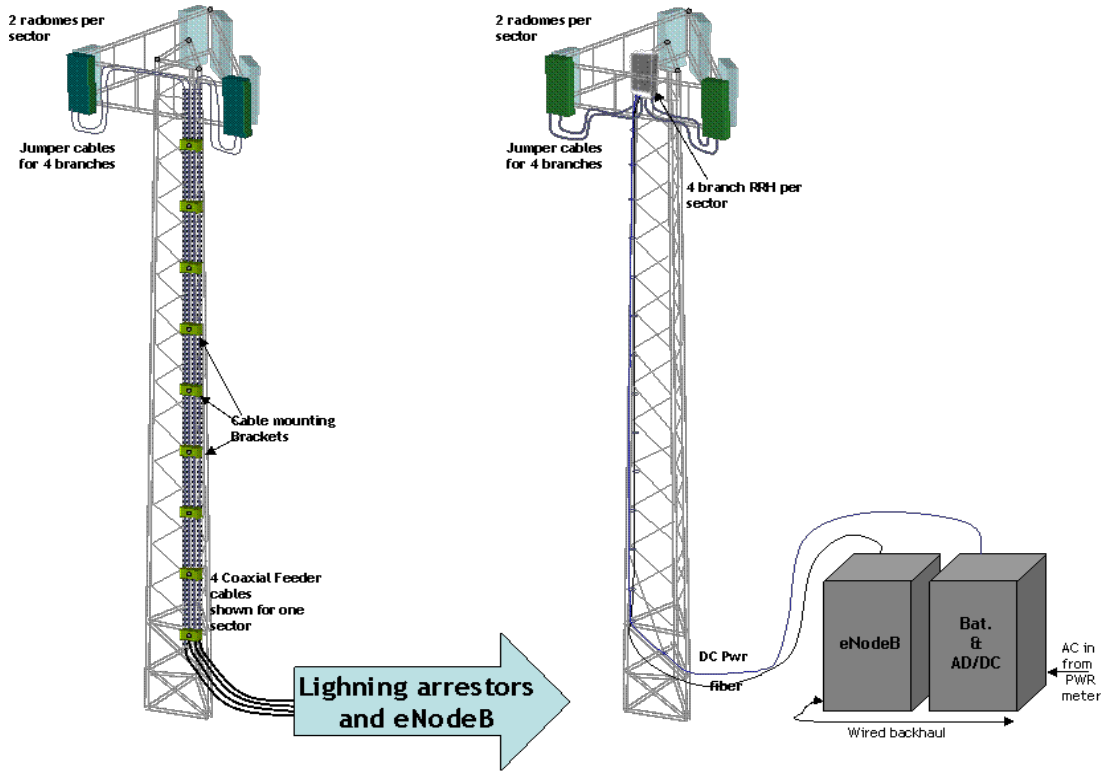


Figure 42. Components of cell site, highlighting a single sector's tower equipment.

A photograph of a typical site with outdoor cabinets connected directly to the antennas with coaxial cables such as to the left is shown below in Figure 43.



Figure 43. Cell site under construction showing outdoor base station cabinets awaiting coaxial cable connection to the tower mounted antennas.

Optionally, instead of RRHs, one may have tower-mounted Low Noise Amplifiers, antennas with remote electrical tilt capability. On occasion, legacy base stations supporting one or another frequency band with various air interfaces will sometimes be multiplexed with a newer base station so as share the same cable and perhaps the same antenna system. When one antenna cannot support both frequency bands then duplex filters atop the tower may be used to direct the various bands to their respective antennas.

8.2. CURRENT DEPLOYMENTS

One operator contributed that the percentages of various types of antenna placements are as given in Table 2. We see here that towers and monopoles are used extensively (59 percent) while rooftops account for about 19 percent of installations. As one might expect, rooftops are more commonly used in urban settings.

Table 2. National cell site categories (all towers include the 3 following subcategories of towers).

Cell Site Types	%
Rooftop	19%
All Towers	29%
Self support	19%
Guyed Tower	7%
Utility lattice tower	3%
Monopole	30%
Water Tank	5%
Others	18%

In addition, these sites have the following numbers of antenna radomes per sector.

Table 3. Number of antennas per sector.

Antennas (Radomes) per Sector	Percentage of Sectors
1	26.9%
2	61.0%
3	11.7%
4	0.3%
5	0.1%

The average number of these antennas (radomes) is 1.9. Additionally, the majority of the sites have 3 sectors.

8.2.1. TYPICAL TOWER TOP DEPLOYMENT

Knowing that about 30 percent of the deployments are on monopoles, it is worthwhile observing in the following figure, the typical mechanical constraints atop a typical monopole where the so-called, “pinwheel” provides a platform for positioning antennas, Remote Radio Heads, tower top amplifiers, LNAs, feeder cables and the like, including workspace for installers. These pinwheels are typically placed no closer than 10 feet vertical separation. Notice the 16 feet of linear separation available for antennas sharing the same “sector face.” For an antenna configuration such as Antenna Configurations (H) or (I) (Div-2X or TX-DIV) in Figure 44, this corresponds to as much as 11 λ at 700 MHz.

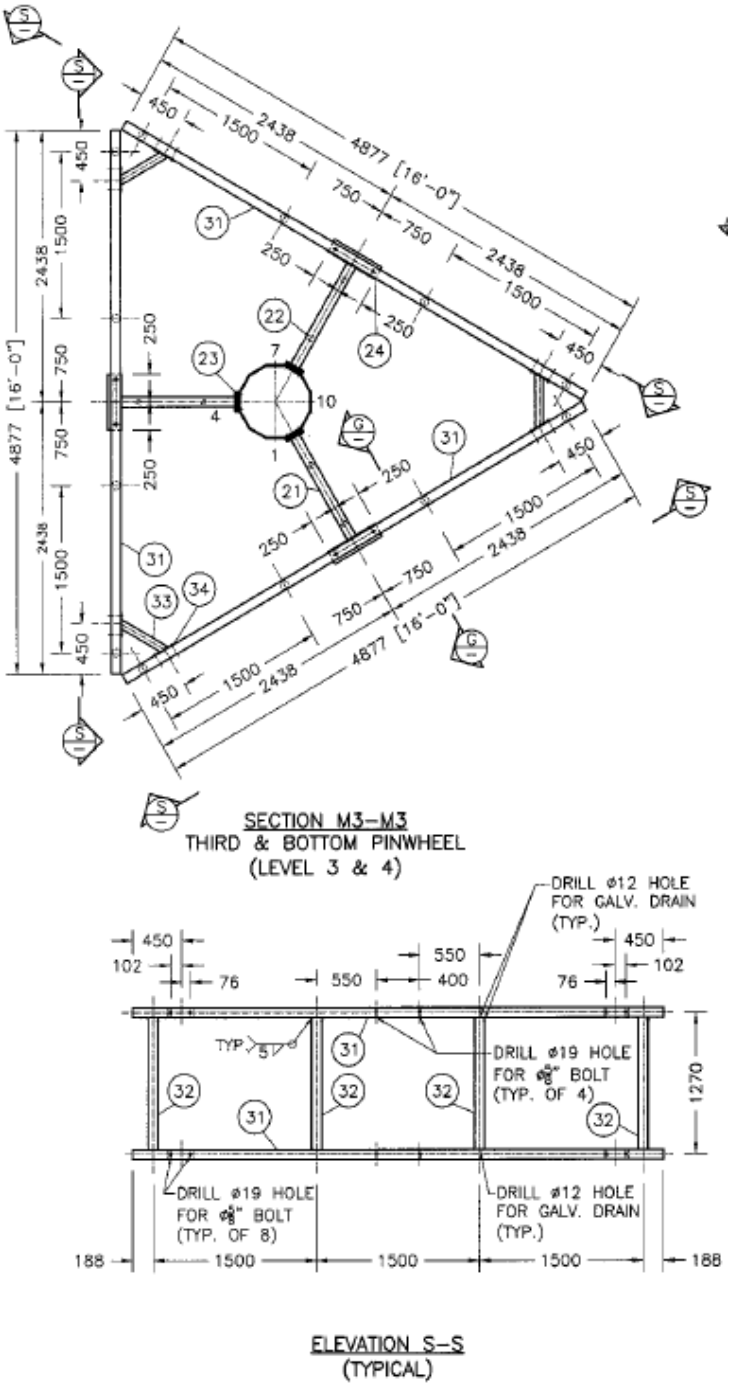


Figure 44. Tower top "pinwheel" with dimensions.

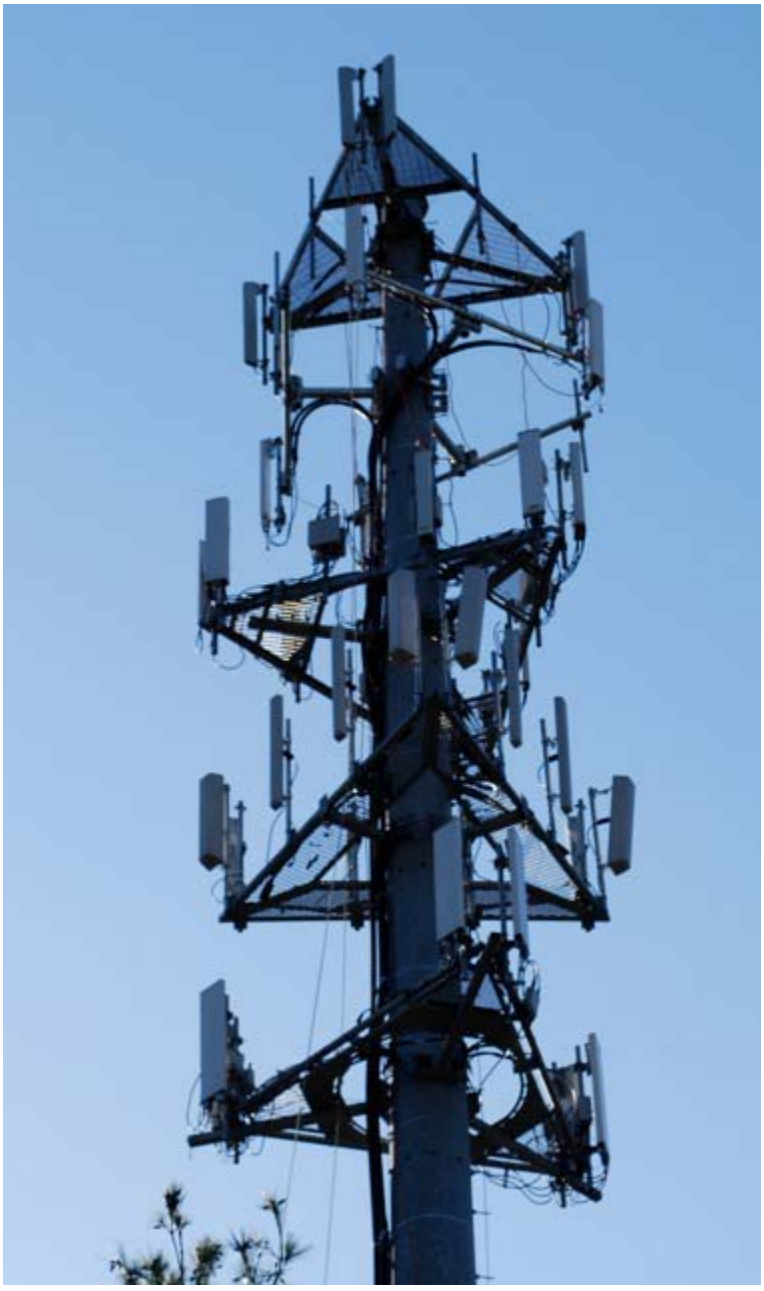


Figure 45. Common monopole during installation of antennas.

The five operators sharing the leased monopole above all use coaxial cables to connect to their antennas, and all use similar triangular mounting platforms except for the second from the top. It uses struts such as those shone in Figure 46, below. Ropes for hoisting the antennas are still visible in this photo taken in March 2010.

8.2.2. TYPICAL MAST DEPLOYMENT

One can see in the photograph in Figure 45 above, that the second platform from the top is not a full “pinwheel” but a cantilevered strut assembly detailed below in Figure 46. These platforms do not have the same workspace available

as the full triangular platforms shown above but they can still use Remote Radio Heads and can be equipped with antennas spaced as far apart as those shown above.

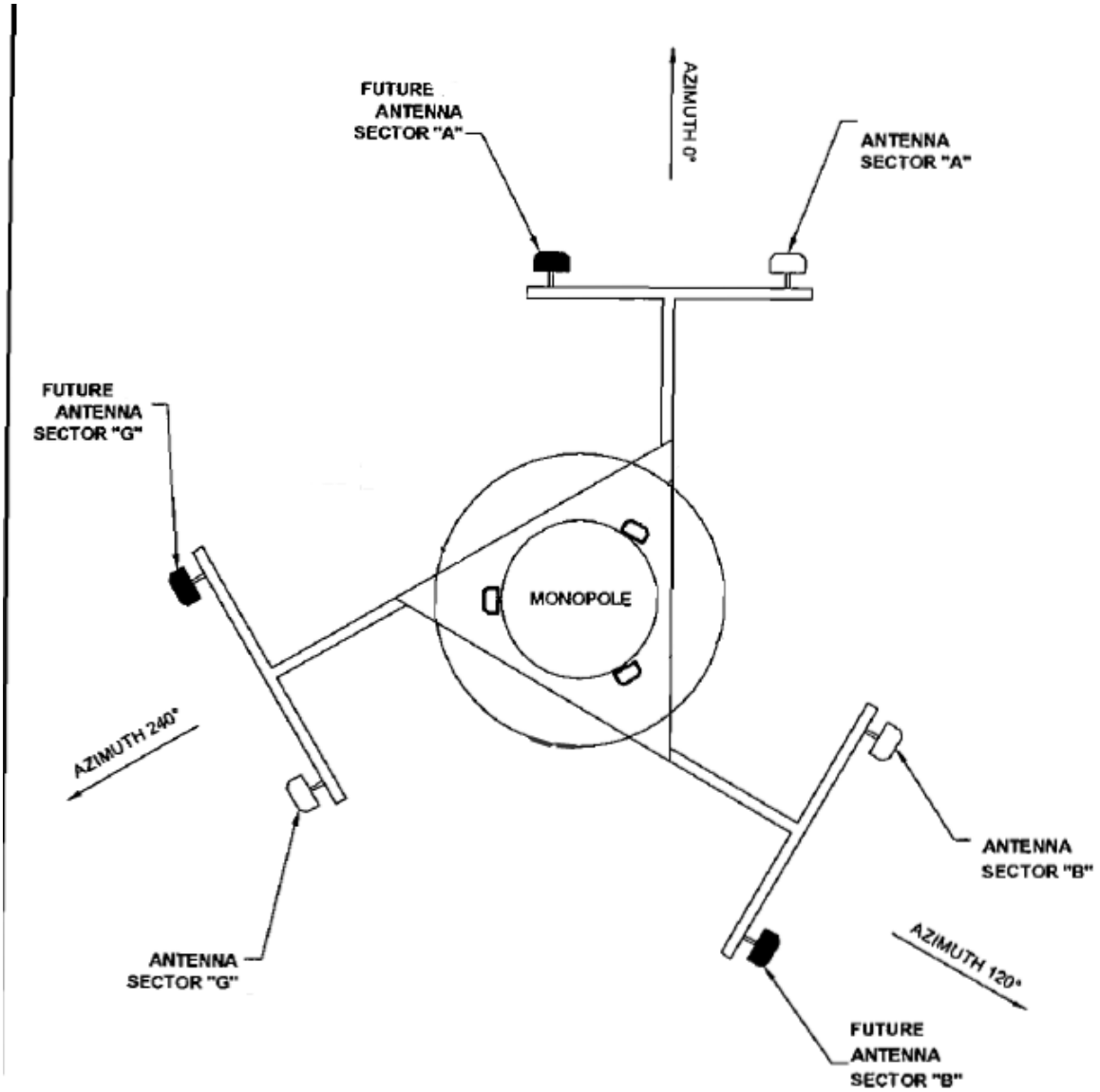


Figure 46. Typical monopole antenna installation as seen from above and with remote radio heads mounted on the monopole.

When mounted on a mast the cabling appears as shown below in Figure 47, where we see how the wind loading from cables can be substantial, and how some sites have limited room for additional coaxial cables.



Figure 47. Mast with 11 operators sharing the same facility (including public safety and low power AM radio broadcasting).

8.2.3. TYPICAL ROOF TOP DEPLOYMENT

Rooftop deployments promise much shorter cable runs as shown in Figure 48 below. However, it is often necessary to place the cabinets indoors on a separate floor for ease of access (elevators often do not go to the roof and so a crane would otherwise be required to place large equipment on the rooftop).

Items 1-3 of Figure 48 are three cross polarized antennas located at three corners of the roof, each placed on non-penetrating mounts (that do not penetrate the rooftop and hence do not threaten to cause a leak in the roof.) Item 4 is the base station cabinet and each antenna has a remote radio head mounted with it as shown in Figure 49.

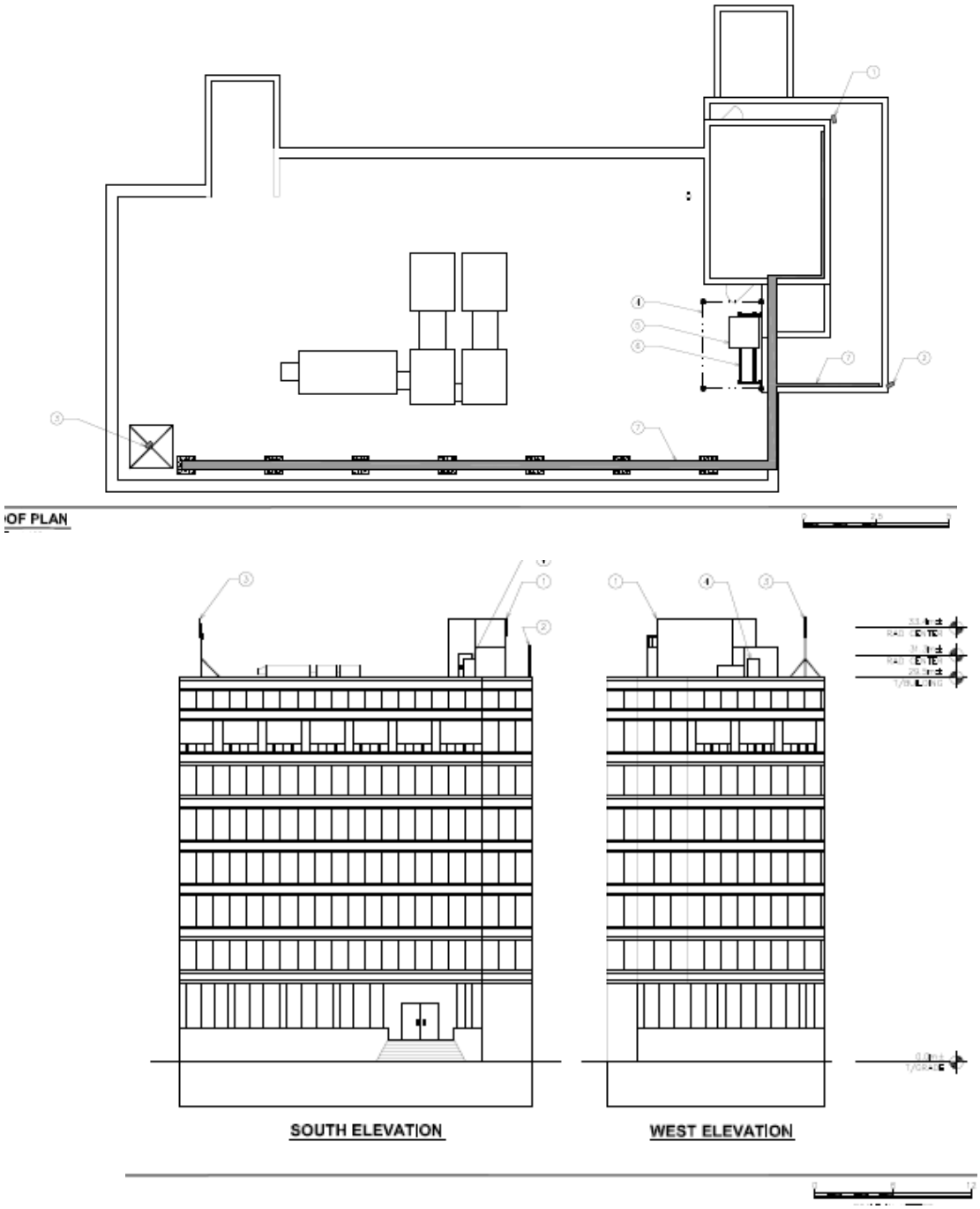
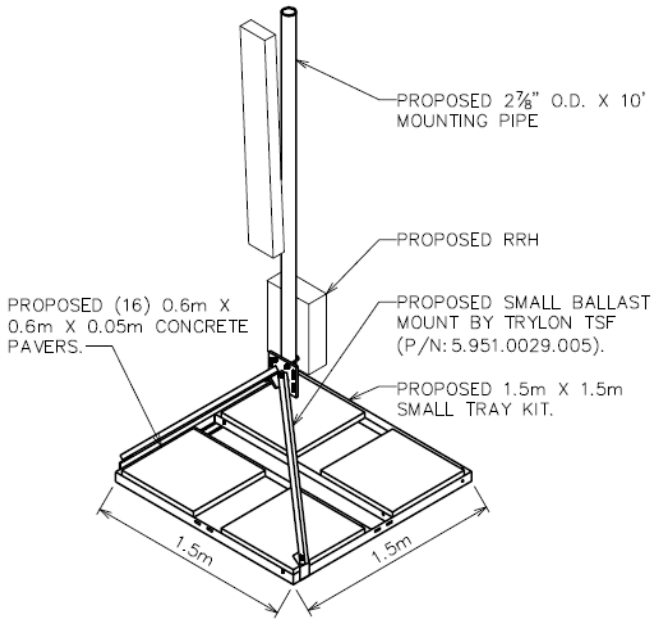


Figure 48. Typical rooftop installation with three sectors. the top scale spans 5 meters and the bottom 12 meters.



NON PENETRATING ROOF MOUNT SLED

Figure 49. Antenna mount with remote radio head.

9. MISCELLANEOUS COMMERCIAL AND DEPLOYMENT ISSUES

Overarching issues of wind loading, zoning, and rental covenants apply throughout the various antenna deployment schemes. Operators often have lease agreements dating back several years that stipulate the number of cables, antenna dimensions, weights and loadings and so forth that would have to be renegotiated at more restrictive terms if configurations were to be changed. While these restrictions are not universal, they can constrain the adoption of smart antennas and 4G systems. To install a larger antenna or RRH, an operator may have to pay for a new engineering study of the weight and wind load on all relevant structures, for example, adding considerable expense to an upgrade.

9.1. CONSTRAINTS ON THE ANTENNA DEPLOYMENTS DUE TO COMMERCIAL CONSIDERATIONS

Standard lease agreements for the placement of antennas, cables, and wireless equipment have become increasingly restrictive. For example, a typical publically available municipal lease agreement requires:[25]

1. Setback should be 300 percent, so a 30 m tower should have a 90 m setback from the property line.

2. Panel antenna **no more than two feet (2') wide and six feet (6') long**, extending above the structure to which they are attached by **no more than ten feet (10').**

3. Antenna, antenna array and support structures not on publicly owned property, which shall not extend more than ten feet (10') above the highest point of the structure on which it is mounted. The antenna, antennas array, and its support structure shall be mounted so as to blend with the structure to which the antenna is attached. The antenna and its support structure shall be designed to withstand a wind force of one hundred (100) miles per hour without the use of supporting guy wires. The antenna, antenna array, and its support structure shall be a color that blends with the structure on which they are mounted

We have seen in other similar lease agreements restrictions specify that the overall loading on towers be restricted to less than 85 percent, but leave it to operators to improve the site or mast to support any additional loads.[26]

These restrictions on antenna form factors are further constrained by the aesthetic judgments of zoning commissions and other municipal boards and property owners. Moreover, installation costs increase substantially if cranes are needed when hoists are insufficient. In order to standardize configurations some tower managers have stipulated that antennas and other equipment mounted on a mast or tower weigh in the range of 20 to 30 pounds for each such entity, for ease of hoisting and positioning by a single climber. The range of sizes can be in the 0.75 to 1.5 foot wide by 5 to 10 inches deep by 70 to 100 inches tall, which can be a severe limitation on the antenna scheme used. For example, a four-column array of vertically polarized antennas spaced at $\lambda/2$, which at 750 MHz (band class 13) takes a width about 2.6 feet.

