Is 2 dB Worth $2 - *Part II*

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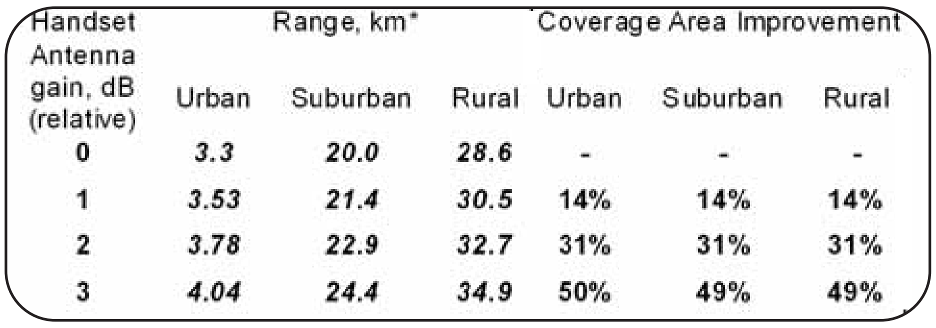
The wireless industry continues to innovate, bringing smaller devices with more functionality and higher data rates to market. Newer wireless technologies (e.g. mobile TV, penta-band cellular, and 4G) will require communication link improvements to deliver on their promise of higher speeds and better user experience. These improvements will then require significant capital investments by operators, both in network infrastructure and new handsets that support the new technology. Thus, it is important to consider the cost implications of improving the base station infrastructure versus an alternate approach of improving the communication link by handset antennas. The cost of base station infrastructure, which includes hardware, land and the permit process, remains high. As additional users are added and as bandwidth-intensive applications are deployed, additional base stations are required to maintain adequate coverage and data rates. While each network technology has its own tradeoff analysis, a simplistic study can model the tradeoff between network and handset improvements to answer the question of which side of the link is cheaper to improve? Ethertronics, a provider of standard and customized embedded antennas, believes the solution can be economically achieved through active antennas for handsets

The Economic Point of View

A handset versus base-station cost tradeoff can be done by estimating the decrease in the number of base stations that could be realized if 2 dB of additional handset antenna performance were provided. Table 1 shows coverage area improvement of a cellular network as a function of handset antenna gain. The assumptions used for this calculation were 1900 MHz (PCS), 16 dBi base station antenna gain, 24 dBm handset TRP, and a COST 231 and Okumura Hata model for propagation environment.

With two coverage area estimates for a cellular system at PCS, a simple calculation estimates the cost savings in the base station infrastructure achievable for the same quality of service (QOS). Figure 1 shows a simplified view of a cellular network plan and how the number of base stations is decreased while maintaining QOS when handset antenna gain is improved by 2 dB. Using a $250K cell site cost and assuming a medium size carrier with 300K subscribers in the 5184 km^2 service area, the number of base stations decreases by 50, for a total savings of about $12 million, even after a $2 handset increase is factored in for the 300K subscribers. Although a simplistic model, the potential for significant cost savings can be seen. Figure 1 details the assumptions made in this cost estimate.



Handset Antenna gain, dB (relative)	Range, km*			Coverage Area Improvement		
	Urban	Suburban	Rural	Urban	Suburban	Rural
0	3.3	20.0	28.6	-	-	-
1	3.53	21.4	30.5	14%	14%	14%
2	3.78	22.9	32.7	31%	31%	31%
3	4.04	24.4	34.9	50%	49%	49%

Assumptions: Freq = 1900 MHz, Tx power = 20 w, Base antenna gain = 16 dBi
24 dBm TRP@handset, Cost 231 & Okumura Hata Model
Estimated figures for discussion

