Technical White Paper
RF Antenna Misalignment Effects on 4G/LTE Data Throughput
Considerations for Maximizing Return on your Spectrum Investments

Abstract
This technical paper describes in detail the need for ensuring that the antenna position closely matches RF design specification at installation, and to have an accurate database of antenna position data for any wireless data network. We will discuss why proper alignment of antennas used in RF (Radio Frequency) mobile networks is important – specifically for newer technologies like 4G LTE, and describe the effect of misalignment on overall network data throughput. Network operators, engineers, and contract installation professionals can use this document as reference to understand how equipment to accurately align antennas is needed to ensure QoS (Quality of Service) and meet KPI (Key Performance Indicator) goals. Network RF design engineers and performance engineers can use this document to improve the overall network data throughput, enhance overall customer satisfaction, reduce subscriber churn, and maximize return on investment in costly RF spectrum.

Introduction
One of the most important elements of efficient mobile network deployment is the antenna system. Proper alignment of that antenna system is critical to the performance of the network in terms of increased of the downlink (DL) and uplink (UL) data throughput.

Planning and deploying mobile data networks is costly – tens (if not hundreds) of thousands of dollars are spent on a single cell site build. Failure to install and align antennas that closely match the original RF design is wasted capital investment – akin to buying a high-performance sports car and then installing mini-van tires.

Engineering a mobile network for the highest-achievable system throughput – while minimizing the potential for interference – will help network operators realize optimum network performance, increase throughput, and reduce time to positive financial return. The data shown will prove the effect of antenna misalignment in deployed systems.

This paper will address in a generalized fashion the importance of proper antenna alignment and its effect on the network data throughput. To illustrate the impact of antenna alignment on performance we took an approved and finalized network design optimized for throughput and then deliberately misadjusted both antenna azimuth and mechanical tilt. We then measured the effect of those changes on network reference signal received quality (RSRQ), signal to interference plus noise (SINR) ratios, interference levels, and data throughput. Our analysis was performed on a 1900 MHz PCS system, FDD-LTE duplex, with a 5 MHz channel bandwidth.

Before reviewing the results of those experiments it's important to define what's meant by "antenna alignment". Most mobile network antennas are "directional sector antennas" (sometimes called "panel antennas") which cover a portion of a circular arc and emit RF in a fan-shaped radiation pattern. Sector antennas are typically deployed in angles of 30°, 45°, 60°, 90°, and 120° according to network design needs. Directional sector antennas have three adjustments for alignment: Azimuth (AZ), Mechanical Tilt (MT), and Roll. Higher-gain antennas typically have narrower beamwidths, so errors in azimuth and tilt have a greater effect on network designs that specify high-gain antennas.

Azimuth Alignment (AZ)

Proper alignment of azimuth is required so that RF signals are emitted towards – and received from – a given area of coverage, known as the Coverage Objective. Proper azimuthal alignment is also required to dismiss unwanted RF signals from adjacent sectors which become interference sources. Antennas are securely mounted to their permanent location on the rooftop site or tower. One method for azimuth alignment is using a compass; however this method is problematic because a compass can be deflected by the ferrous metals and RF signals found on towers, and because Magnetic North and True North are different so proper declination (the difference between the two) must be consistently applied – usually it is not. Also, because the Magnetic North Pole is constantly shifting position, in some locations declination can change by as much as 2° within 10 years. [1] Figure 1 shows the top view of a tower-mounted sector antenna array with the azimuth errors that we introduced for our study. These introduced errors varied from ±15 degrees to ±20 degrees – more details will be covered later in this paper.