Rooftop installations typically restrict the height of towers above the roofline, the mounting of rooftop equipment on non-penetrating plinths (so as not to cause the roof to leak rainwater). And zoning and aesthetic considerations are limiting the visual impact of the antennas. This impacts not only their coloration (to look like trees, for example) but also their overall area. Even in India and China, there are field reports of having to remove eight-column antenna arrays because of their visibility.

9.2. ELECTRICAL AND MECHANICAL TILTING OF ANTENNAS

9.2.1. EFFECTS OF MECHANICAL DOWNTILT ON SECTOR ANTENNA HORIZONTAL PATTERNS

Background

Cellular Networks achieve large capacity capabilities by re-using given frequencies repeatedly in a given system. This concept means that the communication paths are interference limited as opposed to traditional radio systems that were noise limited. To minimize interference, the use of sectorized antennas have been employed, each of which provides coverage to a portion of the cell. In a three-sector arrangement, each sector antenna covers a 120-degree pie shape that extends some distance away from the antenna site. Likewise, for a six-sector site, each antenna covers a 60-degree pie shape.

The cellular concept presents system designers with some challenges. Ideally, each sector antenna should only provide coverage in its 120-degree pie shaped sector so that interference with adjacent sectors is minimized. Often, the elevation beam is tilted downward to minimize interference with other cell sites. However, in both cases, there must be enough coverage overlap to facilitate high-speed handoffs so that calls are not dropped during the handoff process.

Antenna designers go to great lengths to develop sector antennas that have characteristics such as fast azimuth pattern roll off past the 3 dB points, high front-to-back ratios and excellent upper side lobe suppression on the elevation patterns. All of these features help to minimize harmful interference.

Traditional voice networks have been shown to be fairly tolerant of interference since voice conversations are still intelligible even with an occasional interference burst causing a few percent BER. However, with the introduction of high-speed data networks, optimizing the desired-to-undesired signal ratios will become a prime consideration and optimized sector antenna patterns can provide great benefits.

Network Optimization

As networks were built out, it was found that the distance covered by various sector antennas had to be adjusted because of unwanted interference. Issues like terrain coverage, non-optimal site location and capacity driven cell splitting are some examples. Several choices were available to accomplish this including lowering the antenna height, changing to an antenna with lower gain or down tilting the elevation beam of the existing antenna – either mechanically or electrically. The latter option was usually the most cost effective and has been heavily used. This down tilting lowered the gain ***as viewed on the horizon*** since this is the area where interference takes place. As Figure 50 shows, the angle below the horizon generally becomes very small at typical cell spacing distances. The various tilted elevation patterns of Figure 51A and Figure 51B demonstrate how gain on the horizon – noted by the dashed line – changes with beam down tilt. This paper defines the yellow ***horizontal*** pattern cut as the one taken through the dashed line, while the orange azimuth pattern cut is the one taken through the peak of the elevation beam.

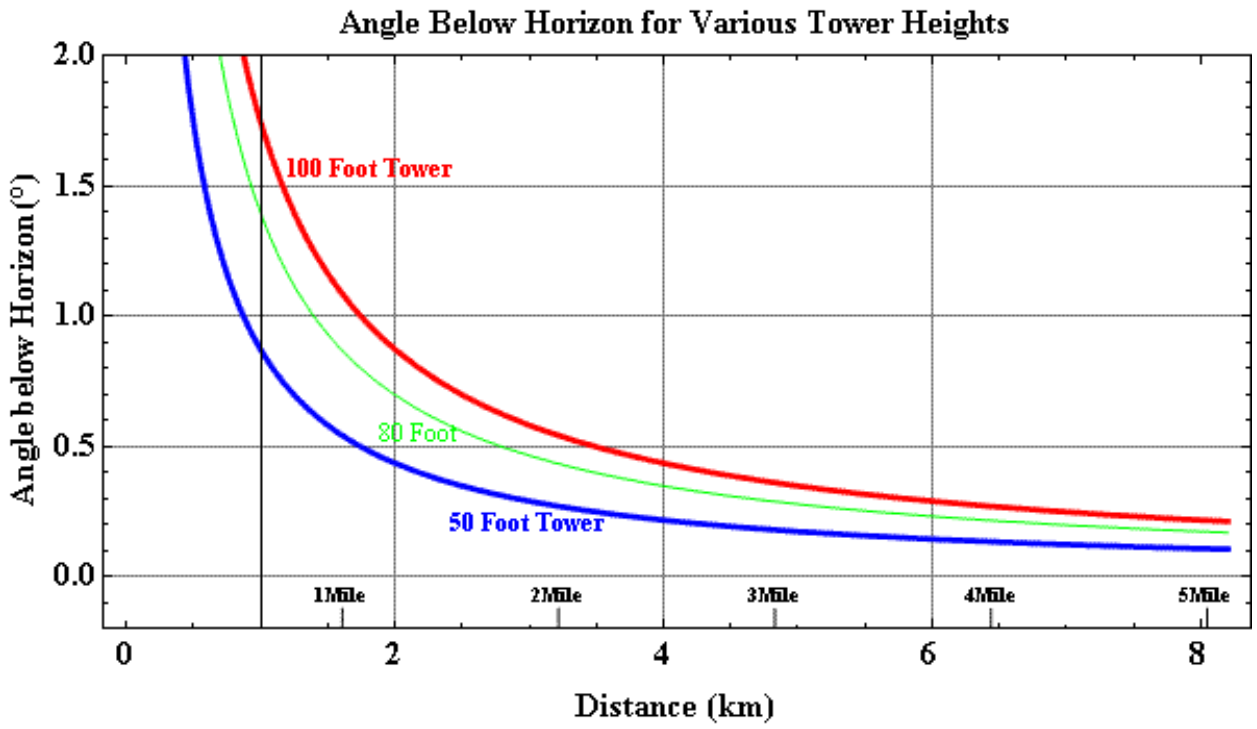
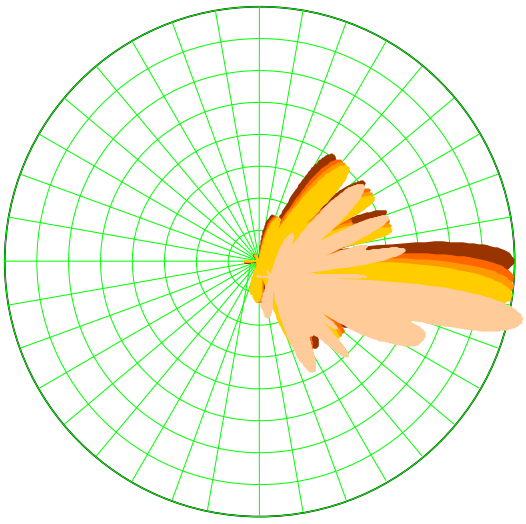


Figure 50. Angle below horizon for various tower heights.



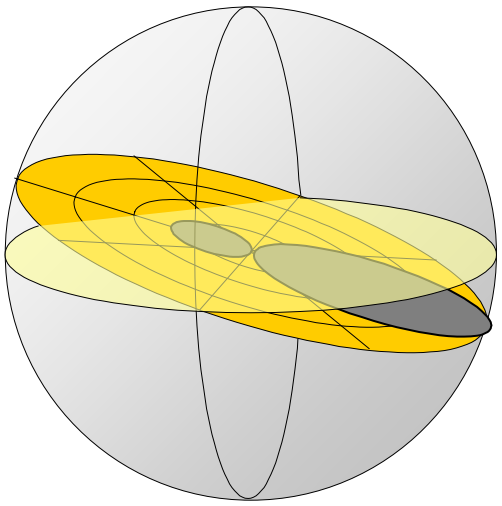


Figure 51A **Figure 51B**

Figure 51. How gain on the horizon changes with beam down tilt.

However, there are some important differences between mechanical and electrical down tilt. Figure 52 shows the results of a mechanically down tilted antenna where the main beam is tilted down at bore sight, tilted up at the 180-degree point behind bore sight and not tilted at all at the ±90-degree points. Figure 52B shows the results for an

electrically tilted antenna where the tilt is the same at bore sight, the ±90-degree points and 180-degree point. This leads to some important differences when viewing the ***horizontal*** pattern cut.

Those differences in the ***horizontal*** pattern cuts are shown in Figure 53A and Figure 53B. As expected, the mechanically down tilted antenna's gain is reduced at bore sight, but interestingly it is not reduced at all at the ±90-degree point. At small values of down tilt, the pattern seems acceptable but with greater amounts of down tilt the pattern takes on a "peanut" shaped look. This is undesirable since the purpose of down tilting is to reduce the coverage in all directions. As the better alternative, the electrically tilted antenna with its gain is reduced in all directions as shown in Figure 52B.

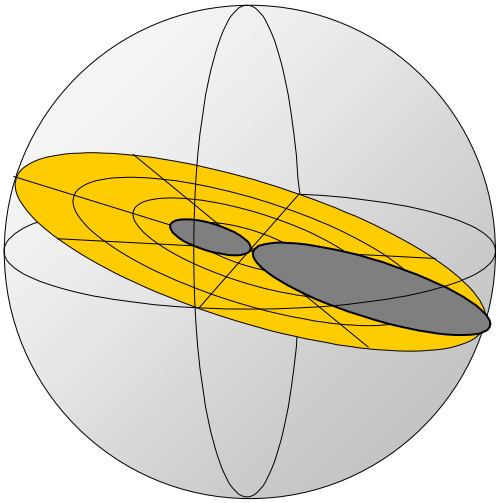


Figure 52A

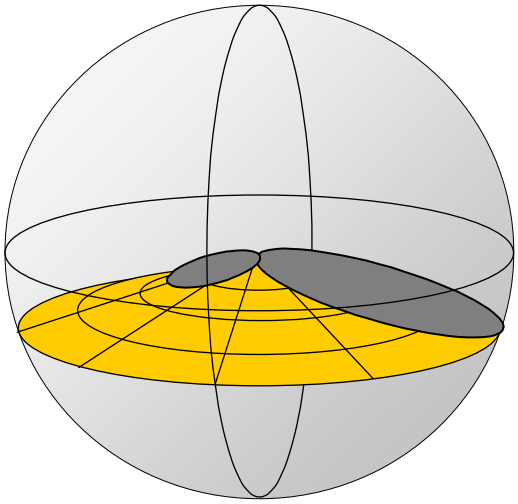


Figure 52B

Figure 52. Differences between mechanically down tilted and electrically tilted antennas.

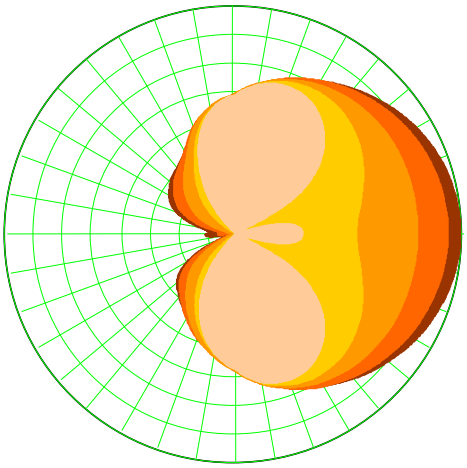


Figure 53A

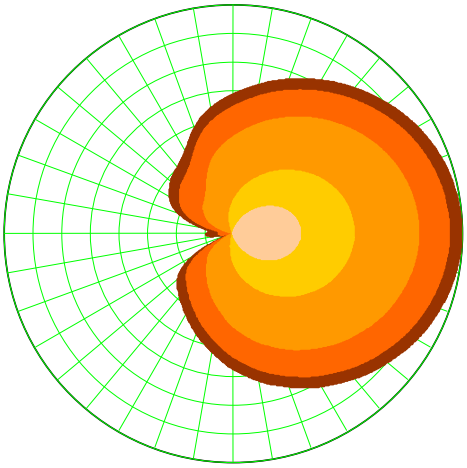


Figure 53B

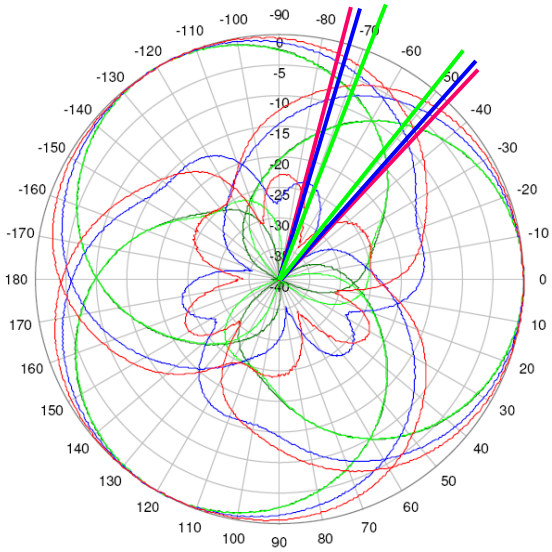
Figure 53. Differences in the horizontal pattern cuts.

Even though the mechanically tilted antenna's ***horizontal*** pattern cuts look acceptable at small values of down tilt, a subtle difference is taking place – commonly referred to as pattern blooming. In essence, the 3 dB beam width is getting larger. Blooming patterns become important from an interference standpoint because they increase the gain

at the sector crossover points and they increase the sector overlap angle. The widely used 65-degree azimuth antenna yields a typical 10 dB crossover gain and this has become the de facto specification for most modulation schemes in high capacity areas.

Legend Table

No.	Color	Dataset Name
1		RP_C_X_M=0_E=0
2		RP_C_X_M=0_E=0
3		RP_C_X_M=0_E=0
4		RP_C_X_M=0_E=7
5		RP_C_X_M=0_E=7
6		RP_C_X_M=0_E=7
7		RP_C_X_M=7_E=7
8		RP_C_X_M=7_E=7
9		RP_C_X_M=7_E=7
10		RP_C_X_M=14_E=0
11		RP_C_X_M=14_E=0
12		RP_C_X_M=14_E=0



M( )E( ) Tilt	Angle	Crossover
M0E0 & M0E7 ----	17°	10 dB
M7E7 ----------	25°	6 dB
M14E0 ----------	29°	4 dB

Figure 54B

Figure 54. Minimal horizontal pattern change using electrical down tilt only.

In Figure 54 the Legend Table shows the value of mechanical tilt as M=[tilt value] and the value of electrical tilt as E=[tilt value]. Note that the normalized dark green pattern for E0_M0 and the light green pattern for M0_E7 practically overlay each other. This substantiates the concept of minimal ***horizontal*** pattern change using electrical down tilt only. The other normalized patterns of Figure 54 also show that when mechanical down tilt or combinations of mechanical and electrical down tilt are employed that the blooming becomes an issue. To determine the overlap angles, this example used a 6 dB differential as a method of comparison. This overlap can contribute to interference in time division multiplex systems and pilot pollution in code division multiplex systems.

In the past, a rough rule of thumb emerged that allowed system designers to determine what amount of mechanical down tilt could be considered acceptable based on blooming of 10 percent. The rule stated that an antenna should never be mechanically down tilted more than one-half of its vertical beam width. However, this rule did not take into account the fact that the antenna may also incorporate electrical down tilt.

Combined Mechanical and Electrical Down Tilt

Initiated by customer complaints about bad interference at a site employing both mechanical and electrical down tilt, an investigation was opened to analyze the effects of combined mechanical and electrical down tilt. This combination of tilts modifies what was shown in Figure 52B such that Figure 55 results. It shows that the ***horizontal*** gain is

reduced at bore sight, somewhat reduced at ±90 degrees and actually increased at 180 degrees compared to the pattern having only electrical down tilt. Similar to mechanical-only down tilt, the ***horizontal*** pattern's uneven gain reduction across the sector again causes blooming to occur. The challenge was to come up with a new rule of thumb that could predict the percentage blooming for a particular antenna given the electrical and mechanical down tilt settings.

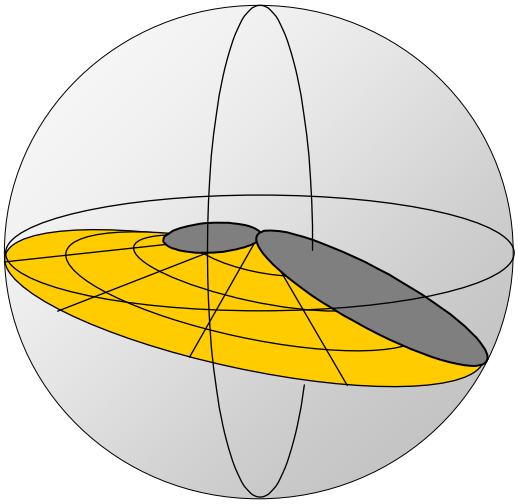


Figure 55. Combination of tilts.

First, range patterns were measured on different antennas for both the azimuth (through elevation bore sight) and ***horizontal*** (on the horizon) cuts. This was done at various mechanical and electrical tilt angles. The findings showed that the old rule of thumb was no longer applicable when electrical down tilt is employed.

Next, a mathematical model was developed that fit the measured data points and curves were generated showing the typical amount of combined mechanical and electrical down tilt allowable for 10 percent and 20 percent blooming. Some typical results are plotted as a function of the antenna's elevation beam width in Figure 56.

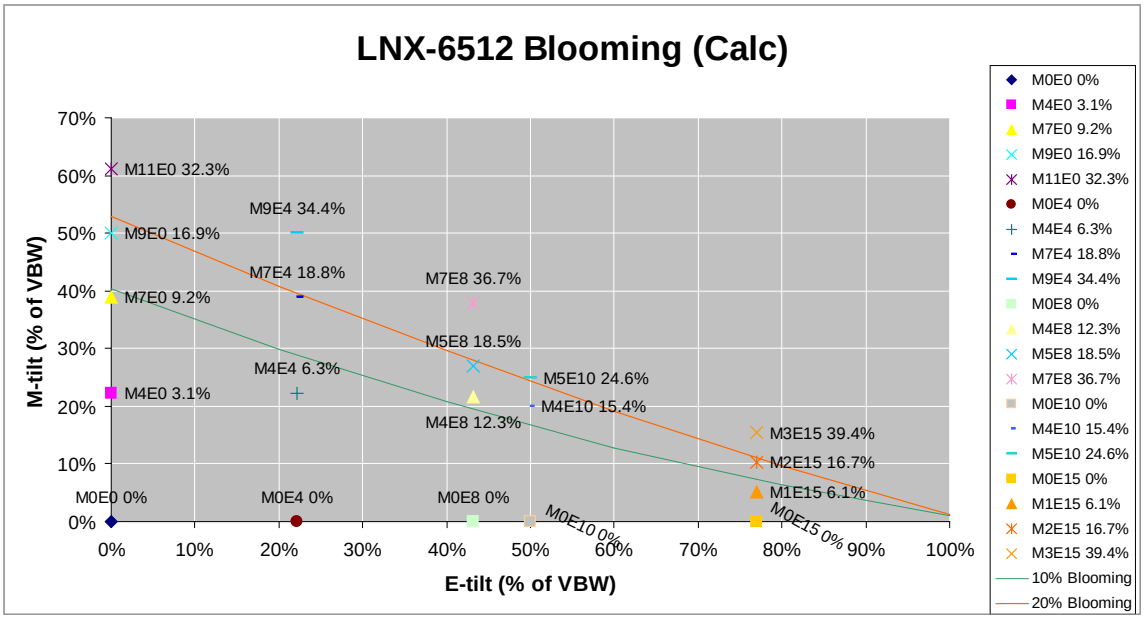


Figure 56. Mathematical results plotted as a function of antenna's elevation beam width.

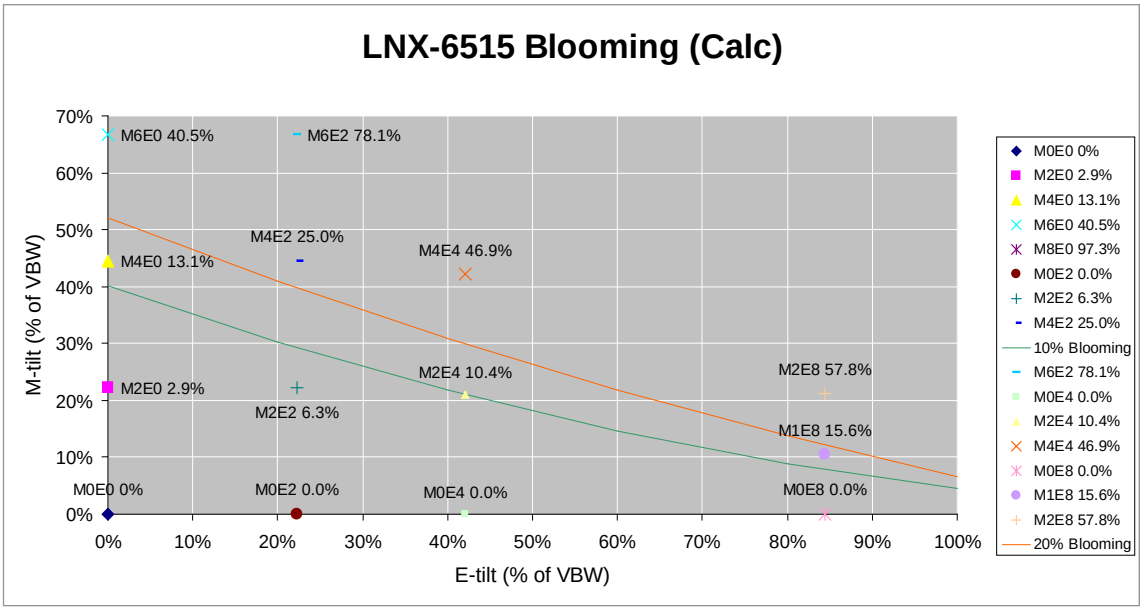


Figure 57. Comparison mathematical results plotted as a function of antenna's elevation beam width.

As these curves demonstrate, the green 10 percent blooming line is a function of both mechanical and electrical down tilt. The more electrical down tilt is employed in an antenna, the less mechanical down tilt can be used to stay within the 10 percent goal. It is interesting to see that when these two different antennas are normalized using their vertical beam widths, the blooming percentages track very closely. This mathematical model has been used on a series of antennas and the blooming percentages track very closely. From these plots, a new rule of thumb has been developed for the common 65-degree azimuth beam width antennas. It states:

$$65^\circ \text{ AzBW M-tilt}_{10\% \text{ Bloom}} = (\text{VBW} - \text{E-tilt})/2.5$$

More accurate range data shows that even with no electrical down tilt the maximum mechanical tilt for 10 percent blooming is no longer half (50 percent) the vertical beam width but that it is the vertical beam width divided by 2.5 (40 percent). When large amounts of electrical down tilt are employed, acceptable mechanical down tilt can be limited to as little as 10 percent (or less) of the vertical beam width.

Another caution should be noted when using ultra-high gain antennas that incorporate electrical down tilt. It is extremely important to mount them exactly plumb to minimize any possible blooming. For instance, an antenna having 4 degrees elevation beam width and 2 degrees of electrical down tilt suffers 10 percent ***horizontal*** pattern blooming with less than 1 degree of mechanical down tilt!

Further investigation of antennas having azimuth beam widths different than 65 degrees showed that their blooming did not follow the rule above. After checking several different azimuth beam width models the graph of Figure 58 evolved.

Figure 58 shows that the k-factor, which is 2.5 for 65-degree azimuth models, ranges from 1.5 for 33-degree azimuth models to 3.3 for 90-degree azimuth models. Note that these rules of thumb describe typical band-center performance and can vary somewhat at the band edges. They also only hold true if the combined mechanical and electrical tilts do not tilt the pattern beyond its first upper null.