Table 1. Coverage area improvement as a function of handset antenna gain

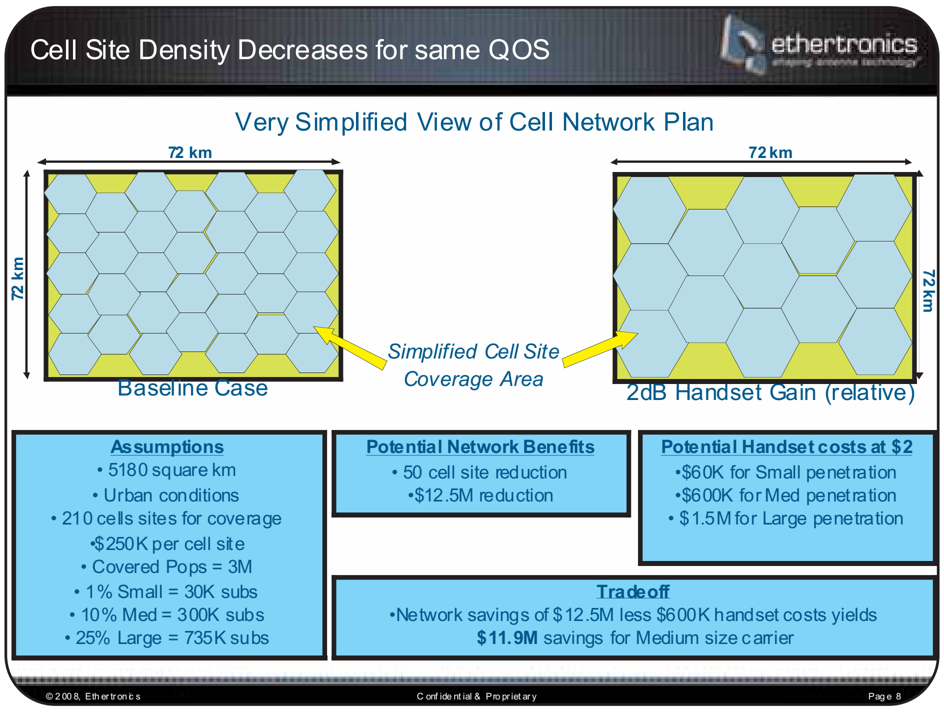
The Problem: Present passive antenna technology approaching limits of physics

Three trends in handset design in recent years make antenna design and integration more difficult: 1) reduced size (volume) of typical handsets, 2) increased bandwidth required from the main antenna as handsets go from quad- to penta-band, and 3) adoption of additional features requiring additional antennas. The result is one trend in opposition with the other two: the shrinking size of the handset will hamper the ability to achieve antenna efficiency from wider bandwidth main antennas, and reduced isolation will be observed between multiple, closely spaced antennas.

As antenna size or volume is reduced it becomes more difficult to maintain a set bandwidth. Wheeler [1] defined the following general formula that links bandwidth of an antenna to its mode volume at a specific frequency:

$$\frac{\Delta f}{f} = K \times \frac{\text{antenna mode volume}}{(\text{radio wavelength})^3}$$

This equation shows that the bandwidth Δf over the central frequency f is linked by a dimensionless number K to the ratio of the antenna mode volume to the wavelength. The K factor is a figure of importance when, all things being equal, we want to compare one antenna to another. The K factor is related to the antenna technology and its design. In Wheeler's original paper, the antennas used to demonstrate this were electric or magnetic dipoles and loops in free space. This allowed the overall antenna mode volume to be defined according to its natural boundaries. For the dipole, it was the sphere enclosing the dipole. For electrically small antennas, the problem is defining the antenna mode volume since it typically significantly exceeds the physical volume of the antenna itself. Some antennas tend to couple strongly to the ground plane making the whole device the antenna. This might lead to an apparent advantage when bandwidth alone is considered but has many drawbacks for multiple antenna systems. Ideally, the antenna alone should be designed to provide sufficient bandwidth. This will translate into higher efficiency and greater isolation due to reduced currents induced on the ground plane. For our discussion, we will assume a K factor of 100; this is based on experience working with electrically small antennas in a handset environment.



Assumptions
- 5180 square km
- Urban conditions
- 210 cells sites for coverage
- $250K per cell site
- Covered Pops = 3M
- 1% Small = 30K subs
- 10% Med = 300K subs
- 25% Large = 735K subs

Potential Network Benefits
- 50 cell site reduction
- $12.5M reduction

Potential Handset costs at $2
- $60K for Small penetration
- $600K for Med penetration
- $1.5M for Large penetration

Tradeoff
- Network savings of $12.5M less $600K handset costs yields **$11.9M** savings for Medium size carrier