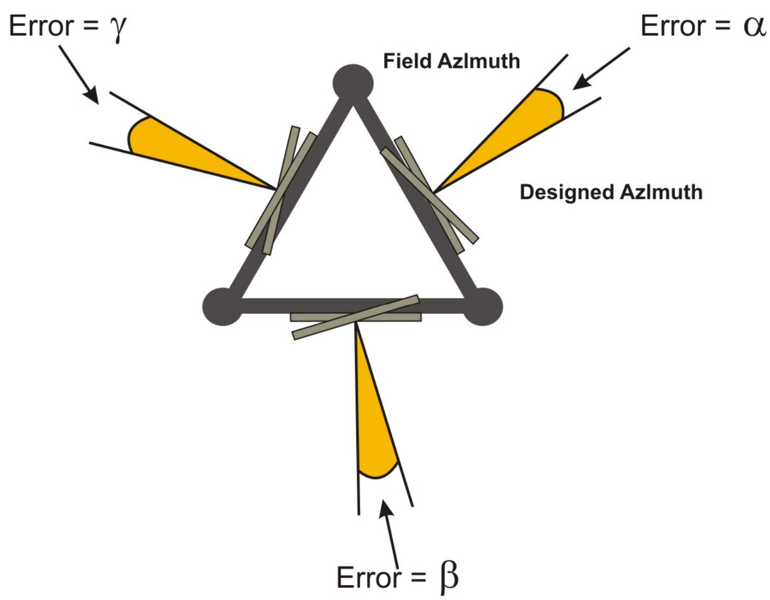

Figure 1, Top view of the mounted antennas, showing AZ errors

Mechanical Tilt (MT)

Mechanical tilt is used in RF systems to aim the main lobe of the antenna's radiation pattern so that RF energy is directed below (or above) the horizontal plane. Some antennas are static and fixed, while others offer a Remote Electrical Tilt (RET) feature which allows the tilt to be tweaked according to need – however in order to realize the full benefit of an RET antenna the initial tilt needs to be set accurately during construction and preventative maintenance. We will see later how accuracy in aligning tilt has a large effect on system performance and investment return, and it should be stressed that a 0° MT reference is critical to ensuring accuracy when using RET equipment.

When an antenna is aimed below the horizontal plane the configuration is called "down-tilt", versus "up-tilt" where the signal is aimed above the horizontal plane. Because antennas are typically mounted high above ground level where mobile subscribers are likely to be down-tilt, which is used to "contain" the RF signal in the most useful direction, it is the most common mechanical tilt configuration. Down-tilt is also used to control and optimize the overlap between adjacent sectors.

Vertical angle calculations are given by:

$$\tan \propto = \frac{X}{D}$$

X = Antenna Height Difference (in feet)
D = Path Length (in feet)
α = Angle to Lower Antenna
2·α = 3 dB Beamwidth of the Antenna

Therefore:

$$\propto = \tan^{-1}\frac{X}{D}$$

Once the angle is calculated, mechanical elevation can be set. Some antenna vendors include an elevation scale on the mounting hardware, so the elevation can be set according to the installation instructions included. If no such scale exists, Figure 2 shows the parameters required to calculate the amount of tilt required.

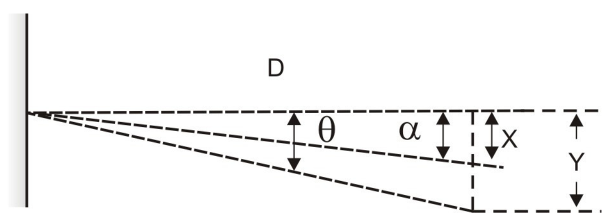

Figure 2, Antenna Mechanical Tilt

Roll

An antenna's roll is the angle of its vertical axis relative to an ideal vertical plumb to the ground. If roll misalignment occurs, the RF radiation pattern's side lobes will become distorted – which can have a negative effect on overall network performance. Most RF propagation software tools assume an antenna is always plumb or zero, and so there is not always a method to predict and simulate roll misalignment. While antenna roll is a minimal contributor to misalignment issues when compared to azimuth and mechanical tilt – the amount of roll would have to be significant to have an effect on network QoS/KPI. For the purposes of this study, the effect of antenna roll was not measured, but the effect of excessive roll is detrimental and should be confirmed during construction and maintenance to be as close to 0° as possible—and tolerances should be set for antenna install.

Channel Capacity as a Function of Bandwidth & Signal-to-Noise Ratio

A foundational concept in communications is the Shannon-Hartley theorem which defines a maximum rate of information transfer as a function of channel bandwidth and the signal-to-noise ratio. [2] The equation is:

$$C = BW \cdot log_2(1 + SNR)$$

Where:

C is the channel capacity in bits per second
BW is the channel bandwidth in hertz
SNR is the signal-to-noise ratio