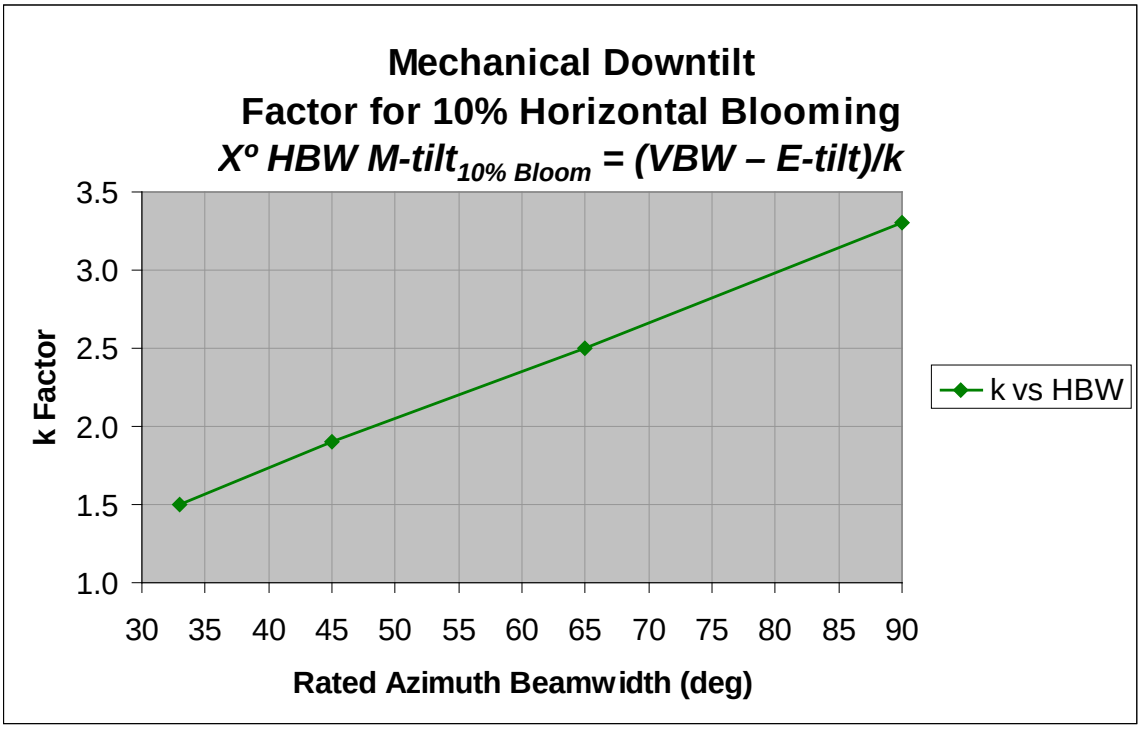


Figure 58. Variations in the K-factor which is 2.5 for 65-degree azimuth models ranges from 1.5 for 33-degree Azimuth models to 3.3 for 90-degree azimuth models.

Recall that the new rules of thumb are most accurate near the band-center of the antenna's specified frequency range. They are also most accurate at the lower portion of the electrical down tilt range. In addition, the combination of electrical and mechanical tilt should never go beyond the first upper null of the elevation pattern.

Further Findings

In addition to ***horizontal*** pattern blooming, several other important antenna specifications were seen to degrade with mechanical down tilt. These include squint, front-to-back ratio and cross-polarization ratio. Unfortunately, these are not easily mathematically modeled like the blooming issue. The following results from a relatively small number of antennas have been extracted from actual measured data.

Horizontal Beam Squint

Squint is defined as the difference between the mechanical bore sight and the electrical bore sight of an antenna as shown in Figure 59. The mechanical bore sight is defined as being perpendicular to the antenna's back tray while electrical bore sight is defined as the mid-point of the 3 dB beam width.

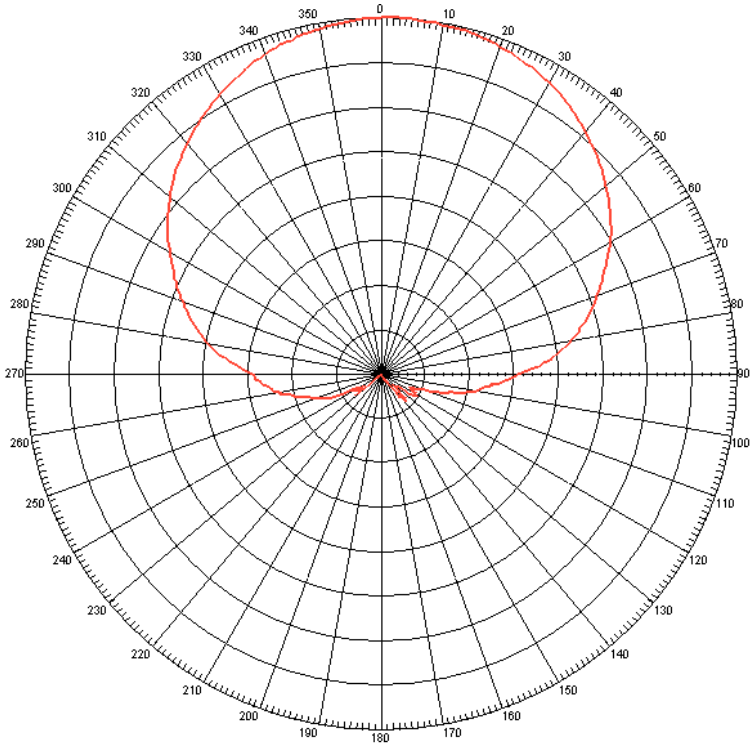


Figure 59. Horizontal Beam Squint. (Note the approximately 10-degree clockwise rotation of the beam compared to the mechanical bore site.)

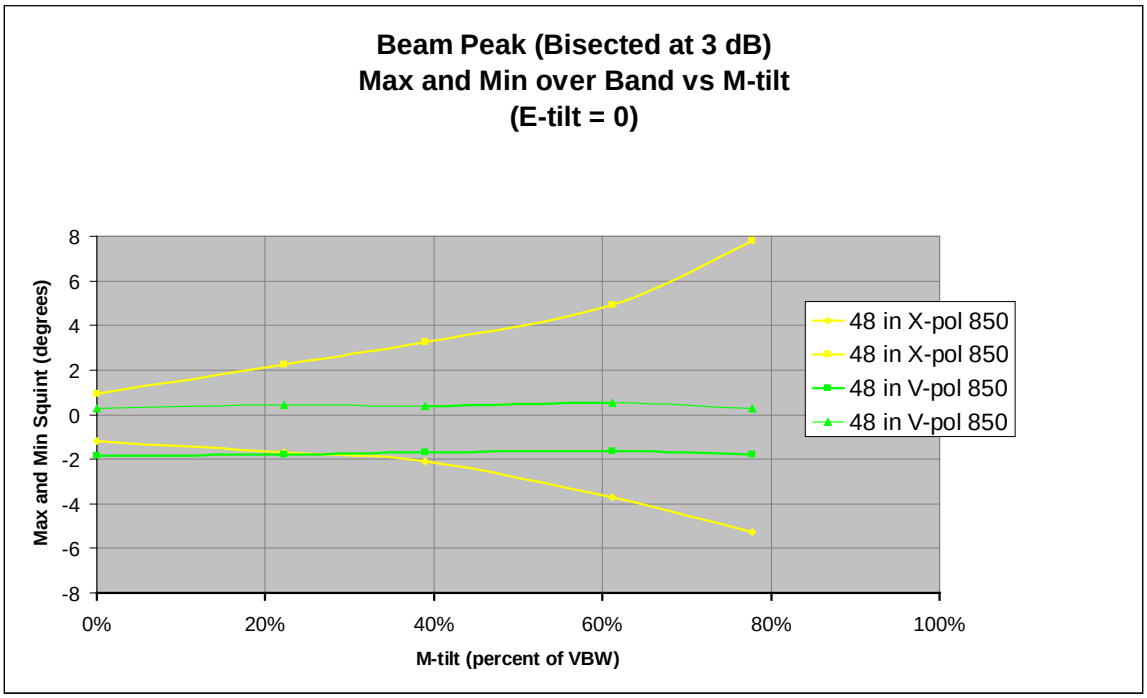


Figure 60. Beam peak versus mechanical tilt as a percentage of vertical beam width.

The previous figure illustrates how squint stays relatively constant for both vertically polarized (V-pol) and Dual-pol (X-pol) 65® models when electrical tilt is varied while mechanical tilt is fixed at zero. Figure 61 analyzes the same antenna models but now mechanical tilt is varied while electrical tilt is fixed at zero. The data is once again presented as a percentage of the antennas' vertical beam widths for easy comparison. It shows that squint on X-pol antennas degrades with mechanical down tilt to the point that it can be greater than 10 percent of the antenna's azimuth beam width at high angles of mechanical down tilt.

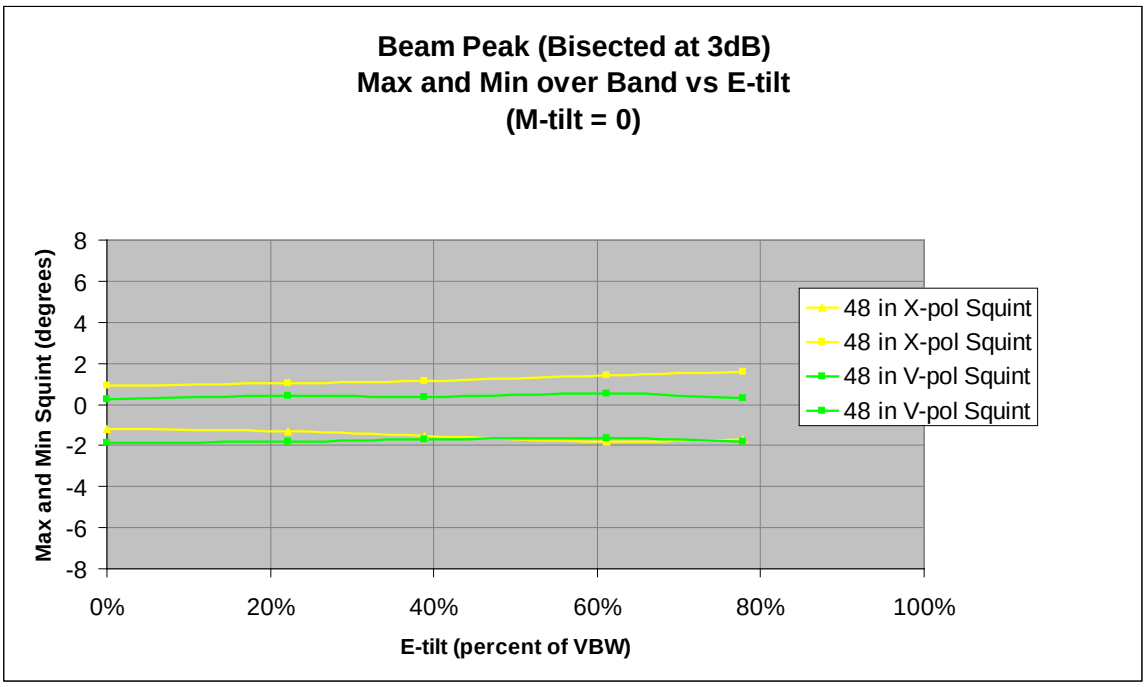


Figure 61. Varied mechanical tilt with electrical tilt is fixed at zero.

Sector Power Ratio

Sector Power Ratio (SPR) is another measure of an antenna's ability to minimize unwanted interference in a cellular network. Figure 62 graphically shows the concept along with the equation used to calculate SPR. In essence, it compares the undesired RF power outside of the sector to the desired RF power within the sector and expresses it as a percentage. Excellent antenna designs provide SPRs as low as 3 percent to 4 percent, while traditional dipole or patch element designs can yield SPRs approaching 8 percent.

Figure 63 shows that similar to squint, SPR remains relatively constant for both V-pol and X-pol models as the electrical tilt is varied while keeping the mechanical tilt at zero. In Figure 64, SPR is shown to degrade significantly for all types of antennas when mechanical tilt is varied while keeping electrical tilt fixed at zero.

$$SPR(\%) = \frac{\sum_{60}^{300} P_{Undesired}}{\sum_{300}^{60} P_{Desired}} \times 100$$

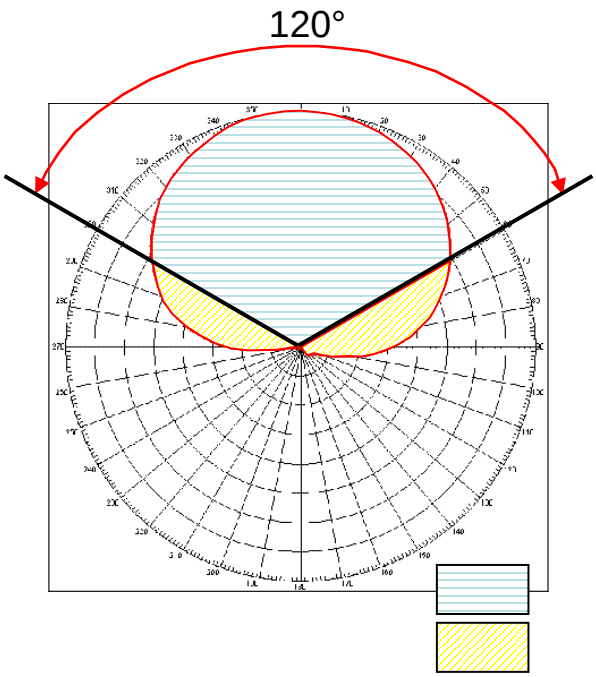


Figure 62. Graphical representation of Sector Power Ratio (SPR).

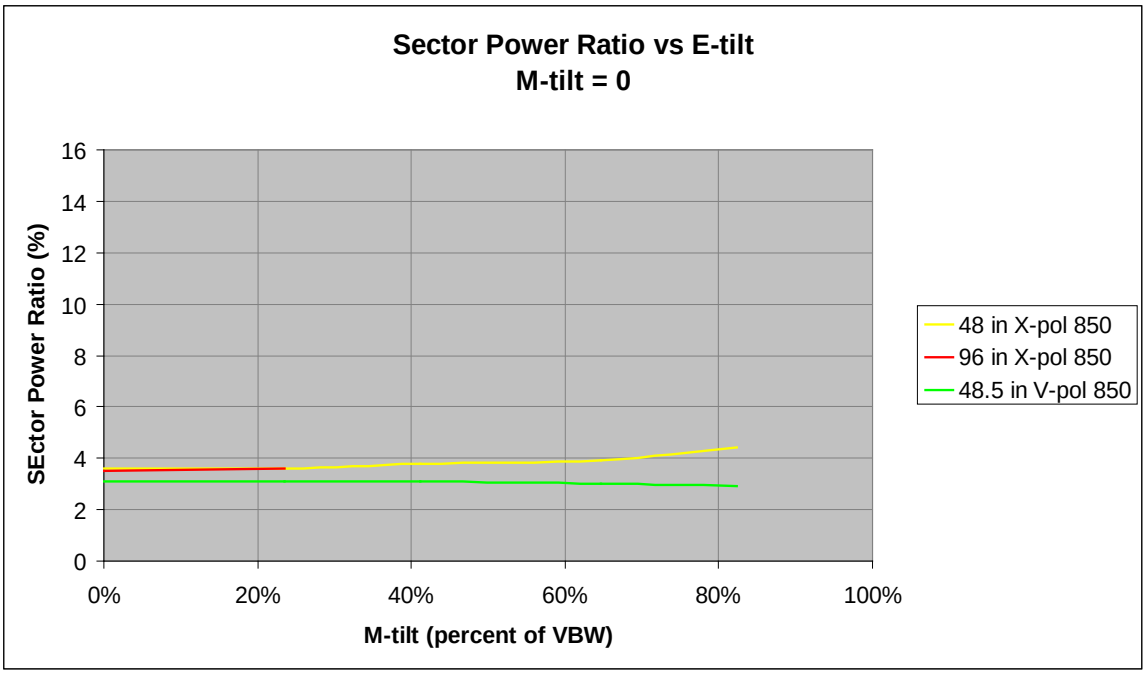


Figure 63. SPR remains relatively constant for both v-pol and x-pol models as the electrical tilt is varied.

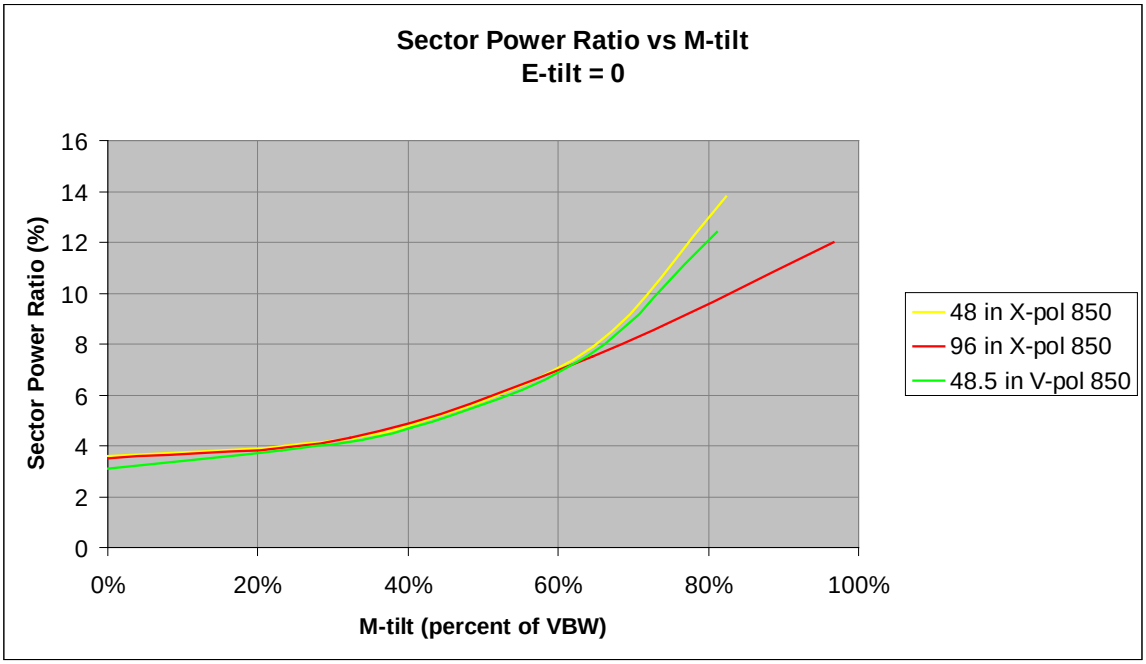


Figure 64. SRP degrades significantly for all types of antennas when mechanical tilt is varied which keeps electrical tilt fixed at zero.

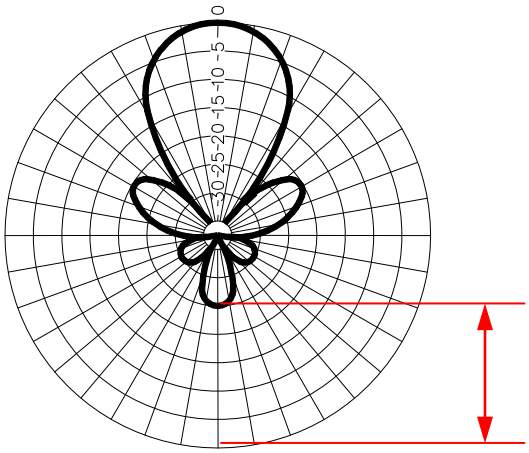
Front-to-Back Ratio and Cross-pol Ratio

When either (or both) of these two specifications degrade, system performance can be affected – but in different ways.

Front-to-back ratio (F/B) is traditionally measured by comparing gain at bore sight to gain at point 180-degree behind bore sight as shown in Figure 65A. Some system specialists have taken this concept to another level by characterizing the F/B ratio over some angle around the 180-degree point – such as 180 ±30 degrees. Either way it is a measure of unwanted interference behind the desired sector.

Cross-pol Ratio (CPR) as shown in Figure 65B is a measure of the de-correlation of the two polarizations used in a X-pol antenna – one at +45 degrees and the other at -45 degrees. Within the sector, having gain de-correlation of at least 10 dB assures good uplink diversity in a multipath environment. Most cellular systems depend on some sort of receive diversity at the cell site to balance the uplink path from the lower power cell phone devices with the downlink path from the higher power cell site transmitters. Lack of good uplink diversity in essence shrinks the coverage distance of the site.

It should also be noted that for X-pol models, the total F/B power is the sum of the co-pol energy plus the cross-pol energy.



F/B Ratio @ 180

0 dB – 25 dB = 25

Figure 65A. Front-to-back ratio measured by comparing gain at bore site to gain at point 180 degrees behind bore site.

--Co-Polarization

--Cross-Polarization

(Source @ 90°)

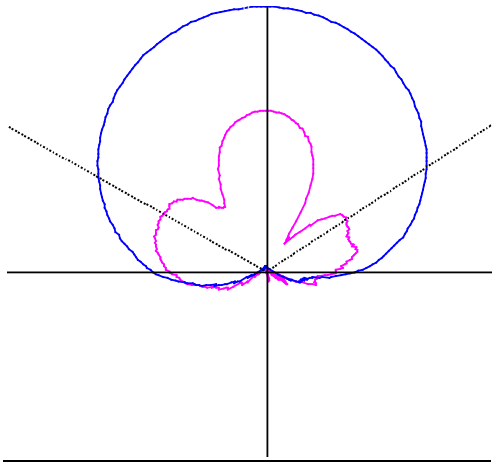


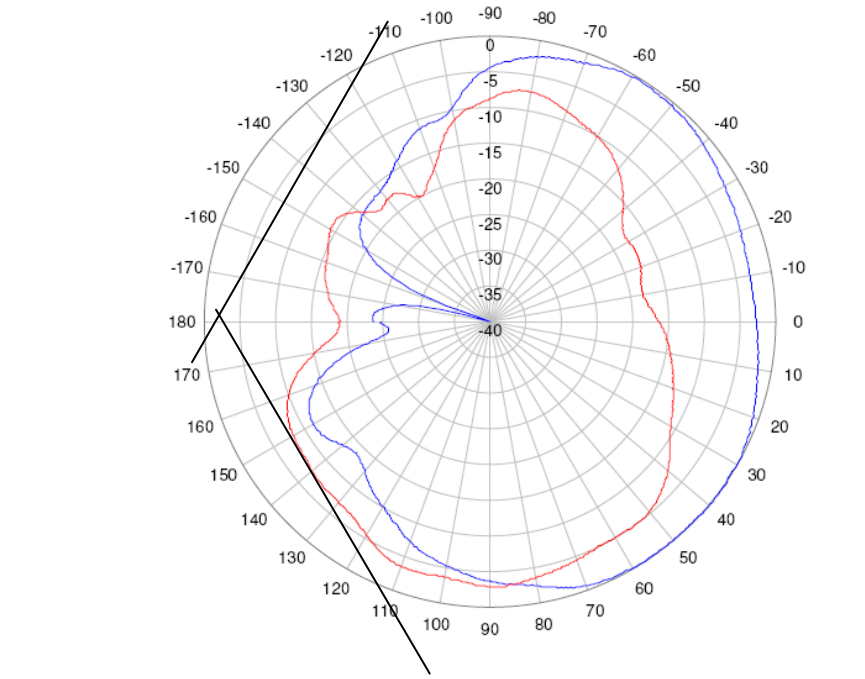
Figure 65B. Cross-pol ratio is a measure of the de-correlation of the two polarizations used in an x-pol antenna — one at +45 degrees and the other at -45 degrees.

Figure 65. Front-to-back and Cross-pol ratio.

To demonstrate the huge amount of degradation that can happen to both F/B ratio and CPR when mechanical down tilt is applied to an antenna already having a large amount of electrical down tilt, the measured patterns of Figure 66 are presented. The patterns are for a typical 4 foot, 65-degree antenna employing 15-degree electrical down tilt along with a 5-degree mechanical down tilt. The co-pol pattern is shown in blue and the cross-pol pattern is shown in red. With a vertical beam width of ~16 degrees at 850 MHz, the tilt combination is well beyond even the 20 percent blooming curve of Figure 56. In fact, the ***horizontal*** beam width is in the neighborhood of 160 degrees or approximately 250 percent blooming!

The F/B ratio has degraded to approximately 18 dB at 180 degrees and the cross-pol is actually worse than the co-pol pattern. Taken over a ±30-degree angle around 180 degrees this F/B method measures only 8 dB!

Finally, the CPR over the desired sector degrades to only 5 dB at the sector edge – far short of the 10 dB expectation.



Legend Table

No.	Color	Dataset Name	Frequency	Pattern	Pol.
1		AZ/LB/RP/12 (MECH. T=5)	0.836	az	co-pol
2		AZ/LB/RP/12 (MECH. T=5)	0.836	az	x-pol

Figure 66. Demonstration of the huge amount of degradation that can happen to both f/b ratio and cpr when mechanical down tilt is applied to an antenna having a large amount of electrical down tilt.

Conclusions Concerning Electrical and Mechanical Downtilt

The industry has always realized the coverage and interference compromises associated with mechanically down tilting sector antennas and a rule of thumb commonly used to minimize these issues; however, it did not incorporate the use of electrical down tilt.

This sector analysis goes into more detail by showing how various parameters including ***horizontal*** beam width, squint, Sector Power Ratio, front-to-back ratio and cross-pol ratio are all affected by mechanical down tilt.

It presents new rules of thumb that limit blooming to approximately 10 percent when combined mechanical and electrical down tilt are employed. Also included is measured data showing how the other important parameters mentioned above – especially for the popular Dual-pol® (X-pol) models – degrade when mechanical down tilt is used.

As the industry evolves toward data systems supporting higher and higher data rates, more attention must be paid to these parameters, which can severely degrade overall network performance, and the importance of using only electrical down tilt.