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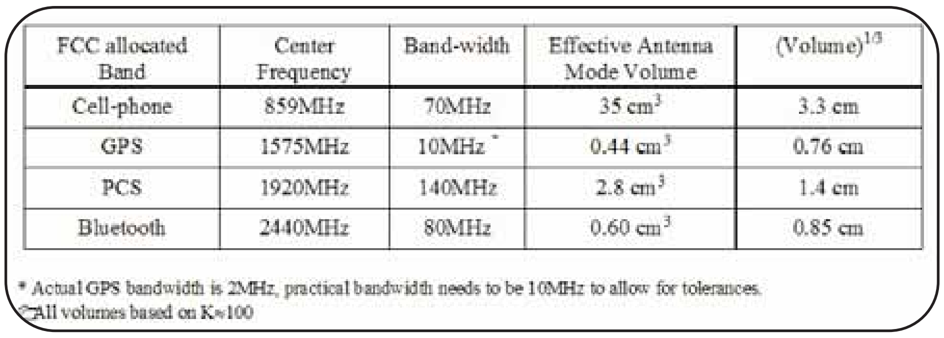
Figure 1. Infrastructure cost savings due to 2 dB handset antenna gain improvement

Table 2 shows calculated antenna mode volumes required to satisfy some typical handset antenna functions. The volume required for an antenna application becomes more problematic as the bandwidth increases and/or the frequency of operation decreases. GPS is an easy requirement to satisfy due to the minimal bandwidth as well as Bluetooth, due to the higher frequency of operation and 3 percent bandwidth requirement. However, the GSM850 cell-phone requirement requires more volume due to the lower frequency of operation and increased bandwidth.



FCC allocated Band	Center Frequency	Band-width	Effective Antenna Mode Volume	$(\text{Volume})^{1/3}$
Cell-phone	859MHz	70MHz	35 cm^3	3.3 cm
GPS	1575MHz	10MHz *	0.44 cm^3	0.76 cm
PCS	1920MHz	140MHz	2.8 cm^3	1.4 cm
Bluetooth	2440MHz	80MHz	0.60 cm^3	0.85 cm

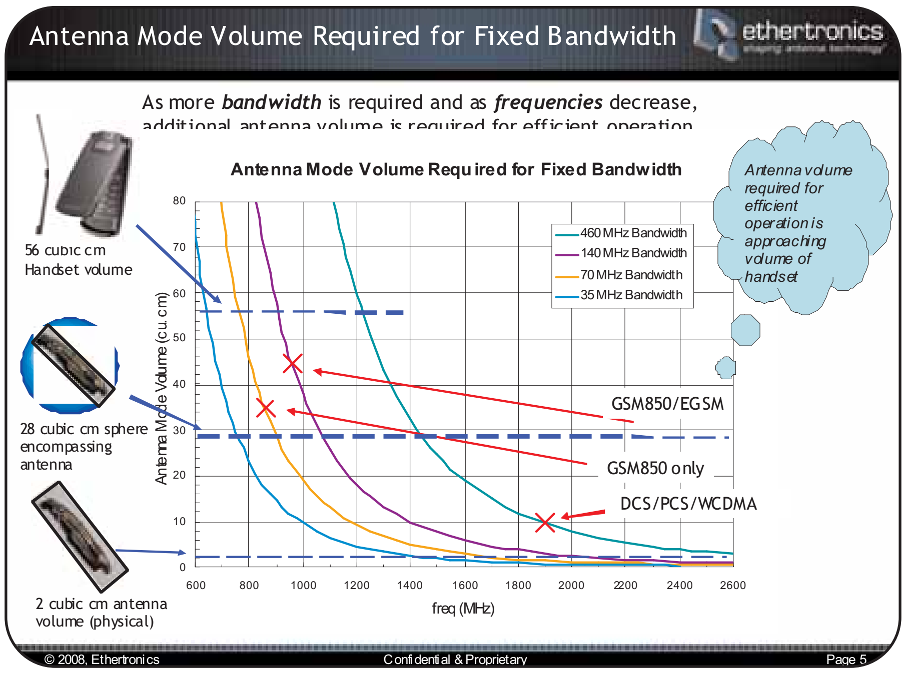
* Actual GPS bandwidth is 2MHz, practical bandwidth needs to be 10MHz to allow for tolerances.
All volumes based on K=100

Table 2. Antenna mode volume required to achieve specific bandwidths for typical handset functions

Figure 2 is a graphical display linking the antenna mode volume required for several bandwidths as a function of center frequency of the bandwidth that is desired. There are several interesting points to consider on this graph:

- Handset volume is 56 cm^3.
- Antenna volume is 2 cm^3.
- The sphere volume encompassing the antenna is 28 cm^3.
- The volume to achieve 140 MHz bandwidth for GSM850/EGSM is 45 cm^3.