If we normalize the channel bandwidth to 1 Hz and examine how the function behaves, we see that variations of SNR have a direct effect on the ability of the channel to carry information. For an SNR = 6, 1 Hz of channel can carry (at most) 8.45 bits of information. For an SNR = 8, 1 Hz of channel can carry (at most) 9.54 bits of information; and thus a -2 dB variation of signal level (presuming channel noise remains constant) reduces channel capacity by over 21%. In a real world 4G system, where data rates can exceed 10 Mbps, this variation would reduce performance by over 1.0 Mbps – a real problem in a market where customer perceptions about network performance are a primary factor in subscriber churn. In many cases the alignment of an antenna is taken for granted, and poor performance is blamed on factors such as ambient RF noise, multipath, rain/snow, etc. when in fact the problem may be that the antennas of the serving site or neighboring sites are misaligned. In addition to traffic capacity, Hand-Off (HO) performance will also be affected due to impact of interference on the control channel. Also, SNR should be considered a more conservative measure since self-induced interference is not included as it is with SINR, which is core to most LTE network design and optimization efforts.

The Effect of Azimuth and Mechanical Tilt Alignment Errors on Network/Performance KPI

To empirically study the degradation of azimuth and tilt misalignment, we chose an Area of Study (refer to Figure 3) and predicted performance of the network using Planet EV™, an industry standard network planning tool. We then deliberately misaligned antenna sectors and measured the degradation in network throughput. Two scenarios were tested for this purpose, with results as summarized in Table 1. It should be noted that these scenarios were simulated conservatively – our experience with real world systems is that there is much more uncertainty caused by random misalignments, and thus more issues. Our analysis is focusing only on sectors with high throughput loss – not total degradation to the overall market, so the overall effect to the network is likely to be much worse.

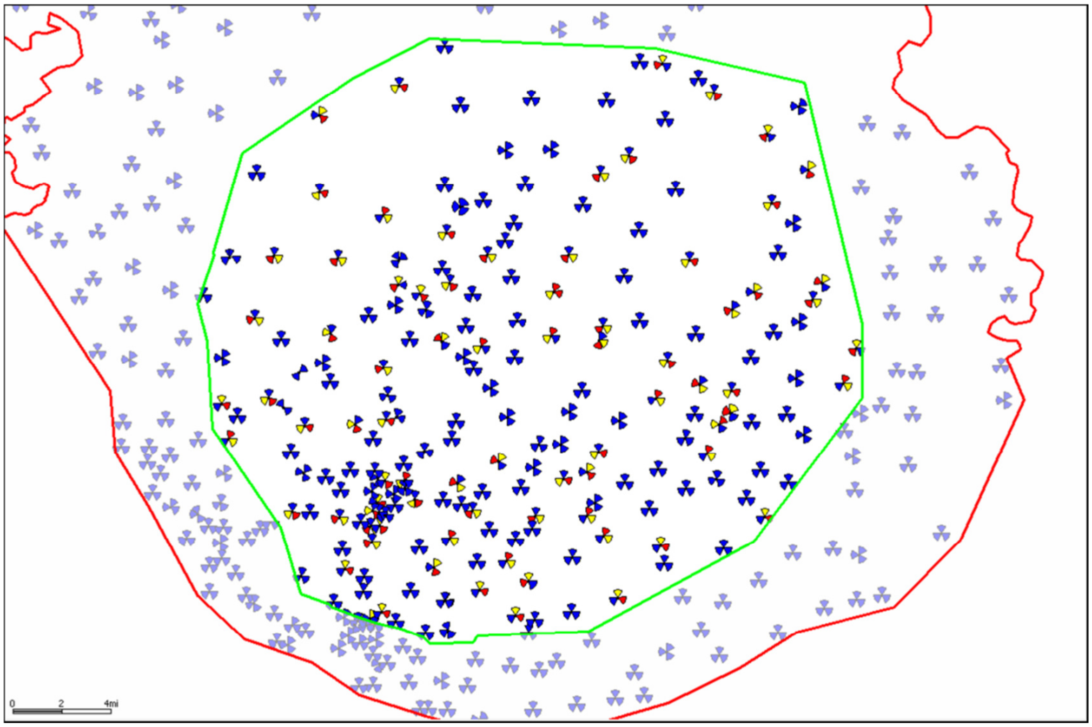

Figure 3, Area of Study (AOS)

				# of DL Sectors w/ Throughput Degradation		# of UL Sectors w/ Throughput Degradation	
Study	Total # Antenna Sectors	# of Sectors Changed	Description/Case Scenario	Throughput Degraded > 2 Mbps	Throughput Degraded > 1 Mbps	Throughput Degraded > 0.5 Mbps	Throughput Degraded > 0.2 Mbps
Case 1	600	160	AZ (±15°) & MT (±2°) (Misalignment applied to 26% out of 200 sites)	11	63	4	85
Case 2	600	240	AZ (±20°) & MT (±3°) (Misalignment applied to 40% out of 200 sites)	13	82	13	92