9.2.2. EFFECTS OF INCORRECT ANTENNA INSTALLATION

Background

As was stated in the previous section, cellular networks re-use frequencies repeatedly again to achieve the capacities demanded by today's customers. In order to achieve optimum performance the sectorized antennas used at each cell site must be installed according to the design engineer's specifications. If they are not installed correctly, network performance will suffer.[27,28]

Real World Issues

Many installers who have the dangerous job of climbing cellular towers have not been properly trained on the importance of correct antenna installation. Some common issues are noted below:

The antenna support pipe must be plumb. Often installers will mount an antenna such that it is parallel to the support pipe. Of course, if the support pipe is not plumb, the antenna will not be plumb. This can produce mechanical down-tilt, mechanical up-tilt or side-to-side skew depending on the support pipe's orientation. The correct procedure is to use a digital inclinometer to plumb the antenna in both planes using the adjustable mounting brackets supplied with most sector antennas.

The azimuth pointing direction is not correct. The design engineer specifies a geographic pointing direction or heading for each antenna to insure optimum network performance. However, if care is not exercised, a couple of issues can cause serious problems. First, magnetic compasses do not read correctly when used near a large amount of metal and since towers use large amounts of metal, readings taken at or near the antenna will be faulty. Usually it requires someone on the ground – away from metallic structures – to establish the correct pointing direction and coordination with the installer on the tower to then point the antenna correctly. The second issue that untrained installers encounter is the magnetic declination angle between magnetic and geographic North. In some areas, differences greater than 15 degrees exist. To complicate things even further, the declination changes from year to year so it is important that installers know where to access the latest information.

Azimuth adjustment tools are available on the market that makes use of relative bearing references to known large objects, such as churches, chimneys and silos, rather than magnetic compass bearings. Relative bearings can be obtained from a map and then used as a reference for the azimuth adjustment tool while adjusting the antenna azimuth direction.



Figure 67. Azimuth Adjustment Tool.

The mounting hardware must be assembled correctly. Antennas either are supplied with mounting kits or have them available as a separate purchased part. If the installer does not follow the installation instructions, some of these mounts have been known to change position under high wind conditions. The network will suffer until another tower climb is initiated to repair such a faulty installation.

9.3. PASSIVE INTERMODULATION (PIM) SITE CONSIDERATIONS

Background

Intermodulation is defined as the mathematical mixing of two or more desired RF signals to generate a family of undesired RF signals.[29] For years, this phenomenon has been well understood in active components such as power amplifiers and preamps. With the introduction of duplexed, high data rate systems the industry has become focused on this same intermodulation happening in passive RF components – especially those that share both downlink (high power transmit) and uplink (very low power receive) signals. If undesired passive intermodulation (PIM) products are produced in the receive frequency band of an FDD system, there is no way to eliminate them by filtering signals and they will interfere with or degrade the desired signals coming from user equipment (UE).

Discussion

Intermodulation can take place whenever multiple RF signals encounter some type of non-linearity. It can take place in the RF path or beyond the RF path after the signals are radiated from the antenna. Things such as rusted tower joints or guy wires as well as rusted or corroded equipment on a building top are all examples of PIM generators. Loose nuts and bolts or rivets are other examples.

All RF path components such as connectorized transmission lines and jumper cables, antennas, diplexers, tower mounted amplifiers (TMAs) etc., have some inherent degree of non-linearity. The industry's challenge is to develop designs that suppress the unwanted intermodulation to acceptable levels. The accepted standard for antenna PIM uses two 20 watt transmitters (A and B) and states that any third order intermodulation products (2A-B or 2B-A) must be at least 150 dB below the two transmitter carriers (-150 dBc).

Another type of third order intermodulation product takes the form of A + B – C where three desired signals are now involved. It also opens up the possibility that different frequency bands and blocks can be involved. This type of PIM can happen when diplexers are used to minimize the number of transmission lines at a site. For instance if a US

operator had PCS blocks B and F and decided to diplex them with the Upper 700 C block, there is a possible PIM hit (756+1973-1952=777). A calculator[30] is available that allows designers to check for PIM problems when various band(s) and block(s) are combined. It is strongly recommended that these combinations be avoided since they are very difficult to eliminate in practice.

Other less complex components like connectorized transmission lines and jumpers normally are specified to have better PIM suppression in the range of -160 to -163 dBc. This is important since in the complete RF path there will be a number of PIM generators and the system PIM will depend on all of the contributors. Each PIM contributor is a vector having amplitude and phase so they can combine in various ways. The typical result is a random combination of the individual vectors, but under worst-case conditions, they could all combine in-phase.

Testing Considerations [31]

There are several test equipment companies that have developed rugged, high performance, portable PIM test equipment. Most can test either throughput PIM or reflected PIM. Since the industry is concerned about PIM coming back into the receivers, most components are tested for reflected PIM. This equipment must be complimented with a good low-PIM 50-ohm test load and a good low-PIM jumper cable before meaningful testing can be done. Testing two-port devices like coax cables for reflected PIM is relatively straightforward and simply requires that the low-PIM load be connected to the output port. Be sure to correctly torque all RF connectors. However, testing antennas for PIM is a much more meticulous process. For best results, the antenna should be tested outdoors facing skyward with no metal within 15 to 20 feet. Testing indoors, even in large warehouses, should be avoided as these environments have shown to produce incorrect results. In addition, no personnel should be close to the antenna during testing. Items like keys in someone's pocket or a cell phone on their belt can cause undesired PIM. Again, applying the correct torque to RF connectors is an important step.

For field-installed connectors on transmission line or jumper cables, use of the recommended cable preparation tools is very important. Follow the manufacturer's instructions closely to insure the best results. Smooth flared surfaces with no burrs on either the center or outer conductor is required for low-PIM connectorization.

Finally, use only 7-16 DIN style connectors on all RF path components where possible. It is important that the connectors being used are approved for the cable brand being used to ensure the correct fit and sealing. Also, insure that the installers have the correct 25 Nm (222 inch-pound) torque wrenches.

9.4. INDEPENDENT ANTENNA TILT OPTIMIZATION BY AIR INTERFACE

It is common for operators that have multiple air-interface technologies in their network to elect to optimize the services independently. For example, an operator that is utilizing GSM in the PCS band and UMTS in the AWS band, may elect to use two separate variable electrical tilting antennas rather then diplexing the services on one antenna. This approach is chosen even though the use of one antenna could have advantages for wind loading, leasing costs, and feeder cable reduction. Often quad antennas are used for independent tilt to minimize the radome count on the tower. Likewise an operator who deploys a multi-band antennas using GSM on the cellular band and UMTS on the PCS band can implement independent tilt to optimize the two services and associated frequency band separately. This independent tilt is particular important for muti-band antennas given the relative differences between 1 GHz and 2 GHz for RF propagation, antenna gain and vertical beam width.

As described in Section 6, novel new active antenna arrays are emerging that allow for the phase and amplitude weighting of signals on all antenna elements, not just columns of elements. This enables beam forming and MIMO operations in both the azimuth and now the elevation direction. Moreover, this can be done on a per carrier bases, or even on a per user basis.

With proper support in the baseband processing, these Active Antenna Arrays can conceivably tilt different air interfaces on different carriers in the same band by different amounts. This can be particularly attractive for introducing LTE for hot spot coverage, where GSM/GPRS/EDGE or WCDMA/HSPA is tilted up for broad coverage while LTE is focused down at the local vicinity.

9.5. REMOTE RADIO HEADS FOR MIMO

Remote radio heads (RRH) also known as remote radio units (RRU), are currently being deployed not just for new technologies (such as LTE) but also in new and replacement infrastructure using older technologies (2G, 2.5G, 3G), primarily for reasons of lower capital and operating expenditures. The deployment of remote radio heads is accelerating as system operators become more comfortable with the reliability of the equipment, and are prepared to move the transmit and receive electronics close to the antenna(s) in each sector. In some cases, where there is not high confidence in the reliability or for other reasons, RRHs are deployed at ground level and traditional coaxial feeders are used to connect to the antenna(s). These ground level remote radio heads are also called transmitter-receiver duplexer units or TRDU, also known as a Radio Unit (RU).

9.5.1. REMOTE RADIO HEADS AND TRANSMITTER-RECEIVER DUPLEXER UNITS

The major components of an enhanced Node B (eNB) include the transmitters and receivers (transceivers), power amplifiers, duplexers, antennas, low noise amplifiers (LNAs), operations and management (OA&M) controllers, antenna controllers, and baseband processing units. Traditionally the majority of the components of an eNB reside in a shelf at the base of the tower. RF cables are used to connect to the antennas at the top of the tower.

Transmitter-Receiver Duplexer Unit

The TRDU is a shelf-mounted module that integrates several functions of the eNB and is typically located near the base band unit in the eNodeB cabinet. In a typical implementation, the TRDU includes the transceivers, power amplifiers, antenna controllers, and duplexers. The TRDU is connected to the baseband processing unit via a high-speed optical serial interface and connected to the antenna via RF cabling. Forced air-cooling is employed in the eNB shelf

Remote Radio Head (RRH)

A RRH, also known as a Remote Radio Unit (RRU), incorporates much of the same functionality as a TRDU. However, the RRH is a pole-mountable, weatherized, self-contained module that uses natural convection cooling. In a typical installation, the RRH is installed close to the antennas at the top of the tower with minimal RF cabling.

Figure 68 shows the block diagram of a TRDU/RRH with two transmitters and four receivers. The interface to the baseband processing unit is a high-speed optical interface (here a CPRI interface is shown). The interface board in the Figure incorporates some of the control functions such as antenna control (AISG) and alarming.

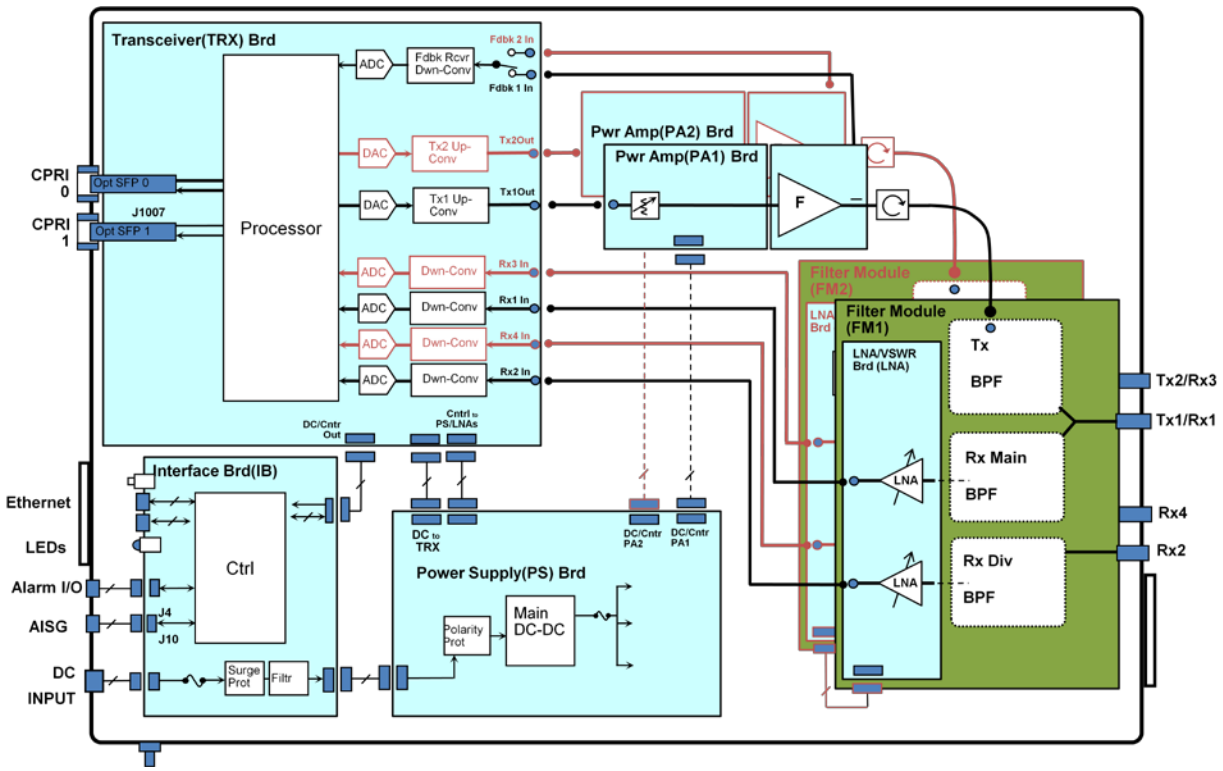


Figure 68. Block diagram of a RRH/TRDU.



Figure 69. Examples of Remote Radio Heads with two transmit and receivers and with one transmitter and two receivers.

9.5.2. REMOTE RADIO HEAD ADVANTAGES AND CONSIDERATIONS

Remote radio heads have several advantages over traditional Node-B architectures.

- **Site Footprint--**Since they are mounted directly on a pole, they require little or no site footprint. This can significantly reduce capital expenditure by reducing site planning and maintenance costs
- **Power Consumption--**The proximity of the transmitter to the antenna can minimize feeder cable losses and thus improve the overall base-station power consumption.
- **Receiver Performance--**The proximity of the receivers to the antennas also improves the sensitivity and noise figure of the receivers.
- **Flexible Network Coverage--**Limited site space availability in some areas can prevent the installation of a traditional BTS. An RRH can fill such coverage holes.
- **MIMO Capability--**The gains, phases, and delays of each individual carrier and/or the composite signal in each transmitter and receiver in a RRH can be digitally adjusted. Each RRH also has a measurement receiver that is used to calibrate the digital pre-distortion algorithms. The measurement receiver can be used to make accurate measurements of the gains, phases, and delays of each transmit path. These features enable easy implementation of MIMO and SIMO processing architectures with RRHs.
- **Daisy-chaining RRHs--**Multiple RRHs can be daisy-chained using the optical interface and programmed to operate in a coordinated manner. This feature can be used to increase site capacity and coverage. It can also enable higher order MIMO and SIMO systems. For example, an RRH with two transmitters and two receivers can support a 2X2 MIMO system. Daisy chaining two such RRHs can enable a 4X4 MIMO system.
- **Reliability--**RRHs and TRDUs are inherently more reliable than traditional eNBs because of the integration of several subsystems in a single functional unit. RRHs, which are convection cooled, are less reliable than TRDUs, which are cooled using forced air. Innovative thermal designs and highly efficient amplifier designs have significantly improved the reliability of RRHs.
- **Installation--**A typical RRH can weigh 15-20 kg. Rooftop installations of RRHs are simple and straightforward. Tower-tops installations are more complex and require planning for tower climbs.
- **Weatherization--**Unlike a sheltered shelf RRHs are exposed to the elements. Damage, performance degradation, and failures can result from improper mechanical design. Therefore, careful thermal and mechanical design is required to ensure proper weatherization.
- **Battery Back-ups--**Though an RRH can be installed at the top of a tower, battery back-ups will still be required for emergency operation. Most battery back-up systems will require some site footprint. Innovative solutions for the installation of battery cabinets near the RRHs are now available.

9.5.3. REMOTE RADIO CONFIGURATIONS

Currently, RRHs are being deployed in multiple frequency bands, across several power levels and in various configurations.

Frequency Bands

UMTS (Node B) RRHs are commonly deployed in 2100 MHz and 900 MHz. RRHs to support the LTE trials in North America have been deployed in the 700 MHz and 800 MHz bands. Several LTE deployments in 2600 MHz are also underway. Additional frequency bands with early LTE deployments include 1500 MHz in Japan and 2300 MHz and 1.8 and 2.3 GHz in China with TDD-LTE installations.

The bandwidth of operation of the Remote Radio Heads is typically limited to 20 to 30 MHz in which multiple carriers can be located.

Power Levels

Macro cell installations with transmitter powers ranging from 10 Watt – 60 Watt are most common in initial deployments. Micro cell installations with power levels per transmitter ranging from 1-5W shall follow the macro cell installations. Multiple transmit ports typically divide the overall transmit power so there are 1 TX x 60 Watt and 2 TX x 40 Watt units as well as 4 TX x 10 Watt units.

Transmitter-Receiver Branches

At 700 MHz a 2X2 configuration (two transmitters and two receivers) is most common. A 2X4 configuration is preferred at higher frequencies like 2600 MHz, 2300 MHz, 1500 MHz, 1800 MHz, 1900 MHz, and 2100 MHz. As described earlier, multiple RRHs can be combined to form other configurations such as 4X4 and 4X8. At 2300 MHz, an 8X8 installation for TDD-LTE is expected to be widely deployed.

Air Standards/Multi-Standard

Currently RRHs are widely deployed in all major air standards such as GSM, CDMA2000, UMTS, WiMAX, and LTE. Most RRHs will be capable of supporting multiple air standards in one unit. Common multi standard implementations include LTE+UMTS, LTE+CDMA2000 or LTE+UMTS+GSM. An LTE+CDMA2000+UMTS configuration is expected to be less common. RRHs shall be software configurable and capable of supporting any carrier combination with these multiple standards.

Interface Standard

The optical high-speed serial interface between the baseband processing unit and the RRH/TRDU typically use the Common Public Radio Interface (CPRI) standard or the Open Base Station Architecture Initiative (OBSAI) standard. Current RRHs support data rates up to 6.144 Gbps. It is expected that the next generation of RRHs will require line rates up to 12.2288 Gbps or higher.

This data rate on the high-speed serial interface reflects the maximum bandwidth of the spectrum transmitted and received by the Remote Radio Head/Unit as well as the number of branches, and the number of units that may be daisy chained with one optical high speed interface.

FDD vs. TDD

Most RRHs deployed support FDD (Frequency Division Duplexing). However, RRHs also support TDD (Time Division Duplexing) for WiMAX (licensed and unlicensed bands) and LTE (2300 MHz).

Efficiency

The efficiency of an RRH is defined as the RF output power delivered divided by the DC input power. At macro power levels, the power amplifier is the largest contributor to the overall power consumption of the RRH. This is not to say

that the power consumption in the other subsystems is negligible. The power consumption in the digital subsystem can be significant (20-30 W) and this is especially critical for micro RRHs.

9.6. FEEDER CABLE FOR REMOTE RADIO HEADS

A perennial challenge in placing antennas at appropriate heights has to do with the costly, bulky and lousy coaxial cables. There are often many tens of meters of cable connecting the antennas and the radio transmitters, which are often located in climate-controlled enclosures on the ground near a tower base or in a central location either on the roof of a building or on a lower floor.

So-called "hard line" coaxial feeder cable is typically 7/8" to 1-5/8" or even thicker is used for long straight runs, such as up a tower, with more flexible and thinner jumper cables making shorter connections to the antenna itself on one end and to a lightning arrester and the base station on the other end. These cables along with their connectors, lighting arresters and sometimes combiners, often contribute 2.5 to 3.5 dB of RF power losses, requiring an amplifier twice as powerful (and consuming twice as DC power) as strictly required at the antenna. In addition, these cables add weight and wind load to a tower or mast installation.

In contrast is a remote radio head installation. The remote radio heads use fiber optic cable, either single-mode or multimode, for the transmit and receive signals, and they require power of course. The power is typically 48V DC, but some equipment is AC powered. Installed systems to date have used separate fiber and power cables, often installed in conduit for mechanical protection and electro-magnetic shielding against lightning strikes.

Here we compare the relative weight and wind load of Remote Radio Heads (RRHs) as opposed to running coaxial cables up a mast. For example, we consider the weight and wind load for a 4 branch per sector installation on a 30 m mast[2]. Using the common 1-1/4" LCF114 cable, three sectors would contribute over 310 kg of mass on the tower or 680 pounds. Cable strain relief mounting hardware placed the recommended 4 feet and cable hoist add a minimum of 20 kg depending upon the type of hardware used. The sum total static load on the 30 m tower is therefore at least 330 kg (727 lbs). A remote radio head, on the other hand, typically weights about 17 kg but with mounting hardware, power and fiber takes about 25 kg, which is 13 times **smaller** than the coaxial cables that the RRH can replace. Two branches per sector would of course have half this weight or 155 kg and would mean that the 2 cables per RRH would weigh over 6 times that of the RRH.

Cables are typically run up a mast along a cable run with stress relief clamps that hold the cables adjacent and parallel to each other. To reduce wind load, the cables are run up a tower in a 2 x 6 cable arrangement with space between the cables. Consequently, the maximum wind load is when the 2 rows of 6 cables are facing the wind with an effective area of 0.234 square meters per meter of height, 7 m^2 for the full 30 m height.

The IEC 721-3-4 standard indicates a peak wind burst of 50 m/sec (180 km/hour) be considered; corresponding to the 3-second gust wind speed measured at 33 ft. above ground. [IEC72134]

The EIA/TIA-222-G standard [TIA222G] prescribes tables and equations for calculating the wind load as a function of height above the ground, so that the relative torque and twist on a mast can be evaluated. Assuming the default values of Topographic and Exposure categories corresponding to a flat field, the force on the cable versus 3 RRHs are shown in Figure 70. The wind velocity varies with the height and so the force is shown for every 1-meter section of cable.

[2] Civil and structural engineers make a distinction between a self-supporting tower such as monopole while a mast uses guys or stays anchored into the ground for lateral support. Masts require an extended area surrounding them to accommodate the stay blocks. Towers are more commonly used in cities where land is in short supply.

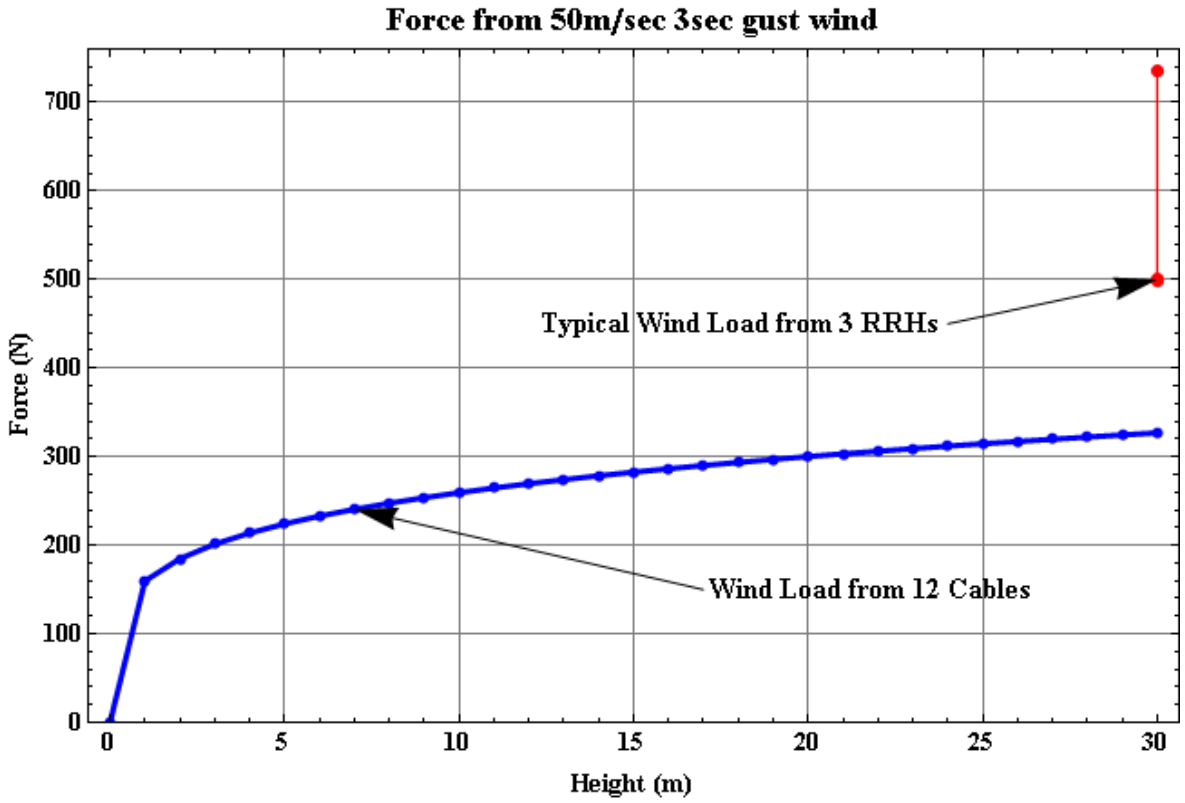


Figure 70. Force on the cable vs. remote radio heads on a typical mast. this is assuming the 1-1/4" cables are stacked two by six. the remote radio heads ranged from 12 kg to 20 kg and from 0.12 m^2 to 0.18 m^2.

The weight and moment (torque) resulting from this wind load (described above) integrated over the 30 meters of mast height are tabulated below:

	Twelve 1-1/4" LCFS114 Coax Cables For 4 branches/sector	6 Typical 2xpol Antennas	3 Typical Remote Radio Heads
Weight	330 kg	2x3x 15 kg = 90 kg	3x 17 kg = 51 kg
Moment	136 kNm	120 to 170 kNm	15 to 22 kNm

The representative antenna had an area of 0.48 m^2 and the Remote Radio Head (RRH) was exemplified with an area of 0.118 to 0.18 m^2. The moment is generally proportional to the area and to the square of the wind velocity. Keep in mind, too, that 2 branches per sector would amount to half the weight and as half the moment.