The antenna mode volume required to achieve DCS/PCS/W-CDMA performance, GSM850/EGSM (900 MHz), or even GSM850 only clearly exceeds the physical volume allocated for the antenna and is approaching the volume of the handset. The GSM850/EGSM and GSM850 only requirements exceed the volume of the sphere encompassing the antenna. How is this antenna capable of operating? Currents are induced on the handset circuit board to increase the "electrical volume" of the antenna element. The circuit board becomes part of the antenna; coupling to the circuit board results in reduced efficiency and isolation. As more antennas are introduced into the small handset, less performance will be realized due to reduced efficiency and isolation. Ethertronics' IMD antenna technology was developed to minimize this coupling effect, yet future handset sizes, increased bandwidth requirements from next-generation wireless standards, and continued allowable antenna volume reductions will limit antenna performance. The solution is a more resonant (i.e. narrow band) antenna that couples less to the surrounding structure: a tunable antenna.



Antenna Mode Volume Required for Fixed Bandwidth

As more ***bandwidth*** is required and as ***frequencies*** decrease, additional antenna volume is required for efficient operation

Figure 2. Antenna mode volume required is approaching the volume of the handset

A Comprehensive Active Antenna Approach

Ethertronics will provide large improvements in bandwidth and efficiency required from the main antenna in the next-generation handset through three approaches:

1) Active Matching
2) Actively Switched Antennas
3) Null Steering

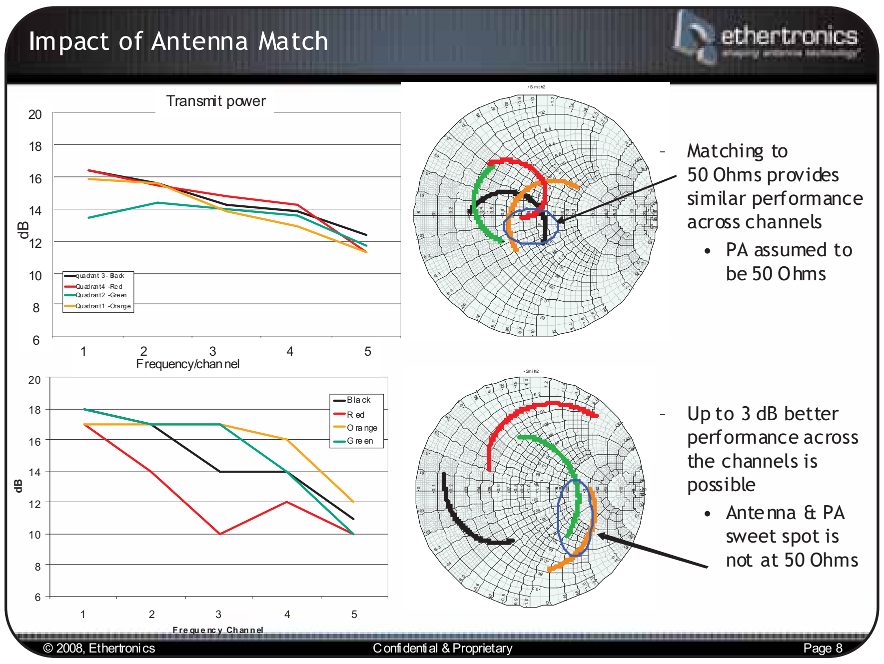
Active Matching

Active Matching is the most well known of the three techniques and the easiest to implement. Active matching uses active components in a matching circuit to optimize the impedance match between the antenna and transceiver, thereby minimizing mismatch loss. The active matching circuit can maintain an optimal impedance match dynamically, providing "real-time" retuning of the antenna matching circuit to account for environmental changes such as placement of the handset against the user's head or a change in hand placement on the handset. The active matching circuit can also be used to optimize TRP (Total Radiated Power) performance of the handset; this is realized because the best antenna impedance for use with the power amplifier is often not 50Ω.

When a handset is moved from one environment to another, i.e. tabletop to user's hand, user's hand to against the head, etc., the antenna impedance will change given changes in the near field of the antenna. An active matching circuit would be instrumental in correcting for environmental effects.