Table 1, Results of sector counts w/ throughput degradation

Case 1: Azimuth (±15°) & Mechanical Tilt (±2°), applied to 26% out of 200 sites

In this case the azimuth (±15°) & mechanical tilt (±2°) were adjusted on 52 out of 200 sites. It should be noted that 50% of the changed sectors had only their azimuth or their tilts changed, and the other 50% of the changed sectors had both their azimuth and their tilt changed. In cases where the tilt was changed; half were up-tilted, half were down-tilted.

After running simulation on the area of study (refer to Figure 3) observation of the throughput clearly showed that 11 sectors had degraded throughput in excess of 2 Mbps, while 63 sectors were degraded by more than 1 Mbps – including the 11 sectors which degraded by > 2 Mbps. (Refer to Table 2) Uplink throughput measurements showed 4 sectors degraded by more than 0.5 Mbps, while 85 sectors degraded by more than 0.2 Mbps – including the 4 sectors which degraded by > 0.5 Mbps.

Measurement showed that RSRP at the LTE noise floor (approximately -113 dBm) degraded from 89.61 % of the network coverage to 89.23%. Also the percentage of measurements with 4 or more servers observed within 5 dB increased from 2.81% to 2.95%, implying that higher interference levels were introduced to the network by misalignment.

Measured SINR DL values ≤ 10 dB showed degradation from 13.61% of the network to 13.26%. Average DL throughput per sector degraded by 0.04 Mbps. Total network DL throughput also degraded by 28.16 Mbps – decreasing 2.469 Gbps to 2.441 Gbps. (Refer to Table 2)

Case 1		Before	After	Delta	Results
RSRP, dBm	**-113**	89.61	89.23	-0.38	degraded
RSRQ, dB	**-15.0 @ 100% Load**	90.92	90.67	-0.25	degraded
% Area with 4 or more servers within 5 dB		2.81	2.95	0.14	degraded
% Area with 2 or more servers within 5 dB		36.85	37.25	0.40	degraded
% Area with 7 or more servers within 10 dB		1.17	1.57	0.40	degraded
SINR (DL), dB	**5**	31.06	30.56	-0.50	degraded
	10	13.61	13.26	-0.35	degraded
	20	0.33	0.34	0.01	same
SINR (UL), dB	**5**	99.92	99.93	0.01	same
	10	98.86	98.87	0.01	same
	20	80.37	79.60	-0.77	degraded
Total Number of LTE Sites		200	200		
Total Number of LTE Sectors		596	596		

Table 2, Case 1 Network results.

Case 2: AZ (+/- 20^{o}) and MT (+/-3^{o}), applied to 40% out of 200 sites

In this case the azimuth (±20°) & mechanical tilt (±3°) were adjusted on 80 out of 200 sites. It should be noted that 50% of the changed sectors had only their azimuth or their tilts changed, and the other 50 % of the changed sectors had both their azimuth and their tilt changed. In cases where the tilt was changed; half were up-tilted, half were down-tilted, for sectors on same site.

After running simulation on the area of study (refer to Figure 3) observation of the throughput clearly showed that 13 sectors had degraded throughput in excess of 2 Mbps, while 82 sectors were degraded by more than 1 Mbps – including the 13 sectors which degraded by > 2 Mbps. (Refer to Table 3) Uplink throughput measurements showed 13 sectors degraded by more than 0.5 Mbps, while 92 sectors degraded by more than 0.2 Mbps – including the 13 sectors which degraded by > 0.5 Mbps.

Measurement showed that RSRP at the LTE noise floor (approximately -113 dBm) degraded from 89.61% of the network coverage to 88.07%. Also the percentage of measurements with 4 or more servers observed within 5 dB increased from 2.81% to 3.51%, implying that higher interference levels were introduced to the network by misalignment.