In addition, ice can accumulate on the cables and hardware, doubling the weight and adding to the effective area. In Table C.1 of the TIA-222-G standard, the impact of two different thicknesses of ice is prescribed for a 9-antenna configuration along with nine 1-5/8" cables configuration. This is a composite of all the antennas and cables together. (Note that the cables here are larger than the earlier example.)

Table 4. Example wind load for a nine-antenna (and nine-cable) tower with ice loading.

	No Ice		ICE T ≤ 0.5"		ICE 0.5" ≤ T ≤ 1.5"	
	Eff. Area	**Weight**	**Eff. Area**	**Weight**	**Eff. Area**	**Weight**
9 antennas 9 1-5/8"	6.5 m^2	337 kg	7.9 m^2	337 kg	10.2 m^2	693 kg
Scaled 6/9	4.3 m^2	225 kg	5.3 m^2	225 kg	6.8 m^2	462 kg
Moment	182 kNm		222 kNm		285 kNm	

The important comparison is that remote radio heads have less than 1/13 the weight and 1/6 to 1/9 the moment in high wind bursts. Icing and larger cables such as 1-5/8 inches make the comparison even more strikingly in favor of RRHs.

Both self supporting and guyed masts are susceptible to ice and wind, but of course monopoles with cables inside the single hollow tube, shield the cables from icing and wind, but in monopoles, access to the cables is more difficult and constrained by size limits as all must fit through access holes such as those in the following photo.



Figure 71. Photograph of the constrained access panel for running coaxial cable into a monopole.

In those cases where the lease agreements on the mast charge explicitly by static weight or wind load, the RRHs have a clear advantage, but the physical size of the RRH (though smaller than typical antennas) is occasionally an issue. On the other hand, maintenance and upgrades to an RRH can also present some difficulties due to the required tower climb. Therefore, making the RRHs robust and "future proof" with versatile software is a priority.

Moreover, when placing an RRH next to the antenna, the 2.5 to 3.5 dB of cable loss is reduced to less than 0.5 dB, which can be used to either increase the transmitted power by 3 dB (doubling the power) or it can be used to reduce the power requirements on the amplifier, thus reducing the power consumption of the base station. When multiple carriers can be configured within the operating bandwidth of the RRH, the reduced RF losses can potentially permit about twice as many carriers at their full power.

While Remote Radio Heads (RRH) can be placed either near the antennas or on the ground with traditional cables running the distance to the antennas, the most appropriate configuration is unclear. Active equipment such as RRHs and Tower Mounted Antennas require "tower climbs" to repair or replace and requires that other sectors be turned down when field service engineers are working nearby. Upgrades to add additional power amplification or bandwidth beyond that originally provided by the RRH may require tower climbs to upgrade services, and some lease agreements require renegotiation when equipment of a different size/weight/appearance is installed.

9.6.1. HYBRID FIBER/COPPER REMOTE FIBER FEEDERS

Now available are armored cables, remote fiber feeders (RFF), combining the fiber and power elements in a single construction. A typical cable is shown in Figure 72. The cable consists of two fiber cable subunits each containing either 2, 4 or 6 tightly bundled fibers, which can be either single-mode or multimode. These are stranded around a central strength member along with three power conductors (positive, negative, ground). Around this stranded core is a water-blocking tape, ripcord, outer shield/armor and the outer jacket. The conductor sizes are either 8 AWG or 10 AWG, depending on the power requirements of the Remote Radio Head Units, and the outer jacket can be either outdoor grade black polyethylene, for tower and monopole installations, or a low-smoke zero halogen compound for building installations.

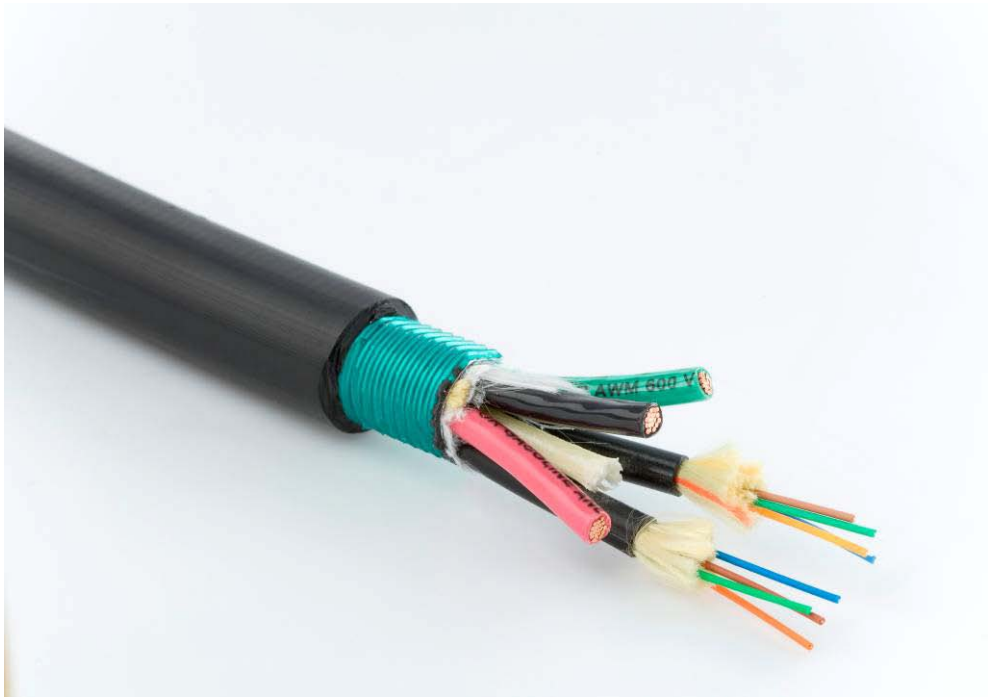


Figure 72. Hybrid Fiber/Copper Cable.

These cables are typically installed one per sector between the main unit and the remote radio heads. Other configurations are possible, however, depending on the power consumption of the remote units and the associated voltage drop across the remote feeder. For example, a single cable might feed a remote unit at the top of a tower, which contains the radios for all three sectors. These would then connect to the antennas with regular coaxial cables.

Multiple fibers allow for flexibility, redundancy and future-proofing of installations. Any or all of the fibers in one or both fiber subunits can be terminated with appropriate fiber connectors. Alternatively, the appropriate fiber and copper "break-outs" can be made and some fibers left to be terminated at some later date.

These cables, being a stranded construction, also allow the possibility of including additional elements such as an RET control cable, or an alarm cable, in custom designs.

9.6.2. ASSEMBLIES

Because the sizes are so small, correct termination of fiber optic cables requires more specialized tools and equipment and a higher skill level than does termination of coaxial cables. For this reason, fiber cables used with remote radio heads up to now have usually been pre-terminated assemblies. It is expected that the same will be true for the remote fiber feeders, at least for initial deployments. However, as this technology becomes more widespread there will likely be a requirement for field termination of fiber cables.

A typical breakout and termination scheme is shown in Figure 73. The outer shield and jacket are stripped back to the required lengths (say 0.5 m at the RRH end and 1 m at the main unit end) to expose the power conductors and one or both fiber subunits. The power conductors can be enclosed in heat-shrink or other tube material, and the main breakouts are sealed with epoxy and heat-shrink, which provides mechanical support and water blocking. The tightly-

bundled fibers are individually broken out from the subunit cable a few inches from the ends, and terminated with suitable connectors per the equipment interfaces. Dual LC connectors seem to be the most commonly used currently.



Figure 73. Breakout and Termination Scheme.

9.6.3. LIGHTNING PROTECTION

The outer shield on the Remote Fiber Feeder (RFF) cable provides basic support and mechanical protection, but also acts as a lightning shield. Power cables for outdoor installations often require electro-magnetic shielding outside the conductors to reduce the induced transients on the conductors and minimize the possibility of damage to the electronic equipment, even though this may include integral or added surge suppression. The shields on the RFF feeders will withstand simulated strike currents in excess of 100 kA with no damage to the cables. This is also a typical value for coaxial cables.

9.6.4. ACCESSORIES

Hoisting grips, hangers and ground straps are available for the remote fiber feeder cables, and continue to be developed. Typical accessories are shown in Figure 74. These are similar to, and in some cases identical to, standard accessories for coaxial cables with which the installation community is familiar.



Figure 74. Accessories.

9.6.5. ADVANTAGES OF REMOTE FIBER FEEDERS

There are a number of advantages in using the combined fiber/copper remote fiber feeders, compared with the separate fiber and copper cables used up to now.

- Lower total material and installation costs. No conduit required.
- Ease of handling. One cable per sector. Ease of routing.
- Environmentally and mechanically protected.
- Reduced tower loading.
- Reduced tower real estate cost.
- Standard coaxial accessories.

9.7. CO-SITING OF MULTIPLE BASE STATIONS AND TECHNOLOGIES

9.7.1. SEPARATE FEEDERS FOR EACH SYSTEM

In an ideal world, each base station and air interface technology deployed on a cell site would have its own feeders and antennas. This would have several benefits:

- Individual optimization of antenna pattern, azimuth direction, and down tilt for each service.
- Minimum RF path loss and mismatch.
- Reduced concerns for interference and intermodulation between systems.
- Maintenance work on one system need not impact other services.

However, a number of constraints influence the site architecture and reduce the system designer's options. In most situations, factors that must be considered include:

- Zoning restrictions on the quantity and design of antennas and other equipment.
- Limits on weight and wind loading of feeders and tower mounted equipment.
- Cost savings opportunities on capital expenditures, lease costs, and installation labor.
- Time to market requirements for rollout of new services.

A variety of co-siting solutions have been developed to address these constraints while enabling efficient operation of multiple technologies in a shared architecture. Today, these solutions are widely used within major carriers' networks and competing operators have also joined together to reap the benefits of sharing site equipment.

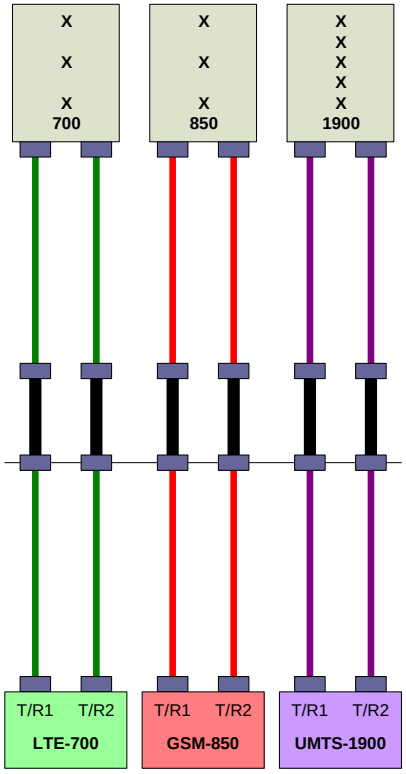


Figure 75. Multiband sector with separate feeders.

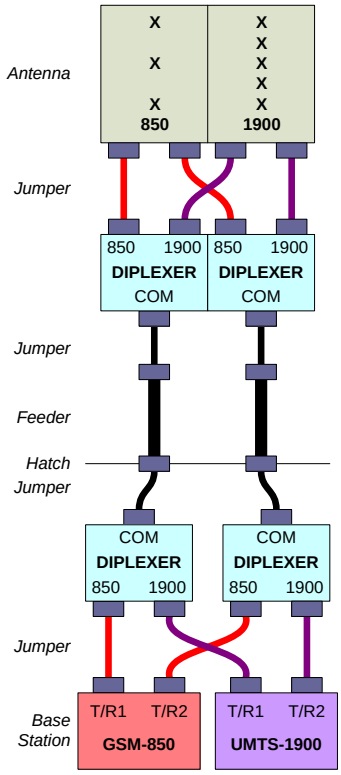


Figure 76. Shared feeders using diplexers (crossband couplers).

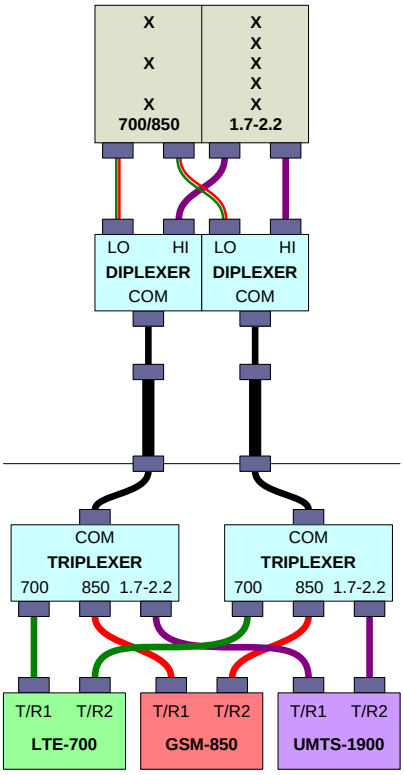


Figure 77. Shared feeders and antennas using triplexers and broadband antennas, diplexers.

9.7.2. SHARED FEEDERS—FREQUENCY MULTIPLEXING

Feeder cables are generally suitable for any frequency band and air interface technology and can therefore easily be shared. By combining services at the foot of the tower and again separating them just below the antennas, the benefit of individual antenna optimization is retained while reducing the number of feeders. Existing feeders can be used for additional frequency bands, helping accelerate rollout of new services.

Two or more frequency bands are combined or separated using Crossband Couplers. According to the number of paths combined, they are also known as Diplexers, Triplexers, etc. When the frequency separation between the bands combined is relatively wide, such as between 700 MHz to 1000 MHz, 1700 MHz to 2200 MHz, and/or 2400 MHz to 2700 MHz, crossband couplers can be compact, low cost devices while introducing almost negligible loss and mismatch. When combining more closely spaced bands, for example a 700 MHz band with another in the 850 MHz range, the components need to become somewhat larger and more complex in order to maintain acceptable performance.

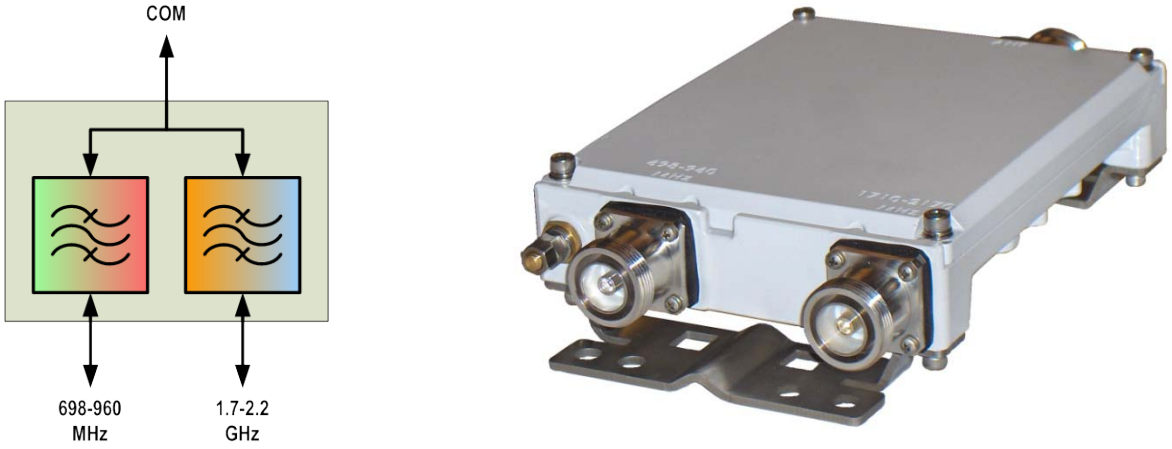


Figure 78. Diplexer.

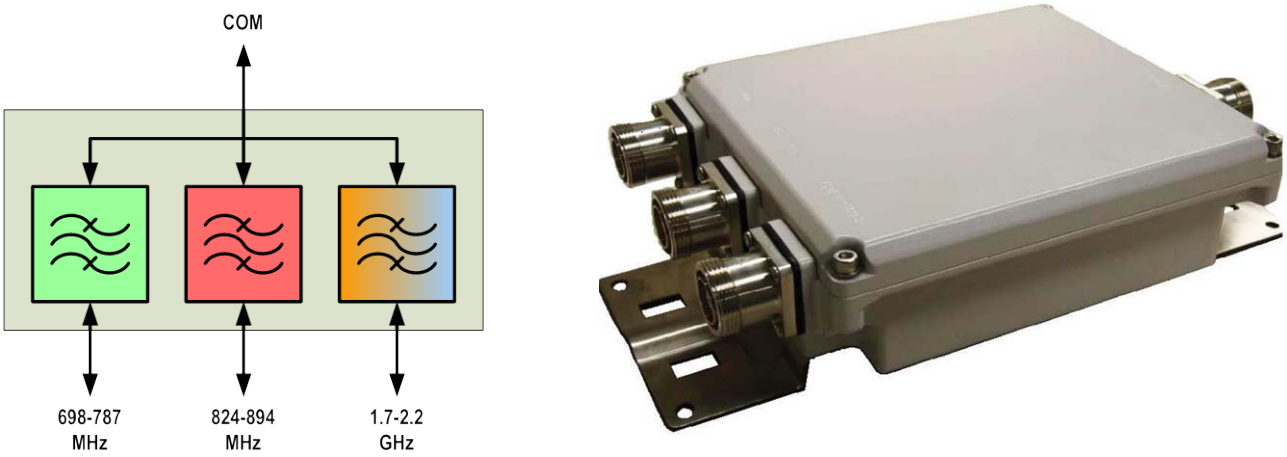


Figure 79. Triplexer.

9.7.3. SHARED ANTENNAS

Where individual antennas for each band and service cannot be installed, multiport and multiband antennas are used. This typically restricts the azimuth angle to be the same for all bands while beam tilt can be set independently for each antenna port or pair of ports. Crossband couplers or dual band TMAs are most often used to separate the bands below the antenna. However, multiband antennas (mainly dual band) with built in crossband couplers are also available on the market. These provide a very clean installation but with the disadvantage of not being able to support a TMA on one of the frequency bands.

Using broadband antennas specified for, e.g., 1700 MHz to 2200 MHz, more than one band and service can be combined on a feeder and connected to a single antenna port. Antenna selection and adjustment may then involve a compromise that is acceptable albeit less than optimal for each service sharing the antenna. Technologies are available that allow individual beam steering but they come at additional cost and complexity.

9.7.4. SHARED FEEDERS AND ANTENNAS—SAME BAND COMBINING

When two or more services or operators share the same license band, regular crossband couplers cannot be used. In this situation, other solutions are available as described below. Same band combining is also often used with a single service to combine base station ports or cabinets when the channel count exceeds the capacity of a single unit. In Frequency Division Duplex (FDD) wireless systems, same band combining always involves distributing the uplink (RX) signals from shared antennas to multiple receivers and may also include combination of multiple base station transmitters to an antenna for the downlink (TX).

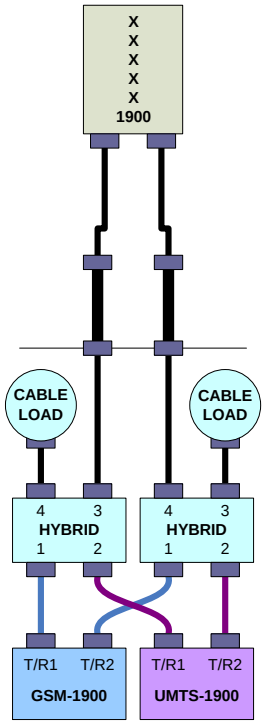


Figure 80. Hybrid Combining Cable Load Used to Ensure Low Passive Intermodulation.

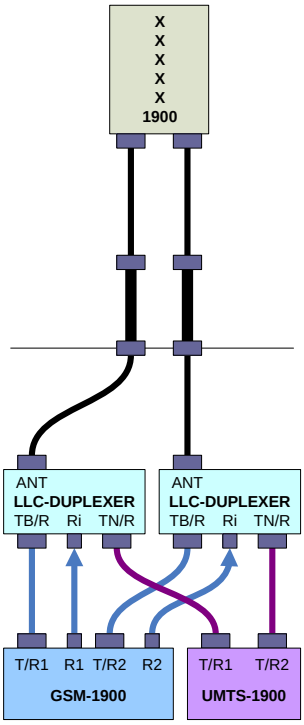


Figure 81. Low Loss Combiner (LLC) with Integrated Duplexer. RX Distribution Provided from GSM BTS.

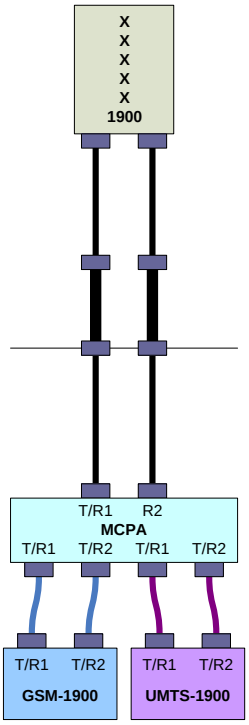


Figure 82. Multi-Carrier Power Amplifier (MCPA) with integrated RX distribution.

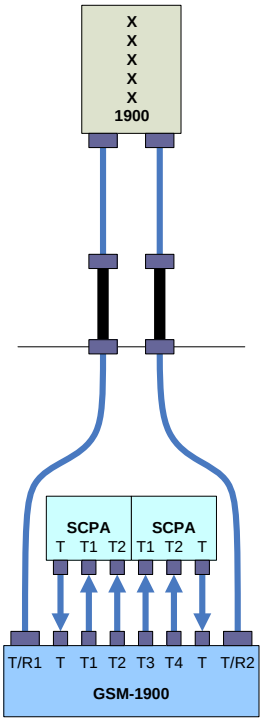


Figure 83. Single-Carrier Power Amplifier (SCPA) installed between radios and bts duplexer.

9.7.5. HYBRID COMBINING

Hybrid combiners provide a low cost method to simultaneously combine TX signals and divide RX signals. The main disadvantage is the high loss incurred in both directions, which increases steeply with the number of ports combined. When used with typical TX power levels, there is significant heat dissipation that must be managed. Therefore, this

solution has limited popularity in cell site situations and is rarely used to combine more than two ports. It is more widely deployed for in-building coverage and similar applications.

9.7.6. LOW LOSS COMBINER—MULTIPLEXER

The Low Loss Combiner (LLC) is an alternate method to combine base station transmitters. Insertion loss in the LLC is significantly lower than in a hybrid combiner and it is less expensive compared to power amplifiers. On the downside, the LLC places constraints on the frequency ranges available to each system being combined.

Like a crossband coupler, an LLC is a filter multiplexer. While the former combines frequency bands spaced apart fairly widely, the frequency ranges combined in an LLC are all in the same band, leading to very small gaps– guard bands – between the ranges.

In some applications, guard band spectrum must be left unused and in order to minimize waste, the LLC is required to accommodate the smallest guard band possible without compromising insertion loss or distorting the signals. Such requirements lead to designs of increased size and cost. In other cases, the guard band spectrum can be reused on a second feeder and antenna. Thus, the LLC specifications may be relaxed and more economical design options can be chosen.

The LLC apportions a part of spectrum to each system. Future growth and de-growth, and other spectrum redistributions will require reconfiguration, retuning, or replacement of the LLC. Remotely tunable equipment has been introduced to partially alleviate these restrictions.

While LLCs are primarily employed for downlink combining, a corresponding filter multiplexer can also serve to distribute uplink signals. It holds the advantage of not requiring supply power but is overall less popular than the receiver multi-coupler method described below.

Some base stations on the market also have the ability to distribute part of the signal from each RX branch after the receiver LNA. This makes it possible to design a smaller combiner unit without the need for other compensation of uplink combiner loss.

9.7.7. SINGLE CARRIER POWER AMPLIFIERS (SCPA)

Preceding a hybrid combiner, an SCPA compensates for the combining loss. Being a non-linear amplifier, an SCPA can itself be quite energy efficient but is suitable only for GSM and some similar technologies. Overall efficiency is reduced by hybrid losses and need for heat management. The relatively simple amplifier circuits moderate unit cost.

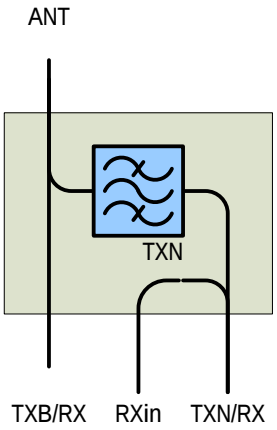


Figure 84. LLC combines narrow portion of TX band into broadband path. Includes duplexer for RX re-injection.