The active matching circuit could also be used to optimize the handset TRP by optimizing the impedance match between the power amplifier and the antenna. Current passive antennas in handsets are typically optimized during the design process by "active matching" to the PA. This is often a compromise due to the multiple transmit bands required of a quad- or penta-band antenna. The use of an active matching circuit would allow for optimization of antenna impedance per transmit channel in "real time", providing better transmit performance.

We can take this analysis further and show how the TRP of a handset varies as the antenna impedance is varied. Figure 3 is a set of measurements that clearly show the improvement in TRP that can be achieved when the antenna impedance is optimized for operation with the power amplifier. A single antenna was matched using a four component matching circuit; the topology and component values of the matching circuit were such that there were four unique matching circuits for the same antenna. The smith chart on the top right of the figure shows the antenna impedance for the four matching circuits, and the TRP is shown on the rectangular plot on the top left. This set of data assumes that the power amplifier is a 50Ω load.



Impact of Antenna Match

- Matching to 50 Ohms provides similar performance across channels
  - PA assumed to be 50 Ohms
- Up to 3 dB better performance across the channels is possible
  - Antenna & PA sweet spot is not at 50 Ohms

Figure 3. TRP of a handset as a function of antenna impedance

The smith chart and rectangular plot on the bottom part of figure 4 shows the antenna impedance and TRP when connected to an actual power amplifier, which does not represent a 50Ω load. The four matching circuits diverge from the center of the smith chart, with one matching circuit providing a good match to the power amplifier. This results in a 3 dB improvement in TRP at several of the channels

In order to solve the issue of antenna de-tuning due to environmental changes, and in order to optimize the antenna impedance to a non 50Ω match for best TRP performance, an active matching circuit with feedback loop can be implemented. This circuit will optimize the antenna impedance in real time. This can be implemented by using tunable capacitors along with fixed inductors in a matching circuit, and using a dual-directional coupler to sense forward and reflected power. By sampling and monitoring the ratio of forward and reflected power, the tunable capacitors can be adjusted to minimize the reflected power. Figure 4 shows a schematic of a potential circuit topology.

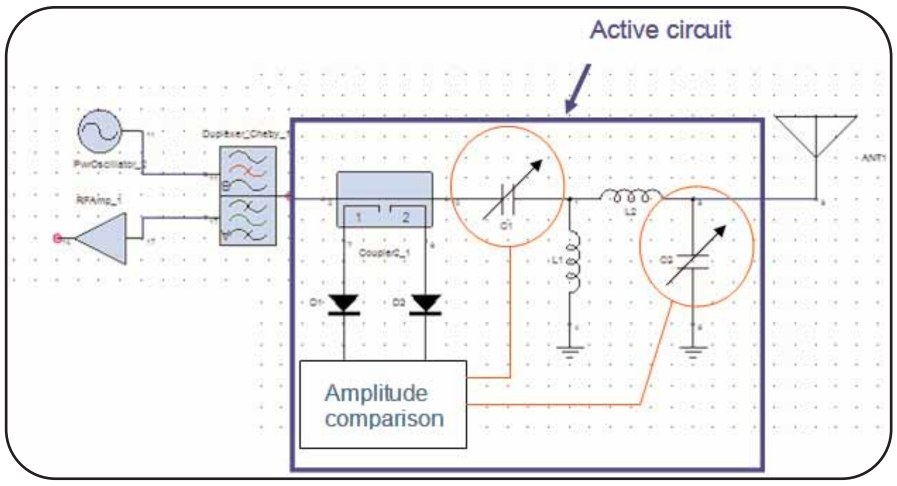


Figure 4. Circuit schematic of active matching circuit

Actively Switched Antennas

Actively switched antennas involve implementing techniques that are unique to a specific antenna technology. Ethertronics has developed a method of changing the frequency response of its IMD antenna structure by coupling active components to the antenna. This method of changing antenna characteristics improves antenna efficiency, since the antenna structure is re-tuned in real time, instead of just optimizing the impedance match of the antenna as with Active Matching. By tuning the antenna structure, the antenna is tuned for the specific frequency band or sub-band at that instant whereby, the antenna efficiency can be optimized over a narrower instantaneous bandwidth.