Measured SINR DL values ≤ 10 dB showed degradation from 13.61 % of the network to 11.79%. Average DL throughput per sector degraded by 0.16 Mbps. Total network DL throughput also degraded by 97.55 Mbps – decreasing from 2.469 Gbps to 2.371 Gbps. (Refer to Table 3)

Case 2		Before	After	Delta	Results
RSRP, dBm	**-113**	89.61	88.07	-1.54	degraded
RSRQ, dB	**-15.0 @ 100% Load**	90.92	89.03	-1.89	degraded
% Area with 4 or more servers within 5 dB		2.81	3.51	0.70	degraded
% Area with 2 or more servers within 5 dB		36.85	39.06	2.21	degraded
% Area with 7 or more servers within 10 dB		1.17	2.28	1.11	degraded
SINR (DL), dB	**5**	31.06	28.32	-2.74	degraded
	10	13.61	11.79	-1.82	degraded
	20	0.33	0.40	0.07	same
SINR (UL), dB	**5**	99.92	99.84	-0.08	same
	10	98.86	98.30	-0.56	degraded
	20	80.37	77.54	-2.83	degraded
Total Number of LTE Sites		200	200		
Total Number of LTE Sectors		596	596		

Table 3, Case 2 Network results

Analysis

All sectors in both Case 1 and Case 2 with deliberately misaligned mechanical tilt were equally adjusted; 50% were down-tilted, and 50% were up-tilted, sectors on same site. This was done to create a more realistic scenario where the down-tilted sectors were definitely contributing in improving overall network interference, and consequently data throughput. If we had chosen to more randomly misalign all mechanical tilts as up-tilted, then our KIP results would have worsened dramatically. For example; Case 2 clearly shows that 14 % of network sectors have degraded DL throughput of more than 1 Mbps – this percentage would have doubled if we had chosen to replace down-tilt misalignment with up-tilt misalignment.

The results of this empirical test clearly show that misalignment of antenna sectors has a direct and measureable effect on network performance. Intuitively, this is not surprising – any technician or engineer would have guessed that degradation would be the outcome. What is perhaps surprising is the number of antenna sector misalignments which exist today in real networks. An audit conducted in the first half of 2013 found that 2,541 out of 6,046 antennas were out of tolerance. 27% of the antennas were 4 - 10 degrees out of tolerance, 15% were more than 10 degrees out of tolerance, and shockingly *6% of the surveyed antennas were 21 - 90 degrees out of tolerance*. (Refer to Figure 4) Given the observed degradation in the empirical tests caused by our (relatively minor) misalignments, we can only guess at how badly a network with 21 – 90 degree misalignments would perform.

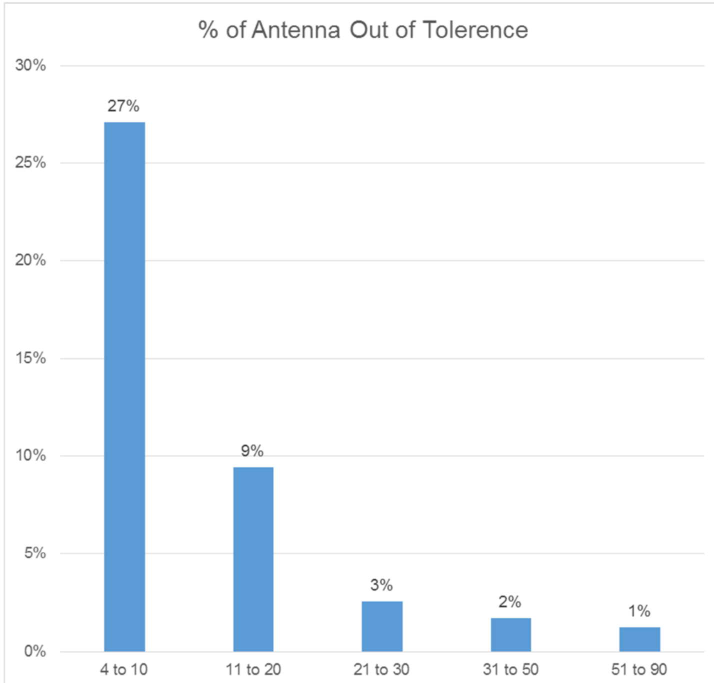

Figure 4, 1H-2013 Antenna Site Audit Results (Degrees misalignment)

Causes and Solutions

So how do antenna sites get out of alignment, and what can we do to correct the problem? Azimuth and mechanical tilt errors are largely the result of improper measurement methods and inadequate tools.