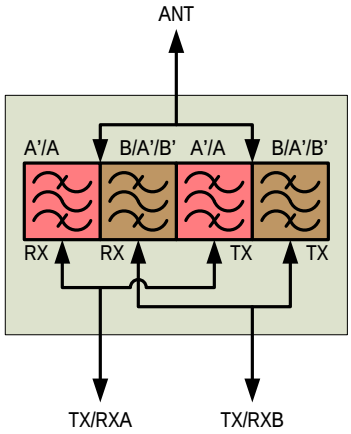


Figure 85. Filter multiplexer for downlink and uplink-- quadriplexer.

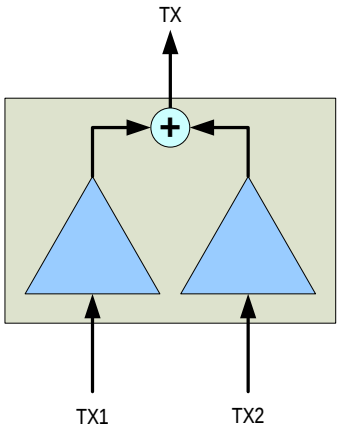


Figure 86. SCPA module amplifies and combines two transmitters into one path.

9.7.8. MULTI-CARRIER POWER AMPLIFIER (MCPA)

The MCPA is a high power linear amplifier capable of combining and amplifying multiple RF carriers into a single output. An MCPA usually includes one or more amplifier "bricks" that work in parallel to provide the needed output power. Input circuits can be expanded to accommodate from two up to eight or more ports. Integrated duplexers route the uplink signals around the MCPA and RX amplification/distribution can be incorporated.

Advantages of the MCPA include the ability to boost downlink power for increased coverage and/or capacity as well as complete frequency agility, placing no restrictions on what channel frequencies are used within a license band. They can be used with any air interface technology, even combining multiple technologies. On the other hand, large MCPA systems can entail a significant investment and they are not very energy efficient.

Modern base stations, such as for UMTS and LTE, mostly include MCPAs as an integrated part of the Radio Unit. Here the Power output of the PA is closely monitored and adapted to current traffic situations as part of the overall base station performance management. As an external MCPA will be connected outside of this monitor and control loop it is less suitable for co-siting with this type of base stations.

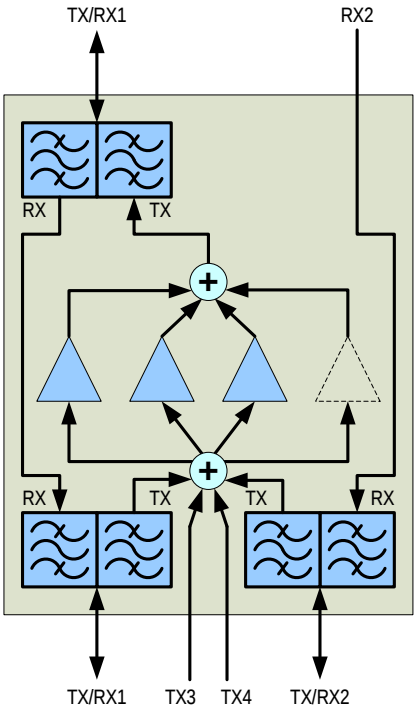


Figure 87. MCPA for one sector with two duplexed inputs and two simplex inputs, three bricks installed.



Figure 88. MCPA for three sectors, two duplexed inputs and six simplex inputs per sector, one PA brick per sector, and one hot standby brick.

9.7.9. RECEIVER MULTICOUPLER

A Receiver Multi-coupler (RXMC) distributes uplink signals from shared antennas to multiple receivers. A power splitter divides the input signal to a number of output ports. Preceding the power splitter, a Low Noise Amplifier (LNA) compensates the splitting loss, preserving uplink sensitivity. At the input to the LNA, a preselector filter may be integrated with the RXMC or exist as a part of other site equipment.

Characteristically, the RXMC distributes the full RX frequency band to all outputs. The net gain or loss is often the same for all outputs but unequal division is also a design option where the RXMC serves receivers with differing input level requirements or where the signal will be further divided before reaching the receivers.

For applications with few outputs – usually just two – a power splitter without LNA is sometimes used.

9.7.10. INTEGRATED DEVICES—SAME BAND COMBINER

The generic term Same Band Combiner (SBC) refers to a device that passes uplink and downlink signals, incorporating some combination of same band transmit combining and/or receive signal distribution using any of the methods described above, excluding power amplifiers. The configurations vary with application.

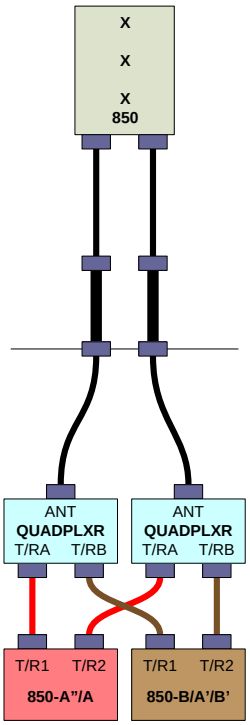


Figure 89. Antenna sharing using TX/RX quadriplexer.

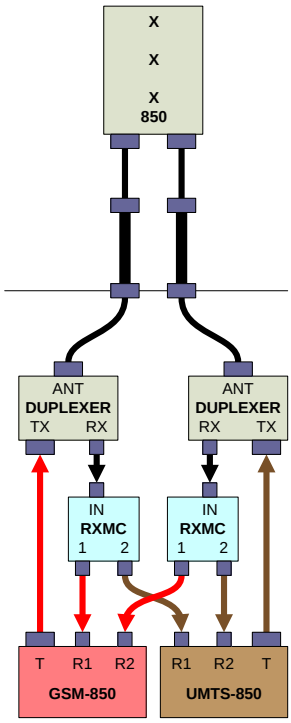


Figure 90. RX distribution to simplex BTS using duplexers and RXMC.

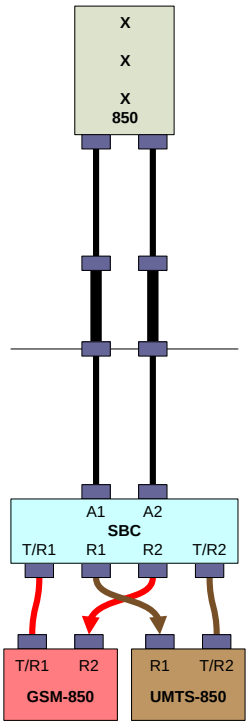


Figure 91. Antenna sharing using integrated SBC.

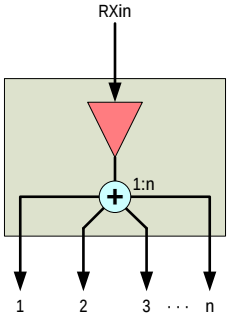




Figure 92. Dual RXMC with Eight Outputs per Cannel.

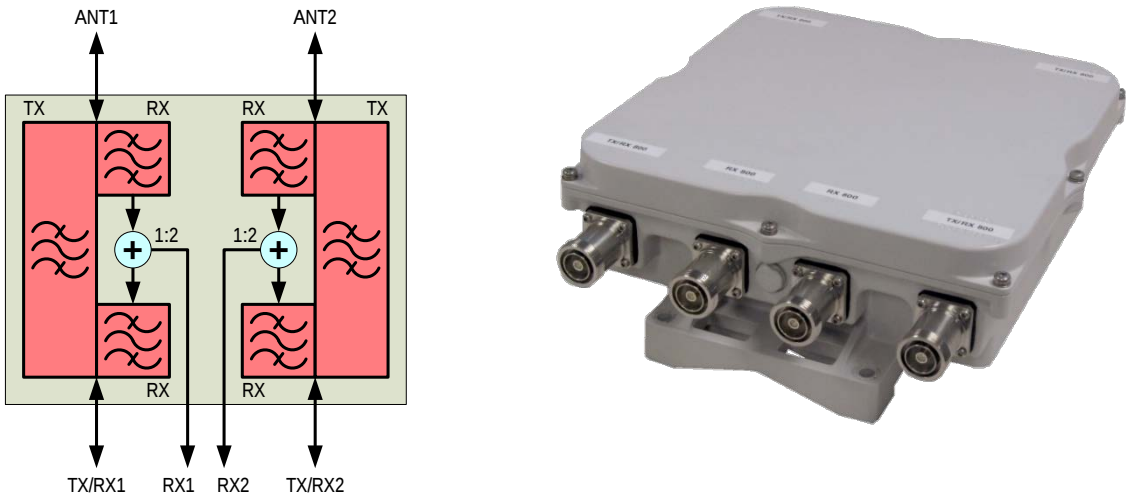


Figure 93. Integrated Same Band Combiner (SBC).

9.7.11. TOWER MOUNTED AMPLIFIERS

A Tower Mounted Amplifier (TMA) is installed near the receiving antenna. Its purpose is to boost the uplink signal before it is degraded by losses in the RF path to the receiver, thereby improving signal quality and base station sensitivity.

9.7.12. BENEFITS OF TOWER MOUNTED AMPLIFIERS

TMAs provide benefits for all air interface technologies. Their fundamental effect on the uplink is an improvement in carrier-to-noise ratio (C/N). Improvement of around 5-6 dB is typical but the amount varies according to RF path configuration. This additional link budget margin can be utilized to improve various network performance parameters such as:

- Coverage – in terms of cell radius as well as weak spots and indoor locations
- Accessibility – failed access attempts
- Retainability – dropped call rates
- Co-channel interference – call capacity in spread spectrum systems
- Data throughput – enabling higher order modulations
- Average handset output power – battery drain

Adjusting base station settings, the operator can optimize between the available benefits to obtain the best overall Quality of Service (QoS).

9.7.13. CONFIGURATIONS

The key element in the TMA is the Low Noise Amplifier (LNA). It is always preceded by a preselector filter. Today's TMAs are universally of the dual duplex type, which allows use in duplexed feeders. Thus, two additional filters are included to pass the downlink and isolate the LNA. Most often, the filter bandwidths cover a full license band but other variants occur, including filters with additional out-of-band rejection to improve BTS interference immunity.

A TMA can be a single band device as above. Increasingly, single-band TMAs are provided as integrated pairs in dual, or twin, assemblies in order to reduce cost, weight, and the number of devices on the tower.

Dual band TMAs combine two single band TMAs in one device. There may be a separate RF path for each band or they may be diplexed into a single path at the BTS port and/or ANT port. Diplexers can also be integrated with single band TMAs creating units with non-amplified RF paths often referred to as bypass or pass-through configurations.

Deployment of additional license bands is leading to further consolidation into TMAs supporting more than two RF paths and frequency bands, again driven by efforts to avoid additional units of tower mounted equipment.

9.7.14. ENHANCED FEATURES—AISG

The Antenna Interface Standards Group (AISG) is an organization whose membership includes the majority of leading wireless equipment manufacturers and many major wireless operators. Since its foundation in 2001, AISG has driven the development of a protocol for communication between base stations and tower top equipment, including antennas, TMAs, and other devices. The universally adopted AISG protocol facilitates control and monitoring of functions such as antenna down tilt and TMA alarms.

Early implementations utilized separate cables for the connection between base and tower. More recently, a system is increasingly favored where the signals are borne by a 2 MHz carrier on one or more feeder cables. The components in the RF path must then be designed for compatibility with AISG communication whether they process the signals or simply pass the low frequency carrier for example crossband couplers may have DC and control signal bypass or block on one or more of their branches.

The AISG protocol provides a platform for implementation of advanced features in tower top equipment, allowing better performance optimization and diagnostics while ensuring interoperability between any devices supporting the standard. Adding remote connectivity to the AISG system will also reduce the frequency of site visits, having beneficial impact on the operating budget.

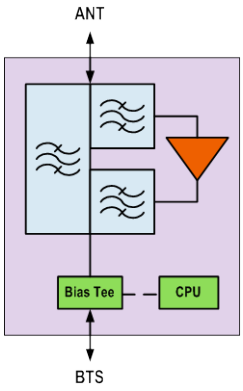


Figure 94. Single band TMA.

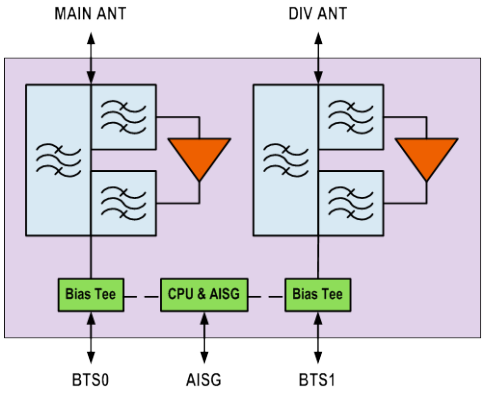


Figure 95. Twin single band TMA with AISG support.

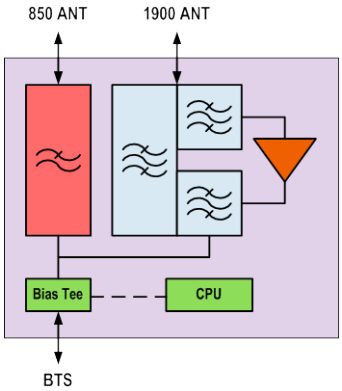


Figure 96. TMA with integrated diplexer.

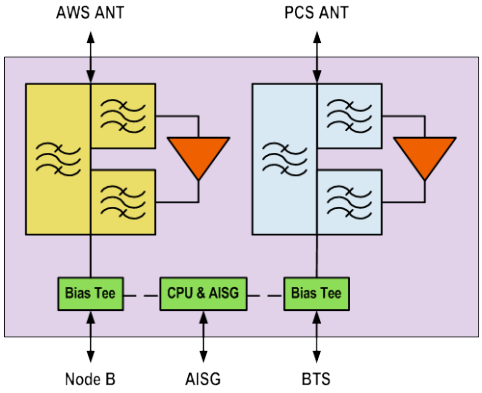


Figure 97. Dual band TMA with AISG support.

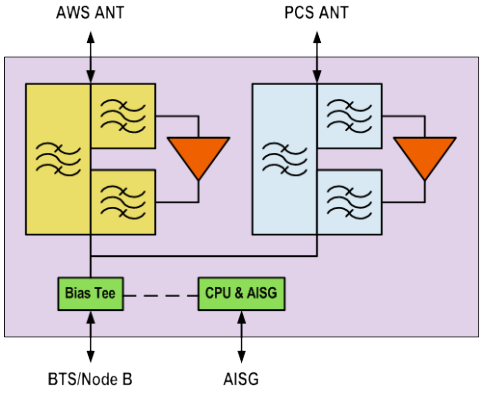


Figure 98. Diplexed dual band TMA with AISG support.

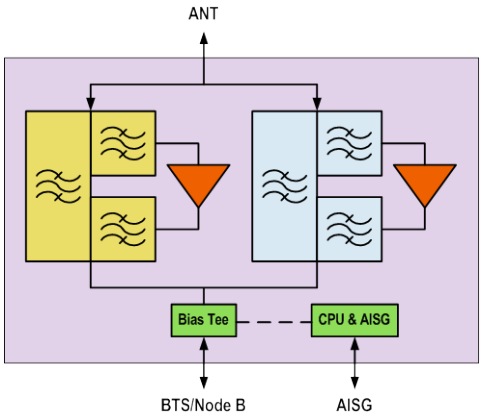


Figure 99. Dual diplexed dual band TMA with AISG.

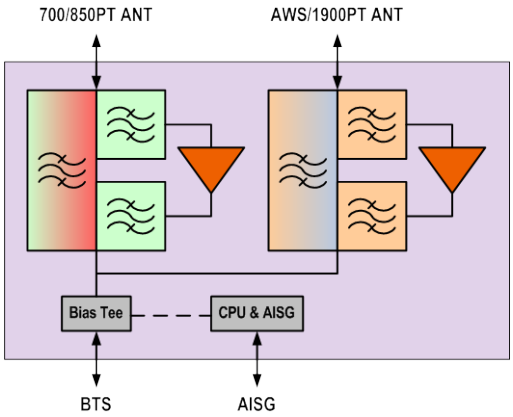


Figure 100. Diplexed dual band TMA with pass-through and AISG.

9.8. MIMO CAPABLE DRIVE TEST EQUIPMENT

9.8.1. DRIVE TEST OVERVIEW

Users of wireless networks are by nature mobile. Whether riding in moving automobiles, walking through shopping centers, running through airports, or traveling in mass transit vehicles, wireless customers expect their conversations to be uninterrupted and their data devices to remain connected. Mobile test systems both drive and walk-test are required in order to replicate the user experience when measuring network performance. These mobile test systems record measurements tagged with time and position to zero on the exact locations of network problems and the time of day those problems occur. Fixed location measurement systems simply are not up to the task.

The scope of drive testing may include optimizing and maintaining a service provider's own network or may extend to measuring and evaluating the competitor's networks as well. As major carriers compete for customers by featuring coverage maps as a major component of their advertising campaigns, an accurate picture of the coverage and capabilities of all competing networks in a region has become an economic necessity.

Typical benchmark drive test systems consist of the measurement platform connected to UE devices such as phones and wireless data modems assigned to the various service provider networks in a region as well as network independent digital scanning receivers. The test devices are generally directly connected to the personal computer running the measurement software by Universal Serial Bus (USB) cables for small to moderate size systems. For larger benchmark systems, a hardware platform is utilized to connect and power the test devices and transfer data to the measurement software.

The core mission of drive testing is to measure wireless network coverage and signal strength. Only drive-testing can accurately measure signal strength as experienced by the wireless network subscribers as they travel along major highways and secondary and secluded back roads. Digital scanners, capable of measuring and decoding the technologies employed by the network as well as UE devices, generally measure signal strength.

Drive testing also evaluates the ability of subscribers to access the network whether originating voice calls, sending SMS/MMS messages, or initiating packet data sessions to access the Internet or send emails. Since even strong RF coverage is no guarantee that the network has the capacity to support voice and data calls in specific locations, drive-test systems employ UE devices running automated scripts to place voice calls, and initiate data tasks while measuring the success or failure of those tasks.

For voice calls, the call success rate, time required for call origination, and messaging between the UE and base station is recorded as well as the ability of the network to maintain the calls.

For packet data sessions, the ability to successfully initiate a connection to the network and maintain that connection is measured with particular emphasis on data throughput rates.

9.8.2. SCANNING RECEIVER MEASUREMENTS VERSUS USER EQUIPMENT (UE)

A new generation of sophisticated digital scanning receivers is now available for testing new technologies such as LTE. These modular scanners are capable of simultaneously measuring multiple bands and decoding multiple technologies using a single scanner. Plug in receiver modules extend the capabilities of these scanners to measure new technologies and bands as spectrum is released for emerging technologies.

Scanning receiver provides:

- Unlike UE devices which are assigned to specific channels, scrambling codes, or PNs by the wireless networks, digital scanners provide independent measurements of the wireless network. While the scanners can be configured to follow the channel assignments of a UE device, the tasking of the scanner is solely at the discretion of the drive-test technician.

- Digital Scanners have the ability to show individual components of the decoded signals. For example, an LTE Cell ID scan provides measurements such as IPSS, PSS Io, SSS Io, Epss/Io, Esss/Io, Composite Epss/Io, Composite Esss/Io, RSRP Port 0, RSRQ Port 0, RSRP Port 1, RSRQ Port 1, Delay Spread, and Multipath Count for each Cell ID detected in a single scan.

- The Index of the Primary Synchronization Signal (IPSS) provides a relative or absolute time with GPS. This can be used to ensure all cell sites are timed appropriately. The differential times between cell sites can be indentified during drive testing to aid in the optimization for MIMO and highest throughput performance. In addition, if any cell sites are not locked to GPS this index will drift with time relative to the scanner, which is locked, to GPS.

- Some of the new generation scanners feature onboard Digital Signal Processing (DSP) and Field Programmable Gate Arrays (FPGAs). This onboard digital processing and high-gate count programmable logic extends the capabilities of the scanner to intelligently survey a network, detect, locate, and process multi-technology signals rapidly. With the added capability to re-FLASH the firmware in the field product life cycle of the scanner technology is increased significantly over previous generations of scanners. The overall product cost is greatly reduced.

UE provides:

User equipment including phones, mobile data cards, and wireless USB modems, is required in a complete drive-test system to fully test the subscriber experience.

- All wireless networks are affected by subscriber loading. To test voice call capacity, the drive-test platform can task a number of UE phones to simultaneously place calls to stress the network's ability to handle the load simulating performance during rush hour traffic, large sports or entertainment events, or emergencies. To test data capacity, a number of UE data modems can be tasked to download/upload files, access Web pages, and send emails to ensure that the network can handle the data transfer loading.

- The drive-test platform records the success and failures of the UE devices as they perform their assigned voice and data tasks along with time and location information into a log file. For voice calls, statistics such as failed originations, dropped calls, and no service failures, and successful call starts are captured. For data sessions, statistics such as successful connects, failed connects, no data service, dropped connections, and data throughput are captured.

- UE devices can also be captured in the log file of the drive-test measurement platform. Layer 1 and layer 3 communications between the BTS and phone are captured and recorded in the log file. For data sessions, TCP/IP communications are captured and can be viewed in a protocol analyzer application. This communication dialog can be instrumental in tracking down and correcting network issues.

9.8.3. IMPACT OF NEW TECHNOLOGIES ON DRIVE TESTING SCANNERS

The higher data rate capabilities in the cellular environment naturally require higher bandwidths and higher performance in drive test-technology. Scanners capable of sampling IF signal bandwidths up to 20 MHz are required for the new generation of technologies including LTE. With the addition of MIMO, it is desirable for scanners to also provide a two-channel MIMO capability while beam steering effectiveness will require up to four channels.

Support for multi-antenna techniques

- Receive diversity at the mobile device. One of the simplest and conventional diversity methods, a form of multi-antenna implementations, is the use of two antennas at the receiver end. Based on RSSI, the best antenna source is selected for signal reception. While this technique may improve reception under certain conditions where signal-to-noise (SNR) ratio suffers due to multipath fading, data throughput cannot be improved without using other techniques.

- Transmit diversity using space/frequency block coding (SFBC) at the base station Transmit diversity is another conventional method and defined in LTE specifications as evolved Node B, or eNB). In LTE, Space Frequency Block Coding (SFBC) is used to improve signal robustness under fading conditions. The transmitters send the same underlying user data, but in different parts of the RF frequency space.

- MIMO spatial multiplexing at the eNB, for one or two users. True MIMO, with two transmitters and two receivers with independent data content, is also known as spatial multiplexing. Each receiver sees the output of the channel, which is a combination of the outputs from the transmitters. Using channel estimation techniques, the receivers use matrix mathematics to separate the two data streams and demodulate the data. In ideal conditions, data capacity would be doubled, though there is a premium to be paid in better SNR requirements than for SISO. Practically, the doubling of data capacity is never achieved, but definite increases in data capacity can be seen.

- Cyclic Delay Diversity (CDD) at the eNB, used in conjunction with spatial multiplexing. CCD introduces deliberate delays between the antennas to create artificial multipath. It is applied more dynamically in LTE than in other radio systems.

- Conventional phased-array beam steering introduces phase and amplitude offsets to the whole of the signal feeding each transmitting antenna. The basic idea is to focus the signal power in a particular direction. The same technique of applying phase and amplitude offsets can be used on the receiving antennas to make the receiver more sensitive to signals coming from a particular direction. In LTE, the amplitude and phase of individual resource blocks can be adjusted, making beam steering far more flexible and user-specific. Although beam steering does not increase data rates, the end result is similar to diversity in terms of increasing signal robustness. The effectiveness of beam steering increases with the number of transmitting antennas, which allows for the creation of a narrower beam. The gains possible with only two antennas are generally not considered worthwhile; thus, beam steering is generally only considered for the four-antenna option. Scanner technology, which is capable of up to 4 receiver antenna signal paths, can be used to identify the effectiveness of beam steering.

The advancements in multi-antenna technologies to achieve greater capacity and higher data throughput in cellular technologies necessarily demands new scanner technology, which can provide dynamic real-time measurements of the effectiveness of the various antenna and processing techniques. A real-time, channel capacity measurement

capability would be especially valuable. Advances in scanner technology is expected in response to the need operators will have to evaluate and optimize the performance of their next generation networks.

9.9. INDOOR DISTRIBUTED ANTENNA SYSTEM—MIMO COVERAGE

In many countries, more than 70 percent of the traffic on cellular networks originates from or terminates inside buildings. Driven by an increasing demand for mobile data services, the iPhone effect, this number is expected to rise even higher within the next years.[32] When rolling out new systems addressing high-speed data needs, e.g., LTE or HSPA+, a cost effective solution is explored by extending the outdoor macro coverage to inside. In order to reduce the building penetration path loss a relay can be used to amplify and forward (A&F) or decode and forward (D&F) the signal. The benefits of a D&F relay on the achievable LTE downlink indoor coverage extension has been demonstrated in "Relaying in Long Term Evolution: Indoor Full Frequency Reuse."[33] Implementing the D&F relay, however, adds complexity to the system and decreases overall air-interface capacity due to the in-band backhauling.