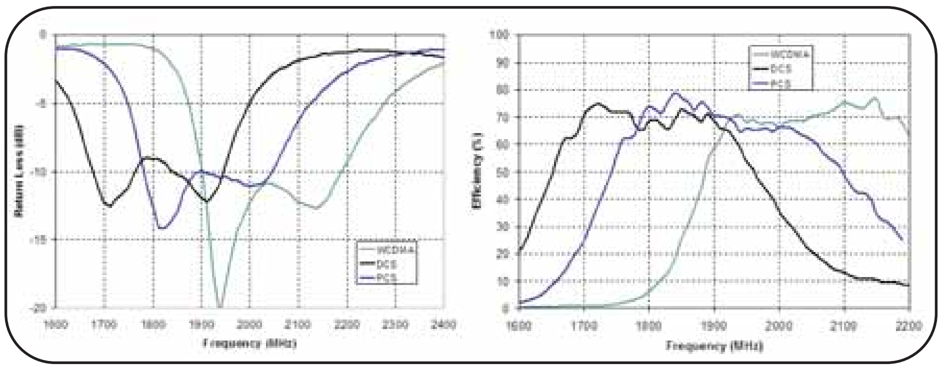


Figure 5. Measured return loss and efficiency of multi-layer active antenna at three tuning states

Ethertronics is developing a multi-layer active antenna that can shift the frequency response of the antenna in real time, enabling a more optimized antenna bandwidth/efficiency characteristic. This antenna will have the size and low-cost attributes required for integration into the next-generation handset. A two microsecond switching speed is presently being prototyped. Figure 5 shows a plot of measured return loss and efficiency for three tuning states of a prototype switched antenna. This data was generated from an antenna that occupies a 1.4 cm^3 volume and on a bare ground plane with dimensions of 40 by 80 mm. The capacitance value of a single capacitor was used to generate this data.

Figure 6 shows a comparison of an active antenna prototype on a bare ground plane and a penta-band antenna installed in a production handset. For comparison purposes, the antenna efficiency of the active prototype antenna was de-rated by 15 percent to account for integration losses typical of handsets. As shown, 2 dB of antenna efficiency can be achieved over a large frequency range when a tunable antenna is implemented.

Null Steering

Null Steering will, in many instances, be the most powerful technique for communication link improvement. Ethertronics has developed a null steering technique that allows for significant change in radiation pattern characteristics of a small, internal main antenna for handsets. The technique is termed null steering to emphasize the

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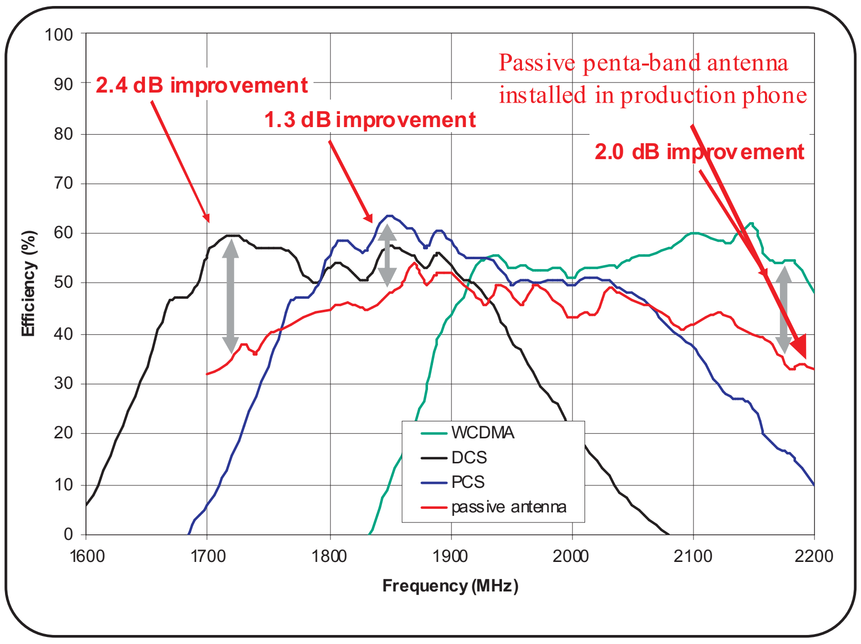

Figure 6. Efficiency of an active, tunable antenna compared to a passive (fixed tuned) main antenna; main antenna is installed in a production handset

fact that as the radiation pattern is rotated, significant increases in antenna gain in angular regions containing nulls or low-gain characteristics can be achieved with the use of active components coupled to the antenna. Antennas in handsets, like all antennas, have radiation patterns that have peak gain regions and regions of low gain (nulls). By rotating radiation pattern characteristics in real time, a significant improvement in link quality will be achieved, providing a robust communication link.