Consider the case of mechanical tilt; many install crews probably use a basic inclinometer for measuring down-tilt. Placement of these inclinometers on antenna for measurement is often random, leading to errors. Free apps on smartphones using onboard accelerometers to replicate functionality of an inclinometer are suitable for hanging pictures in your living room, but on an antenna tower where errors reduce RF performance and impact revenue are uncalibrated, inconsistent, and thus should not be trusted for professional work. Mechanical tilt needs to be measured consistently, at the same reference point on every antenna, based on a published Method of Procedure using approved calibrated tools.

How does down-tilt inaccuracy affect design performance? Recall from the earlier equations (in the Mechanical Tilt section) which related the path length (D) to the antenna height difference (X) and the angle between the tower antenna and target antenna. Solving for path length we obtain:

$$D = \frac{X}{\tan \alpha}$$

As an illustrative example; let's presume that the tower antenna is 200 feet above ground level (AGL). A typical sector antenna down-tilt might be 4.0 degrees, which gives a path length of 2,860 feet – in other words, the antenna is aimed at a point on the ground about a half mile away. What happens if the clinometer is off by ±0.5°? Down-tilt of 3.5° gives us a path length of 3,269 feet, and a down-tilt of 4.5° gives us a path length of 2,541 feet – errors respectively of 409 feet and -319 feet. Presuming a 120° sector antenna, if we calculate the coverage on a tower 100 feet AGL should be 0.307 square miles. A down-tilt variance of ±0.5° causes the site's coverage to range from 0.243 sq miles (4.0+0.5° down-tilt) to 0.402 sq miles (4.0-0.5° downtilt). A small error in mechanical downtilt can equate to a large variance in coverage footprint.

This is a calibrated inclinometer
(Sunsight Classic AAT)

This is not

Azimuth errors are also caused by improper measurement methods and inadequate tools. Magnetic compasses used for wilderness orienteering, or smartphone apps which display the phone's internal compass, are often used by tower crews to determine and set azimuth bearings. Unfortunately magnetic compasses are adversely affected by nearby metal, and can be disrupted by nearby RF radiation or even electric current flowing in power cables. Magnetic compasses must also be compensated for declination, which changes both from region to region – and over time.

This is a calibrated azimuth alignment tool *(New Sunsight AAT-30)*

These are not

Estimating Cost of Degraded Networks due to Alignment Inaccuracies

Given that we can calculate the expected coverage area of an antenna site, we can calculate the value of the spectrum used for the system. Spectrum auctions conducted in the United States are valued by the total bandwidth and population covered. Known a "$ per MHz·POP" the valuations have historically been between $0.20 per MHz·POP and upwards of $1.70 per MHz·POP depending on the spectrum frequency, prevailing economic conditions, and perceived market value. [3] Most recently spectrum auctions have been pricing in excess of the $1.50 per MHz·POP range [4] and we can expect that the upcoming spectrum auctions in 2015 may price closer to $2.00 per MHz·POP.

For purposes of analysis, let's look at the costs associated with Case 2 in the study we conducted on a 1900 MHz PCS system, FDD-LTE duplex, with 5 MHz channel bandwidth. Let's estimate that auction cost of this spectrum was $1.50 per MHz·POP, and that the operator has 250 sites covering 250 square miles in the Santa Clara County, the heart of the Silicon Valley. Santa Clara County has a population (2010 US Census) of 1.78 million people. [5] Total spectrum value for the studied system, if located in Santa Clara County, would be just under $13.3 million. Presume that each site has three 120° sectors i.e. 750 sectors, and thus the value of spectrum in each sector is $17,816. In a perfect implementation, we'd expect each sector in this system to provide an optimal downlink data rate of 18 Mbps. Our study found of the misaligned 240 sectors that 82 sectors had throughput degraded in excess of 1 Mbps (and 11 with 2 Mbps). In other words; 14% of sectors showed a 6.3% degradation, so the spectrum used by those degraded sectors (which cost $1.50 per MHz·POP) is only worth $1.42 per MHz·POP when the system is misaligned, and the value in each misaligned sector is reduced to $16,694. In our hypothetical scenario 14% misliagnments in 750 sectors means that 105 sectors are degraded, resulting in a lost value of $117,810. This rough estimation is based on a very conservative degradation of 1 Mbps in each misaligned section – the actual degradation could be 2 Mbps or more. (Refer to Table 1) To extend this simulation over an average US national operator network of say 40,000 cell sites with a 20 MHz FDD channel would mean that $75.4 million dollars worth of spectrum was not effectively used.