In the A&F mode, the relay terminal simply amplifies and retransmits the signal received from the source terminal. Figure 101 compares the results measured at the Heinrich Hertz Institute in Berlin by applying both relay technologies.

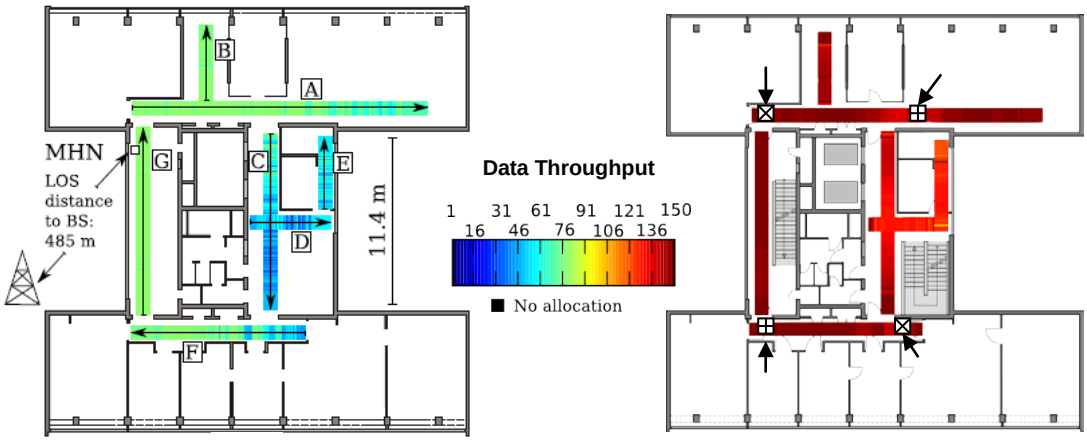


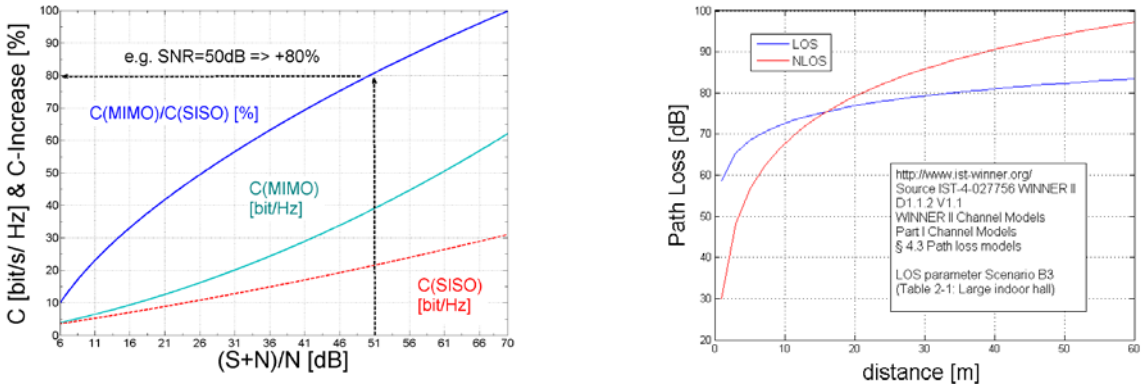
Figure 101. Graphical Representation of the in-building coverage measured with: A) A D&F relay where 50 percent of the link capacity is allocated for in-band backhauling,[32] And B) An A&F optical DAS with an interleaved antenna arrangement.[34]

In order to obtain the best cost-to-coverage solution several antenna configurations have been investigated.[34] Due to the fact that an interleaved distributed antenna arrangement can be set-up by re-cabling of an existing single antenna 2G or 3G distribution system this solution turned out to be the most advantageous. At a minimal upgrade cost, it provides exceptional data rates and the LTE pre-coding supports the transmission of two separate spatial data streams at two different antennas. It is therefore possible to fully exploit the rich scattering that exists in most in-building environments.

In addition to the in-building coverage test, it could be shown that a MIMO coded signal can be transmitted without any performance degradation in good LOS conditions. This is good to remember when the distribution system has to be fed by picking up the signal off air.

In the face of all the enthusiasm about the possibility to boost the in-building data rate by deploying MIMO technologies, it has to be mentioned that a sufficient Signal-to-Interference-and-Noise Ratio (SINR) is the price, which

has to be paid. As shown in Figure 102 A) a minimum SINR of 26 dB is required to enhance the capacity of a single input single output (SISO) system by 50 percent. To justify the cost for a second RF infrastructure it is assumed that a data rate enhancement of 70 to 80 percent (i.e., a SINR of 40 dB to 50 dB is required). For these capacity calculations, a measured average channel condition number[35] of 14 dB, valid for a small/office in-door environment, has been assumed. To estimate the required RF power per antenna at 2.6 GHz in a typical indoor environment the scenario B3 (hotspot large indoor hall) based on the WINNER[36] propagation model is shown in Figure 102. Hence depending on the number and thickness of the walls to be taken into account, a similar path loss can be expected for scenario A1 (indoor office / residential). For simplicity, let us assume a minimum UE receiver's sensitivity of -100 dBm in a 20 MHz bandwidth. Taking into account 60 to 80 dB path loss, a RF power level of -40 to -20 dBm at the receiver is required. Targeting for a minimum data rate enhancement of 70 percent this results in 0 to +20 dBm radiated power at each antenna per carrier bandwidth. Alternatively, to increasing the RF power, the number of antennas can be increased and thus the spacing in between reduced. It also should be mentioned that the situation can be improved by operating at lower frequencies, e.g., at 700 to 800 MHz where the path loss is expected to be 10 to 15 dB lower than at PCS frequencies.



A) B)

Figure 102. Graphs for MIMO link budget considerations: A) data rate enhancement MIMO vs. SISO as a function of SINR, and B) typical indoor path loss graphics @ 2.6 GHz (WINNER II channel model).

Another point of interested, especially for in-building MIMO distribution systems, is the minimum spacing in-between the antenna dipoles to ensure the maximum data rate enhancement. The amount of additional transport capacity, provided by different spatial MIMO streams, is directly linked to the de-correlation of these streams. Since the correlation between two antenna dipoles is increasing the closer they come it might be expected that the data rate enhancement may drop accordingly. However it has been shown that local scatterers, in the near vicinity of the antenna elements, significantly decreases this effect.[37] It turned out that not the antenna spacing but the angular spreading of the incident waves is the determining factor for the antenna de-correlation. Especially in rich scattering indoor environments it has been proven by experiment that a spacing of λ/2 is already enough to guarantee a reasonable data rate enhancement.[38]

In low scattering indoor environments, e.g., large hallways or conference rooms, a low angular spreading has to be expected. A phenomenon, which is well known from outdoor, above rooftop, antenna installation.[39] Unless large antenna spacing, e.g., interleaved indoor antenna arrangements (as described in the previous paragraph) can be used, it is assumed that cross-polarized antennas are advantageous for indoor installations as well. Results show that increasing the de-correlation by polarization performs better than increasing the antenna spacing in strong line of sight (LOS) scenarios. In non line of sight (NLOS) scenarios, the results are of the same order.[40]

10. TERMINAL ANTENNA ISSUES

10.1. PROSPECTS AND CHARACTERISTICS OF MULTIPLE ANTENNAS IN TERMINALS

In a previous 3G Americas white paper on MIMO and smart antenna technology,[3] many of the problems faced by user equipment (UE) vendors were discussed. The problems range from issues of antenna correlation and coupling, the challenges of designing and manufacturing small-sized UE devices, multi-band support and user effects. General knowledge of the solutions to these problems is fairly well known. For instance, as antennas are separated, they tend to have less correlation and coupling. It is very hard to generate specific data on the impact of real antennas on smart antenna systems because the implementations will be diverse across device size and designer preferences (antenna type, polarization and/or pattern diversity). Accumulation of this data will have to be done with the large-scale deployment with many devices. Carriers are probably in the best position to catalogue this information given the large number of deployed devices.

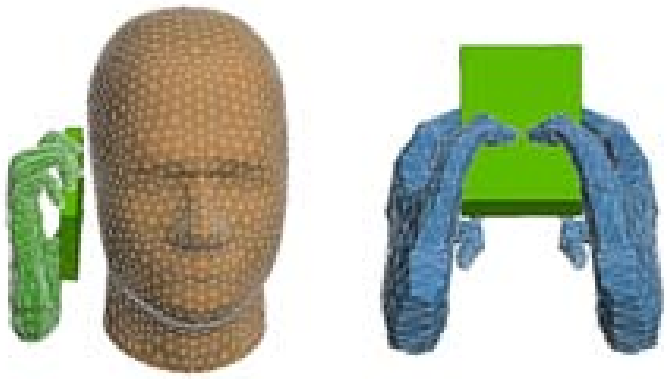
In order to provide insight into the effects that actual deployment of UE antennas will have on smart phones sized devices, we provide an analysis that attempts to address the two most important parameters in wireless communication systems: link budget and capacity impact. One of the first things that a system designer is going to want to know is the antenna gain of the UE, given that there are two antennas now required for LTE. In other words, how much additional gain can be expected with the use of both antennas relative to a single antenna. Given that techniques such as pattern and polarization diversity can be employed to help de-correlate arriving signal paths, the question arises as to what the impact of the antenna patterns is going to be.

To investigate the link budget impact, a study was conducted using an approach similar to that described in.[41] This study was done with antenna types that are likely to be used within a typical smart phone dimension for use in LTE MIMO mobile systems. The objective of the study was to try to characterize the relative performance improvement in the link budget that would be realized in a MIMO-based LTE system from the use of two receive antennas relative to the single antenna systems most commonly used in current UEs.

This study was set up with the following two scenarios.

1. A phone placed in between a phantom head on one side and a phantom hand placed on the opposite side of a phone. This provides a realistic situation in which to examine antenna performance for mobile devices since this is a very common usage pattern of users. This scenario provides fairly large absorption and shielding losses because the antenna is shielded by both the head and hand. However, even though the mutual coupling between the antennas tends to increase the magnitude and phase of the radiation pattern changes such that the antennas tend to be less correlated than in a free space scenario. This de-correlation tends to overcome the absorption loss and increases the performance relative to two antennas in free space. This scenario is illustrated in Figure 103 and is referred to as the Voice Mode.

2. A phone placed in front of the body held with the hands. This is a common usage scenario for texting or web surfing. This scenario is illustrated in Figure 103 and is referred to as the Data Mode



(a) Voice Mode (b) Data Mode

Figure 103. Position of the handheld device for the two scenarios.

In our study, we used several different head and hand models and averaged the results. This probably accounts for most of the differences in performance between our study and reference.[41] However, the exact form factor, antenna location, antenna type and orientation are also factors that will yield different performance values. The study was carried out via software simulations with the GEMS[42] and FEKO[43] software tools as well as anechoic chamber measurements, which confirmed the simulations given the close agreement between the two sets of data. Table 5 shows the results for the Voice Mode. Table 6 shows the results for the Data Mode. The "Improvement" column is the data that was simulated and measured in this study. The "Improvement from" column is the data found referenced in, "Actual Diversity Performance of a Multiband Diversity Antenna with Hand and Head Effects."[41] Note that the simulated and measured results include diversity gain, and are relevant to control channel reception in a UE.

Table 5. Link budget receive performance improvement due to two receive antennas over one receive antenna on a handheld placed between a phantom head and hand.

Frequency (MHz)	Improvement (dB)	Improvement [4] (dB)
700	2 to 5	--
850	2 to 5	5-6
950	3 to 6	5 to 6
2100	6 to 9	8 to 10
2600	6 to 9	--

Table 6. Link budget receive performance improvement due to two receive antennas over one receive antenna on a handheld placed in front of user in a typical data usage fashion.

Frequency (MHz)	Improvement (dB)	Improvement [4] (dB)
700	4 to 6	--
850	5 to 7	8 to 10
950	5 to 8	8 to 10
2100	7 to 10	8 to 10
2600	7 to 10	--

To get an indication of the possible loss of capacity that may occur when using two realistic antennas, we calculate the maximum capacity possible under ideal conditions using uncorrelated isotropic antennas and compare those results to that of a design that would contain realistic antennas. The realistic design for a smart phone will utilize the well-known inverted-F antenna (IFA) technology. The design is cross-polarized and we look at two frequencies: 2.6 GHz (190 MHz bandwidth) and 780 MHz (40 MHz bandwidth). These are two prominent LTE frequency bands. In this study, we do not take into account the effects of the head and hands.

To measure the maximum capacity we use Shannon's generalized capacity equation

$$C = \log_2 \det(I_N + \frac{\rho HH^H}{N_T})$$

where ρ is the average signal-to-noise ratio, **H** is the channel at each subcarrier, $\mathbf{I_N}$ is the identity matrix and N_T is the number of transmit antennas. With this equation, if we can impose the effects of the antennas on the channel matrix, we can generate the upper limit of the capacity of a single MIMO radio link with equal power transmitted per layer.

This can be done by importing the antenna patterns into the spatial channel model (SCM[44] that is used extensively by 3GPP) and generating **H** with their effects. The parameters for 780 MHz that are plugged into the model are shown in Table 7. As you can see we assume that the base station antenna configuration can be modeled as two dipoles separated by 20 wavelengths (i.e., they are uncorrelated). We focus on the Urban Macrocell channel. Figure 107 and Figure 108 exemplify transmit and receive antenna configurations that contain angle spread and orientation.

Table 7. SCM parameters for 2X2 780 MHz antenna system.

SCM Urban Macrocell Parameters	BS	MS
Azimuth Angle Spread	8 deg	68 deg
Azimuth Array Orientation	0 deg	0 to 180 deg
Elevation Angles	0 deg	-90 to 90 deg
Number of Antennas	2	2
Element Separation	20 λ	0.12 λ (cross-polarized)
# Independent Channel Realizations	10,000	

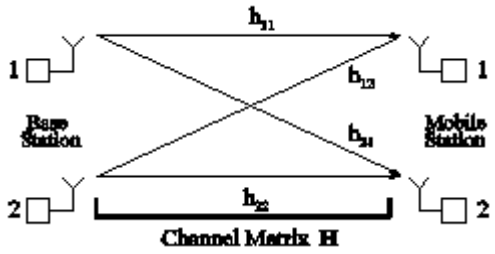


Figure 104. MIMO channel model.

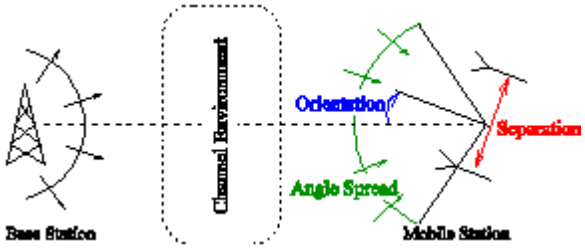


Figure 105. Channel parameters.

In an effort to isolate the effect of realistic antennas, we compute the capacity at a given average SNR at the antenna input by averaging the Shannon capacity over multiple independently faded channel realizations. By further accounting for the angular power distributions in azimuth and elevation,[45] we can compare the results of a realistic set of antennas with the results of doing the same with an isotropic antenna and gain insight into the capacity impact of more realistic antennas.

Figure 106 shows the result of this for both 2.6 GHz and 780 MHz antennas. Note that the orientations are averaged to provide one resulting curve. UE is moving at the speed of 10 m/s. Looking at the 10 dB SNR mark, it can be seen that an extra dB of SNR for the UE with an IFA antenna pair is needed to achieve the capacity upper limit that you would get with an isotropic antenna pair. At 10 dB SNR, there is a loss of 0.5 bps/Hz or 9.5 percent for the UE with 2.6 GHz IFA antenna pair. For 780 MHz antenna pair, there is a loss of 1.8 bps/Hz or 35 percent at 10 dB. Note that in all the simulations, the effect of antenna efficiency is incorporated.

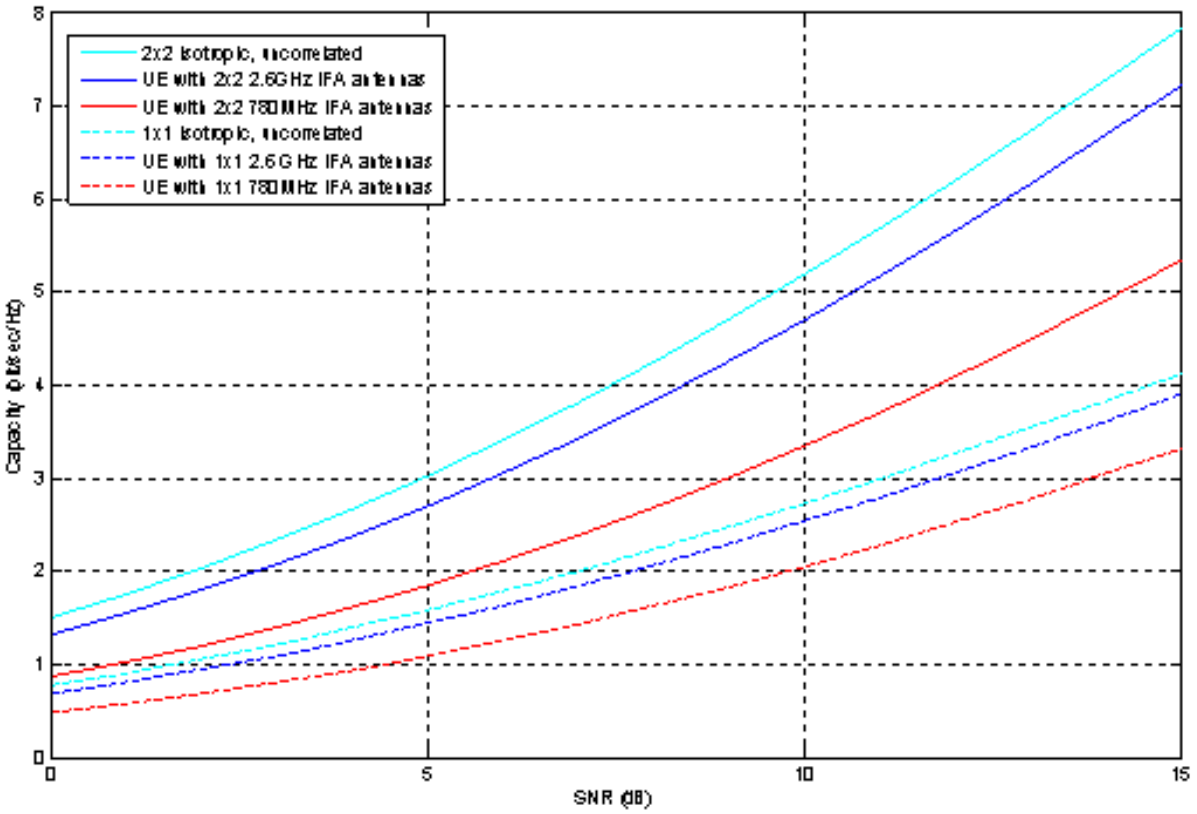


Figure 106. Shannon upper limit capacity at 2.6 GHz and 780 MHz in an urban macro cell environment with two transmit and two receive antennas.

In conclusion, we have examined the effects of realistic antennas in a smart-phone form factor on link budget performance and maximum link capacity. We have noted from a study performed for this document that there will be a link budget improvement of 2 dB at lower frequencies to around 6 dB at some of the higher LTE frequency bands. Others have shown greater gains than that. On the other hand, we see that realistic antenna designs in realistic environments will see a loss of maximum capacity potential of over 30 percent.

10.2. CURRENT STATUS

Multiple antennas are currently found in the terminals of many wireless products, particularly PCs, data cards and USB dongles. See for example, the products whose antennas are photographed below in Figure 108 through Figure 110 below.

It may be instructive to recall that terminals are not just handsets anymore. Mobile terminals such as the Kindle and iPad, not to mention laptops and notebooks that have integrated UT built in have a great deal of room for multiple antennas. Beyond the FM radio antenna, GPS receiver, WiFi and multiple band antennas, they also now support multiple antennas as well. In these emerging pad computers and readers, we see sufficient room to support more than 2 antennas, though they all appear to use two at this time. See for example the two PCS band antennas used in the Kindle reader in Figure 111.

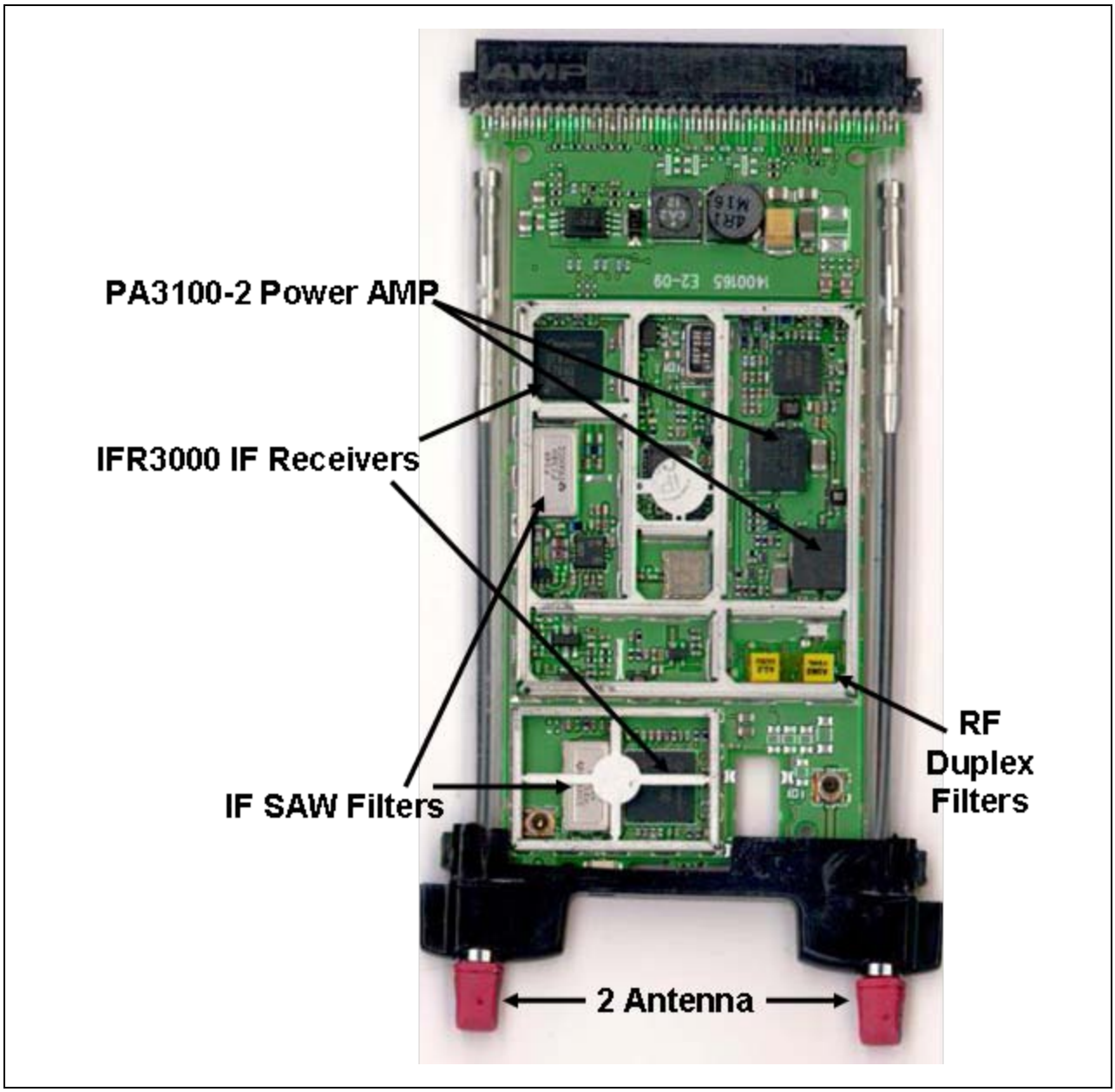


Figure 107. EVDO data card clearly showing two-branch diversity.