The null steering concept uses a single driven antenna element, with modifications, to generate two propagation modes. These two modes have significantly different radiation patterns. With two modes available from a single antenna element, a scheme analogous to a two-antenna diversity system is realized. The two modes, with the different radiation pattern characteristics, can be sampled in real time to determine which radiation pattern will provide the highest signal strength for the communication link for the multi-path environment at that instant in time.

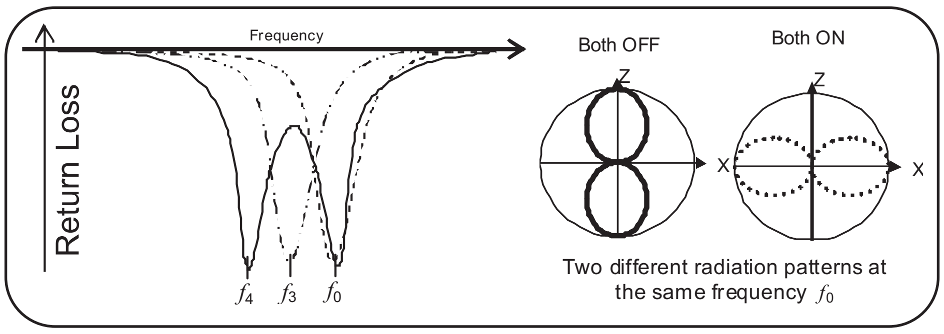

Figure 7. Frequency response and radiation pattern of both modes; solid line is mode 1, dashed line at f_0 is mode 2

Figure 7 shows the frequency response and radiation patterns of the two modes. The solid line is mode 1, while the dashed line labeled f_0 is mode 2. f_3 is the frequency response of mode 2, prior to frequency correction implemented with a second active component coupled to the main antenna. The large change in null location in the radiation pattern provides for good pattern diversity from this one antenna scheme. Two active components are required to achieve the null steering: one active component to generate a second propagation mode, and a second active component to correct for the frequency shift caused during generation of this second mode.

Figure 8 shows the measured frequency response of the two modes for a prototype null steering antenna on a bare ground plane. Figure 9 shows measured radiation pattern contour plots for the two modes. The red regions are regions of high antenna gain, while the blue and black regions are low gain, or null locations. The contour plots show that a significant amount of change in null or low gain regions can be generated between the two modes. This data was measured on a bare ground plane.