To look at the problem another way: Let's consider a scenario with spectrum priced at $1.50 per MHz-POP and a 5 MHz FDD-LTE system in the San Francisco Bay area. Recall the previous discussion about the effect of down-tilt on coverage area. We estimated that a 120° sector antenna 100 feet above ground, with a down-tilt variance of +0.5° caused the site's coverage to change from 0.307 sq miles (4.0° down-tilt) to 0.243 sq miles (4.0+0.5° downtilt). San Francisco Bay Area has an average population density (2000 US Census) of 17,246 people per square mile. [6] By design, one sector of the example antenna site should be providing coverage which is worth $39,746 but because of the mechanical tilt error the site is covering a smaller area which is worth only $31,377. In other words; left uncorrected the mobile network operator has wasted $8,369 for their spectrum – on just that one sector which is misaligned by only +0.5°!

The same spectrum valuation methodology can be applied to azimuth errors. Consider the same site, with a sector antenna that's misaligned by 10° azimuth. The value of that 120° sector (designed to cover 0.307 square miles) is again $39,746 but since it now overlaps with the adjoining sector it's only covering 110° and the covered area is only 0.282 square miles – and the operator is wasting $3,312 in spectrum.

The 2013 audit showed that 27% of site antennas are misaligned up to 10°. Presume that a regional operator of a Tier 2 market network has 250 sites, and that the average cost of spectrum wasted through each misalignment is $4,500 – the total cost of wasted spectrum due to misalignment is $303,750! This is truly conservative – the real number is of course much larger because it doesn't account for the 15% of site antennas found to be misaligned more than 10°.

Extending this estimation to a national operator with a 20 MHz FDD-LTE system across 40,000 sites, if we again estimate that the total loss from wasted spectrum is $4,500 per site, and 27% misaligned up to 10°, results in to $48.6 million in total loss – double that if the national operator has 40 MHz of LTE spectrum.

In conclusion: It's clear from this analysis that when real world antenna installations do not match the RF design's intended position, azimuth, and tilt problems will arise in data throughput performance, spectrum efficiency, and overall network KPI. It is also clear that LTE data capacity is at the mercy of interference more than signal coverage. In order to design or optimize with a focus on interference mitigation it is important to know precise baseline antenna position. We believe that we have established a logical basis for estimating the maximum and minimum economic impact to real-world networks. The actual impact this has on any one network or operator of course depends on how much attention is being paid (or has been paid in the past) to ensure that Methods of Procedure clearly define accurate alignment methodologies, and whether those MOPs specify calibrated test equipment necessary for accurate alignment.

It's important to note that our study and cost estimates examined only the direct effect on lost return from wasted spectrum and do not take into account all losses including lost opportunity cost from providing reduced data throughput to users who are on measured/tiered Data plans, subscriber churn from not meeting expectations, and engineering/maintenance costs incurred by responding to customer complaints or needlessly investigating problem areas deduced from KPI. Also, one thing that could be easily calculated by wireless carriers is the squandered capital investement on underused infrastructure (BTS/RAN), this will vary between carriers and technologies.

As we move forward into 3GPP LTE technologies such as Self-Optimizing Networks (SON), Self-Backhauling, and Automatic Cell Planning (ACP) the need for accurate position, azimuth, tilt, and height information in the RF site database becomes critical. Relative to the lost opportunity costs of deploying RF networks that don't conform to original design criteria, calibrated test equipment which can accurately measure and record antenna location, tilt, roll, and azimuth is an investment which will provide immediate return-on-investment and long-term network dividends.

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David Witkowski is the founder and Principal Consultant of Oku Solutions, a wireless industry consultancy. Over a career spanning 30 years David has held positions of leadership and responsibility in the wireless and telecommunications industry at companies ranging in size from Fortune 500 multi-nationals to early stage startups. David's experience in tower/site engineering began in the US Coast Guard, transitioning to a civilian career deploying and maintaining land mobile radio, public safety systems, and analog cellular sites.   David was Sr. Product Manager at Anritsu Company where he was responsible for several models of handheld instrumentation used in site monitoring, commissioning, and maintenance.   David serves as President of the non-profit Wireless Communications Alliance, as an advisor to the Carnegie Institute of Technology Dean's Council at Carnegie Mellon University, and as a member of the Wireless Communications Initiative committee for Joint Venture Silicon Valley. He obtained his BSEE from University of California with a study emphasis on modulation theory and RF/wireless design.

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