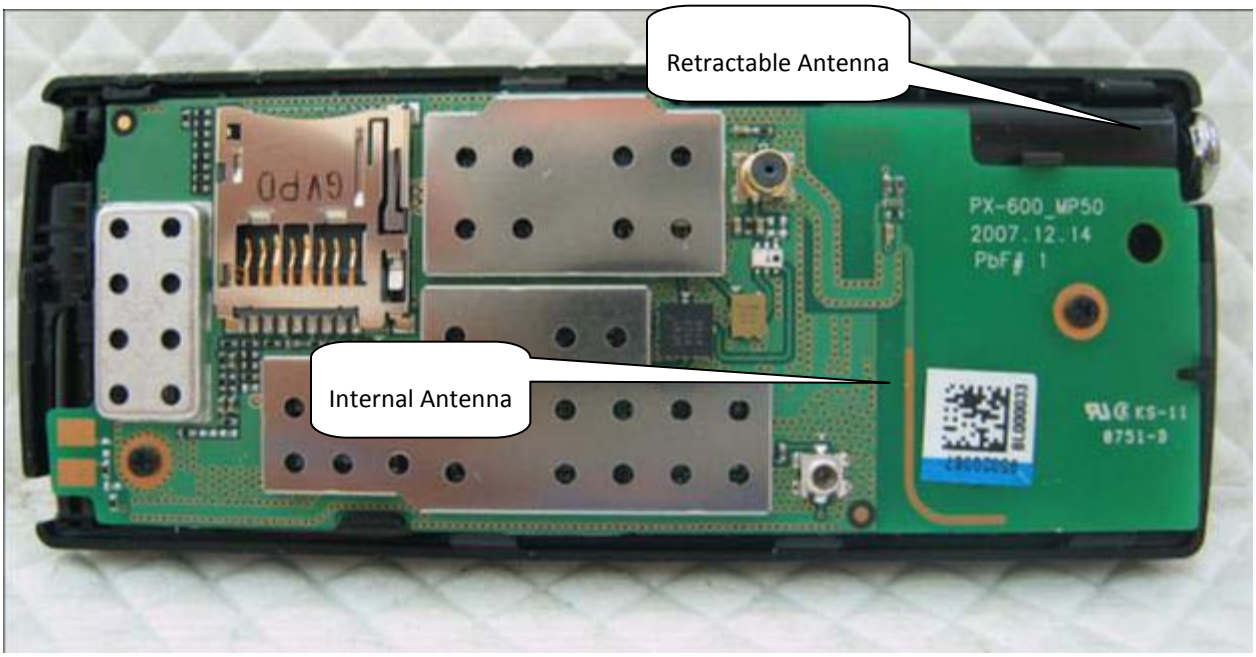


Figure 108. Photograph of the inside of the Pantech UM150 EVDO USB dongle with 2 selectable antennas.

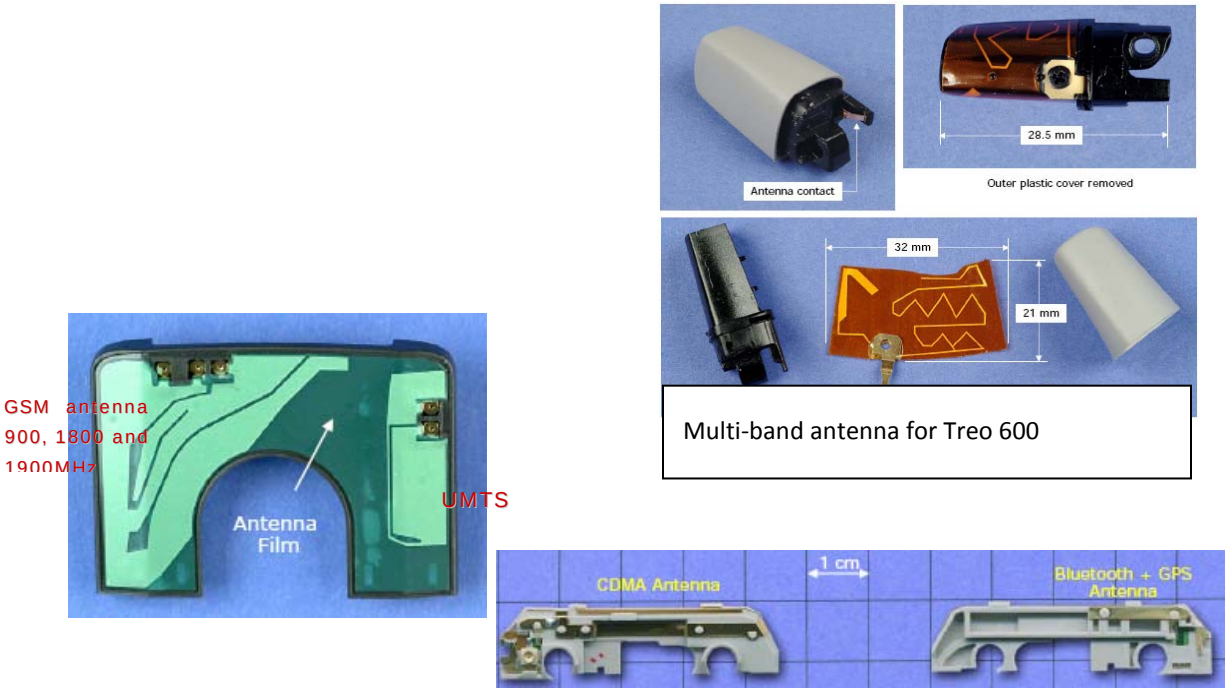


Figure 109. Example antennas from representative handsets, illustrating manufacturing and design approaches.

A commercial WiMAX terminal (Cmotech CMU300) with receive diversity is revealed in the figure below:

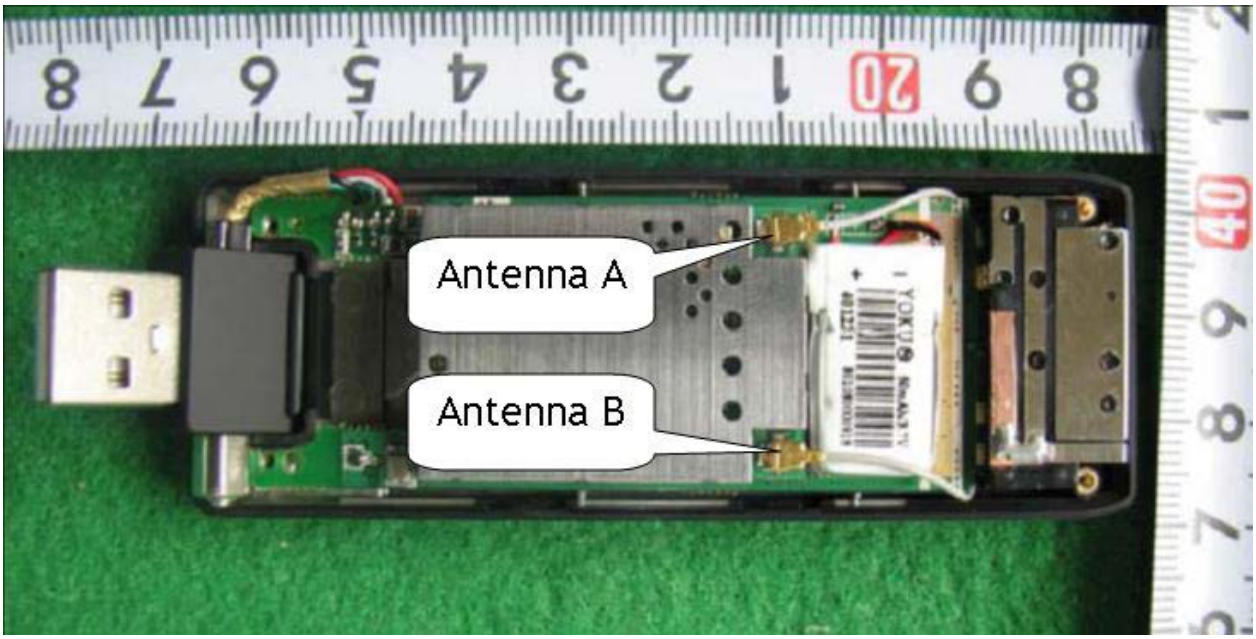


Figure 110. Internal view of the commercial CMU 300 modem with receive diversity. The two diversity antenna ports are indicated.

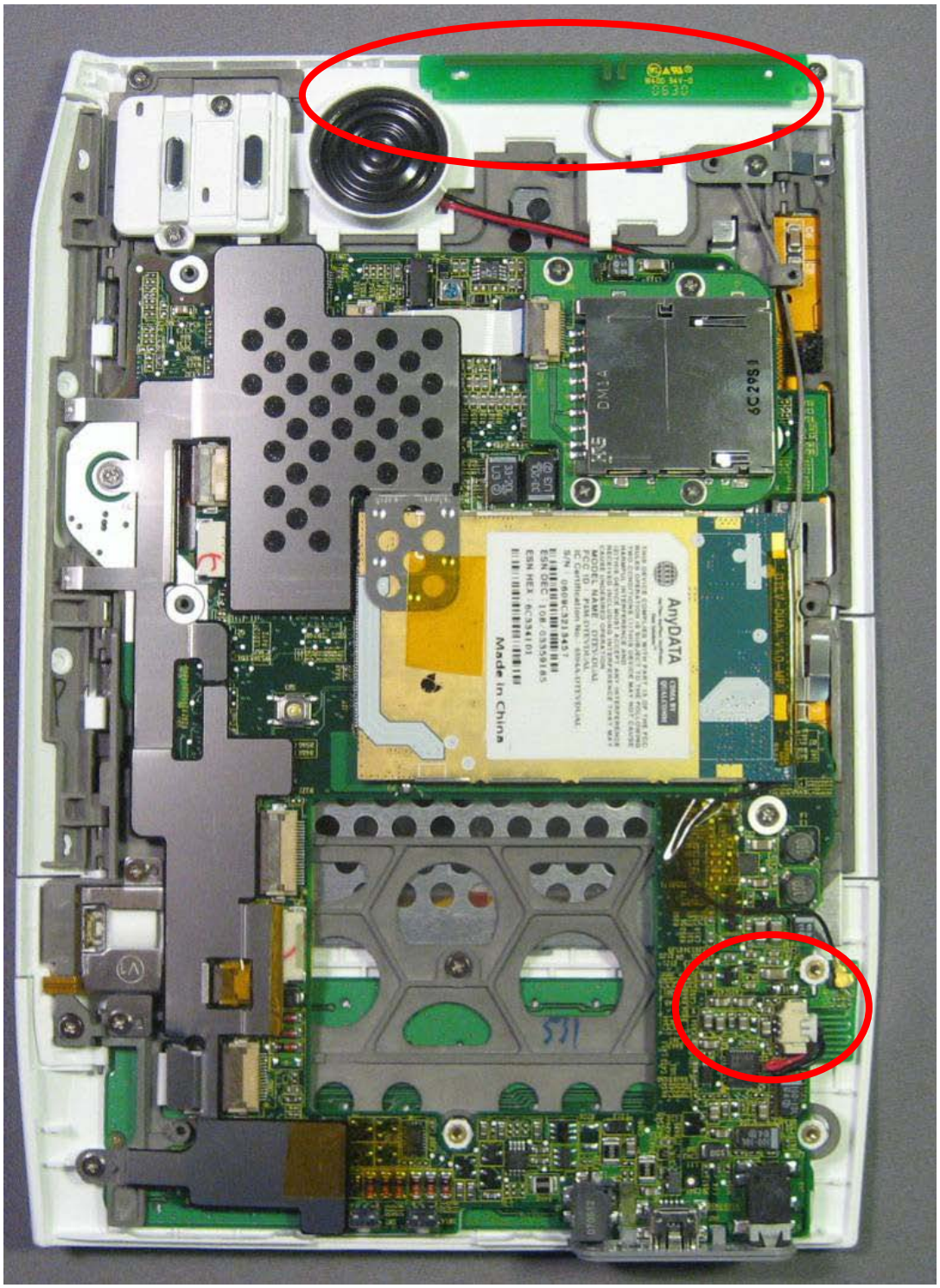


Figure 111. Photo of the inside of the Amazon Kindle showing two antennas for PCS band use.

11. SUMMARY AND CONCLUSIONS

A variety of smart antennas, from those with remote controlled boresight to beam-steering arrays along with beamforming MIMO as well as active antenna array antenna configurations have been reviewed in great depth. Their installation and operational characteristics have been detailed and several deployment and upgrade strategies have been discussed.

General conclusions about how best to upgrade a network are not easily made because every operator has a unique set of constraints such as what frequencies are available, what air interfaces preexist and what network, antenna and user equipment has previously been deployed. Even so, the wide variety of antenna types and processing techniques makes impressive improvements in the capacity and coverage of emerging 4G networks.

12. ACKNOWLEGEMENTS

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13. ACRONYMS

3G	Third Generation
3GPP	Third Generation Partnership Project
AA	Adaptive Array
ABF	Adaptive Beamforming
AFLA	Another Four Letter Acronym
AISG	Antenna Interface Standards Group
ARLBR	Active Radio Link Bit Rate
AWS	Advanced Wireless Service
BF	Beamforming
BRS	Broadband Radio Service
BS	Base Station
BSA	Base Station Antenna
CAPEX	Capital Expenditures
CDD	Cyclic Delay Diversity
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
C/I	Carrier to Interference Radio
CL	Closed-Loop
CPRI	Common Public Radio Interface
CQI	Channel Quality Indicator
DL	Downlink
DPD	Digital Pre-Distortion
DSP	Digital Signal Processing
EBS	Educational Broadband Services
Ec/No	Signal Energy per Chip over Noise Power Spectral Density
EDGE	Enhanced Data Rates for GSM Evolution

eNB	Evolved Node B
EPC	Evolved Packet Core
ePDSN	Evolved PDSN
EPS	Evolved Packet System or Service
ERP	Effective Radiated Power
e-UTRAN	Evolved UMTS Terrestrial RAN
EVDO	Evolution-Date Optimized
FDD	Frequency Division Duplexing
FPGA	Field Programmable Gate Array
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
IF	Intermediate Frequency
IFA	Inverted-F Antenna
IPSS	Index of the Primary Synchronization Signal
LAN	Local Area Network
LLC	Low Loss Combiner
LNA	Low Noise Amplifier
LTE	Long Term Evolution
MCCH	Multicast Control Channel
MCPA	Multi-Carrier Power Amplifier
MIMO	Multiple-Input Multiple-Output
MRxD	Mobile Receive Diversity
MS	Mobile Station
MU-MIMO	Multiple User MIMO
OBSAI	Open Base Station Standard Initiative
OFDM	Orthogonal Frequency Division Multiplexing

OL	Open Loop
OPEX	Operating Expenditures
PA	Power Amplifier
PCs	Personal Computers
PCFICH	Physical Control Format Indicator Channel
PCS	Personal Communication Systems
PDCCH	Physical Downlink Control Channel
PHICH	Physical Hybrid-ARQ Indicator Channel
PMI	Precoding Matrix Indication
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAB	Remote Antenna Beam Width
RAS	Remote Antenna Azimuth
RET	Remote Electrical Downtilt
RF	Radio Frequency
RI	Rank Indication
RRH	Remote Radio Head
RRU	Remote Radio Unit
RU	Radio Unit
RX	Receiver
RXMC	Receiver Multicoupler
SAW	Surface Acoustic Wave
SBC	Same Band Combiner
SCM	Spatial Channel Model
SCPA	Single-Carrier Power Amplifier
SFBC	Space-Frequency Block Coding
SIC	Successive Interference Cancellation
SIMO	Single-Input and Multiple-Output

SINR	Signal-to-Interference-Plus-Noise Ratio
SISO	Single-Input and Single-Output
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Network
SPR	Sector Power Ratio
SU-MIMO	Single User MIMO
TDD	Time Division Duplexing
TD-SCDMA	Time Division Synchronous CDMA
TMA	Tower Mounted Amplifier
TRDU	Transmitter-Receiver Duplexer Units
TX	Transmit
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telephone System
USB	Universal Serial Bus
UTRA	Universal Terrestrial Radio Access
V-pol	Vertically polarized
WIMAX	Worldwide Interoperability for Microwave Access
X-pol	Cross polarized (Dual Polarized)

14. ENDNOTES

[1] Chetan Sharma Consulting, "US Wireless Data Market Q4 2009 and 2009 Update," available on the web at: http://www.chetansharma.com/US%20Wireless%20Market%20Q4%202009%20Update%20-%20Mar%202010%20-%20Chetan%20Sharma%20Consulting.ppt#261,1 on March 3, 2010.

[2] Information Content estimate from www.wolframalpha.com, March 3, 2010.

[3] "MIMO Transmission Schemes for LTE and HSPA Networks," 3G Americas Whitepaper, June 2009.

[4] "Vocabulary of 3GPP Specifications," TR21-905, 3GPP, version 8.8.0, March 2009.

[5] Rysavy Research, "HSPAto LTE-Advanced: 3GPP Broadband Evolution to IMT-Advanced (4G)," 3G Americas White Paper, September 2009.

[6] Jonas Karlsson and Mathias Riback, "Initial Field Performance Measurements of LTE," Ericsson Review No. 3, 2008.

[7] Krishna Balachandran, Qi Bi, Ashok Rudrapatna, James Seymour, Soni, and Andreas Weber, "Performance Assessment of Next-Generation Wireless Mobile Systems," Bell Labs Technical Journal 2009 vol. 13:4, pages 35-58, http://www3.interscience.wiley.com/journal/122211215/abstract last accessed on March 30, 2010.

[8] A.M.D. Turkmani, A.A. Arowojolu, P.A. Jefford, and C.J. Kellett, "An Experimental Evaluation of the Performance of Two-Branch Space and Polarization Diversity Schemes at 1800 MHz," IEEE 0018-9545/94404,00, 1995.

[9] Brian S. Collins, "The Effect of Imperfect Antenna Cross-Polar Performance on the Diversity Gain of a Polarization-Diversity Receiving System," Microwave Journal, April 2000.

[10] R. Bhagavatula, R. W. Heath, Jr., and K. Linehan, "Performance Evaluation of MIMO Base Station Antenna Designs," Antenna Systems and Technology Magazine, vol. 11, no. 6, pp. 14 -17, Nov/Dec. 2008.

[11] Lawrence M. Drabeck, Michael J. Flanagan, Jayanthi Srinivasan, William M. MacDonald, Georg Hampel, and Alvaro Diaz, "Network Optimization Trials of a Vendor-Independent Methodology Using the Ocelot™ Tool," Bell Labs Technical Journal 9(4), 49–66 (2005) © 2005

[12] "Final Report on Semi-Smart Antenna Technology Project," Ofcom Contract No. 830000081, Document No. 830000081/04, July 2006.

[13] M. Petersen, et al., "Automatic Antenna Tilt Control for Capacity Enhancements in UMTS FDD," IEEE 2004, 0-7803-8521-7/04, 2004.

[14] Mano D. Judd, Thomas D. Monte, Donald G. Jackson, and Greg S. Maca, "Tranceive Distributed Antenna Systems," U.S. Patent No. US 6,597,325 B2, July 22, 2003.

[15] "Active Antenna Arrays, Small-Footprint, Scalable RF Solutions for Base Stations," Bell Labs Research Project, Alcatel-Lucent Innovation Days, December 2008. Available on line at http://innovationdays.alcatel-lucent.com/2008/documents/Active%20Antenna%20Array.pdf.

[16] "Nokia Siemens Network Networks and Vodafone Demonstrate Active Antenna Solution," Press Release, July 29, 2009. Available on line at http://www.nokiasiemensnetworks.com/news-and-events/press-room/press-releases/nokia-siemens-networks-and-vodafone-demonstrate-active-ant.

[17] Osman N.C. Yilmaz, Seppo Hamalainen, and Jyri Hamalainen, "System Level Analysis of Vertical Sectorization for 3GPP LTE," Proceedings of the 6th International Conference on Symposium on Wireless Communication Systems, Siena, Italy, pp. 453-457, 2009.

[18] Alan J. Fenn, Donald H. Temme, William P. Delaney, and William E. Courtney, "The Development of Phased-Array Radar Technology," Lincoln Laboratory Journal, Vol 12, no 2, 2000, page 321-340. Available on-line at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.73.2849&rep=rep1&type=pdf , last accessed April 17, 2010.

[19] F. Athley, M. Alm, O. Kaspersson, K. Werner, J. Furuskog, and B. Hagerman, "Dual-Polarized Base Station Antenna Configurations for LTE," to appear in Proc. 2010 IEEE International Symposium on Antennas and Propagation.

[20] K. Werner, J. Furuskog, M. Riback, and B. Hagerman, "Antenna Configurations for 4x4 MIMO in LTE—Field Measurements," to appear in Proc. IEEE VTC Spring 2010.

[21] "Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations," 3GPP TR 25.996, V7.0.0, available on line at http://www.3gpp.org/FTP/Specs/html-info/25996.htm.

[22] L. Wan, S. Tsai, and M. Almgren, "A Fading-Insensitive Performance Metric for a Unified Link Quality Model," Proc. IEEE WCNC, 2006.

[23] "Physical Layer Aspects for Evolved Universal Terrestrial Radio Access (UTRA)," 3GPP TR 25.814, V7.1.0, section A.2, available on line at http://www.3gpp.org/FTP/Specs/html-info/25814.htm.

[24] Section 7.1 of 3GPP Section 7.1 of TS 36.101 V8.7 states: "The requirements in Section 7 assume that the receiver is equipped with two Rx port as a baseline. Requirements for 4 ports are FFS. With the exception of clause 7.9 all requirements shall be verified by using both (all) antenna ports simultaneously." Available on line at: http://www.3gpp.org/ftp/Specs/html-info/36101.htm last accessed on April 18, 2010.

[25] City Code of Lindon City, UT, Title 5: Licensing and Francising, 5.07 Personal Wireless Telecommunications Facilities, available on-line at: http://www.lindoncity.org/government.wireless.html, last accessed March 25, 2010.

[26] "Illinois State Toll Highway Authority Telecommunications Facility Leasing Program" Illinois Tollway, October 2005, available on-line at: http://www.illinoistollway.com/pls/portal/docs/PAGE/TW_CONTENT_REPOSITORY/TW_CR_DOING_BUSINESS/TW_CR_DOING_BUSINESS_LEASING/TOWERPROGRAM.PDF last accessed March 25, 2010.

[27] "The Impacts of Antenna Azimuth and Tilt Installation Accuracy on UMTS Network Performance," Bechtel Telecommunications Technical Journal, Vol. 4, No. 1, January 2006.

[28]

http://www.bechtel.com/assets/files/TechJournal/2009/Comms%2003%20Performance%20Engineering%20Advances%20to%20Installation.pdf

[29]"Frequently Asked Questions for Passive IM Products," Summitek Instruments,

http://www.summitekinstruments.com/passive/faqpim.asp.

[30]Multi-Band PIM Calculator, Andrew Solutions, Software Tools,

http://www.commscope.com/andrew/eng/product/antennas/bsa/sw_tool/1205324_13426.html.

[31] "Intermodulation Products of LTE and 2G Signals in Multitechnology RF Paths," December 2009, http://www.bechtel.com/assets/files/TechJournal/2009/Comms%2001%20Intermodulation%20Products%20of%20LTE%20and%202G.pdf.

[32] "In-Building Wireless Systems – Passive and Active DAS, Repeaters, Picocells, and Femtocells," 2009 ABIresearch, www.abiresearch.com.

[33] V. Venkatkumar, T. Wirth, T. Haustein, and E. Schulz, "Relaying in Long Term Evolution: Indoor Full Frequency Reuse," in European Wireless 2009, Aarlborg, Denmark, 2009.

[34] T. Wirth, O. Braz, T. Haustein, J. Stefanik, and Lars Thiele, "LTE Amplify and Forward Relay for Indoor Coverage Extensions," VTC 2010-Fall Ottawa, to be published.

[35] Peter Cain, "Using Channel Condition Number to Visualize MIMO Performance," IWPC MIMO, 12 November 2008.

[36] IST-4-027756 WINNER, D1.1.2 V1.1, WINNER II Channel Models, 2007, Source: http://www.ist-winner.org.

[37] W. Lee, "Effects on Correlation between Two Mobile Radio Base Stations," IEEE Transactions on Communications, 21(11): pp. 1214-1224, 1973.

[38] S. Caban, , C. Hehlfuhrer, L. W. Mayer, and M. Rupp, "2008 – 2x2 MIMO at Variable Antenna Distance," IEEE Vehicular Technology Conference, VTC Spring 2008, http://publik.tuwien.ac.at/files/PubDat_167444.pdf and http://publik.tuwien.ac.at/files/pub-et_12543.pdf.

[39] W. Lee and Robert H. Brandt, "The Elevation Angle of Mobile Radio Signal Arrival," IEEE Trans. Communications, Vol. COM-21, pp. 1194-1197, November 1973.

[40] J. Jiang, et al., "Correlation Analysis of Multiple-Input Multiple-Output Channels with Cross-Polarized Antennas," Proceedings of APCC2008, 2008.

[41] "Actual Diversity Performance of a Multiband Diversity Antenna with Hand and Head Effects," IEEE Transactions on Antennas and Propagation, Vol. 57, No. 5, May 2009.

[42] http://www.2comu.com/

[43] http://www.feko.info/

[44] http://www.ist-winner.org/3gpp_scm.html

[45] "Angular Power Distribution and Mean Effective Gain of Mobile Antenna in Different Propagation Environments," IEEE Transactions on Technology, Vol. 51, pp. 823-838, September 2002.