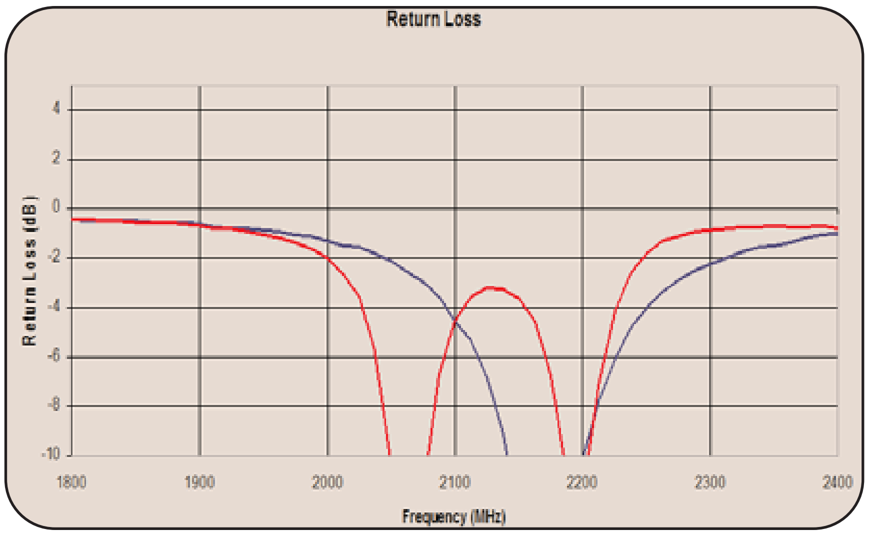

Figure 8. Measured frequency response from prototype null steering antenna

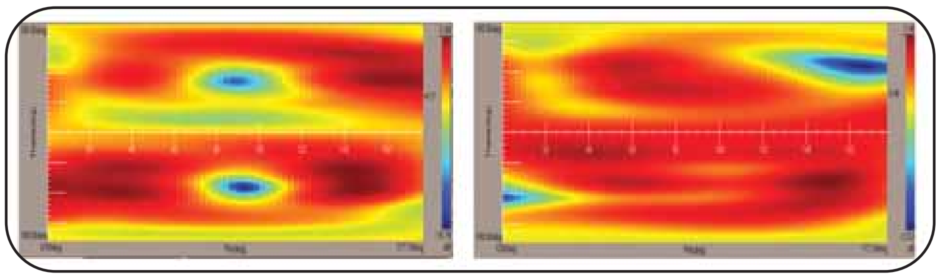

Figure 9. Radiation pattern contour plot for two modes of operation

The next development step for this null steering technique was to implement it in a production handset. This was achieved by installing the null steering prototype antenna into a Samsung handset. Figure 10 shows a photograph of the prototype antenna installed in the production handset. Figure 11 shows 3D plots of the radiation pattern for the two modes for linear polarization. This would be the case for a line of sight communication with a base station. Deep nulls can be seen in both modes at different orientations. The bottom left graph shows the maximum of both modes with several nulls being suppressed. The bottom right graph shows the absolute difference between the two modes or the potential gain achieved by switching from one mode to the other. Peak gains in this case are more than 15 dB.

Figure 10. Prototype antenna installed in a production handset

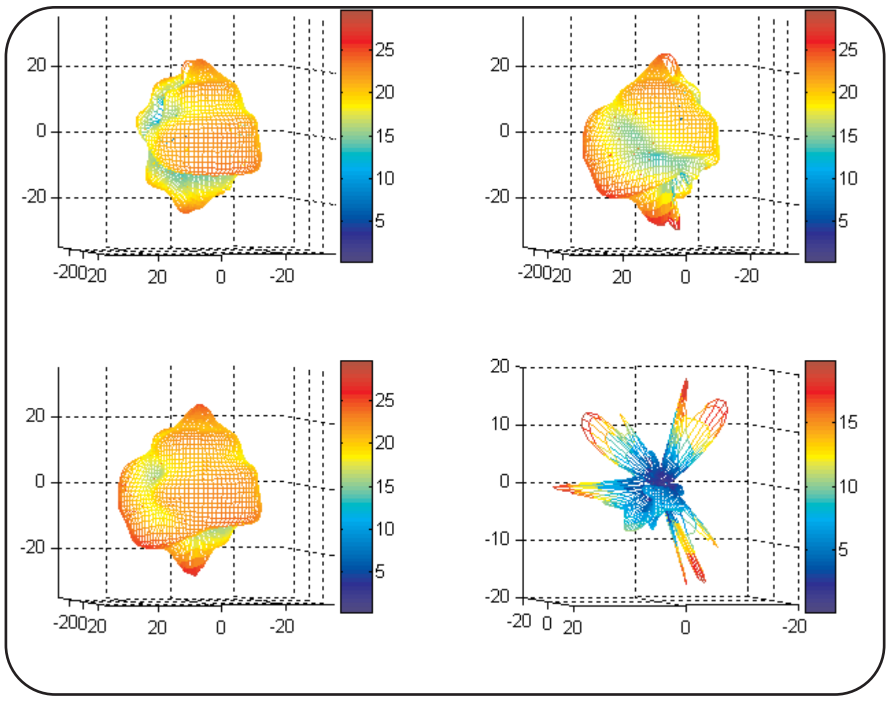

Figure 11. 3D radiation patterns measured for a fixed polarization

Conclusion

Wireless device trends are moving toward smaller devices with increased data rates. Next-generation technologies such as 4G will offer these high data rates through alternate modulation schemes and wider channel bandwidths. However, to deliver on the promise of these technologies, better link budgets will be required. Additional hardware investment on the part of the operators will surely be needed, and as such, cost-effective approaches to increase link quality will also be needed. Ethertronics has developed three active antenna techniques to improve next-generation handset communication link quality with benefits for nearer-term application too. While antenna development activities continue, the broader handset community needs to move in parallel to prepare for integration of this more capable antenna into next-generation handsets as this may be a more cost-effective approach versus base station oriented changes. Indeed, 2 dB in link margin is worth $2 in incremental handset cost when compared to the overall savings in network side infrastructure expenses. This will require disparate parts of the wireless industry eco-system such as carriers, handset vendors, and infrastructure suppliers to work together more closely to harness these significant performance improvements.

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