Femtocells Bringing Reliable Location and Timing Indoors

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Telecom services providers are betting that femtocells – small local versions of wireless base stations – will catch on with customers and also help relieve the load on the carriers' networks. But these microcells will typically be installed indoors in homes and offices by the customers themselves rather than telecom company personnel, which complicates the process for using GPS-based technology to meet timing and frequency need. A hybrid TV/assisted GPS approach may offer the solution.

Femtocells — typically designed for use in residential or small business environments — are generating great interest among telecommunications service providers and consumers alike.

We can think of a femtocell as a cellular base station, shrunk down to the size of a WiFi router and connected to the broadband Internet connection (such as DSL or cable), which can handle several mobile handsets. Within the femtocell coverage area, voice and data calls approved to use the femtocell will be carried not through the macrocellular network, but through the femtocell itself.

These calls are connected via a licensed (GSM, CDMA, WiMAX) or an unlicensed (WiFi) interface. From the femtocell, the call is backhauled over the Internet and into the carrier network through which they are completed just like any other cell call.

Femtocells hold great promise for telecommunications service providers. They provide high-quality coverage across a small footprint, reduce customer churn, generate additional monthly service revenue, and reduce the traffic on the radio access network by offloading in-home voice and data traffic from the macro cell towers. For consumers, better quality of service and rates are among the enticements offered by femtocells.

Participating telecommunications standards associations including the 3rd Generation Partnership Project (3GPP) and the Femto Forum hope to establish globally applicable specifications for femtocell technology by the end of 2008. In the meantime, market research organizations predict a booming business within a very few years. In an ABI Research report released earlier this year, "Femtocell Market Data," the company's vice-president Stuart Carlaw predicted that shipments will likely total tens of millions by 2010.

The devil, of course, is in the details, and several different architectures are being employed for the femtocell carrier network interface under such names as *Cellular Base Station, Collapsed Stack, UMA/GAN,* and *home-node B*. But all of them require accurate position/location and timing to ensure robust operation and to avoid interference between cell towers and femtocells as well as to maintain capabilities and services that consumers depend on.

This article examines the location and timing needs for femtocells and explores the merits of various technologies in meeting these needs, with a focus on a hybrid system based on television transmissions and assisted GPS.

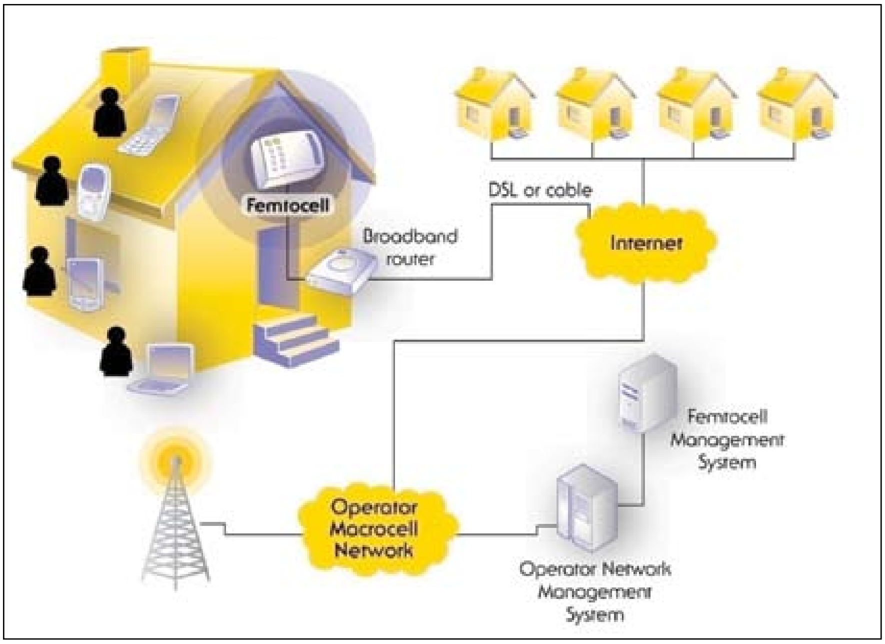
Femtocell Timing and Location Needs

Femtocells have similar requirements for location and timing as macro base stations on a hilltop, and for the same reasons. Accurate real-time location helps service providers meet regulatory mandates and operators' business needs for such things as emergency caller location identification, verification of licensed spectrum operations, and monitoring customer usage.

Emergency caller location identification requirements differ by country. In the United States, the Federal Communications Commission (FCC) E911 rule mandates identification of the cell site or sector where the call is received (Phase 1) evolving into the capability to locate the handset itself (Phase 2). The latter standard generally requires position/location accurate to within 50 to 150 meters, depending on the type of technology used, (handset-based or network-based, respectively).

Recent action by the FCC points to a goal of tighter accuracy requirements (involving compliance at the level of the public safety answering points — the emergency call centers — or the county level), a greater interest in new technologies (such as VoIP and femtocells), and a greater awareness of indoor performance challenges of existing technologies.

As consumers continue to move away from traditional fixed-line service in their homes to alternatives such as wireless-only or VoIP, consumer expectations that E911 service will be available in their homes will increase pressure on carriers. (The Cellular Telephone and Internet Association (CTIA) reports that as of June 2008, nearly 16 percent of all US households are "wireless only" meaning that they depend on only their handsets for 911 calling.) These service expectations have occurred for wireless handsets and VoIP, and we expect that it will be the case for femtocells, both licensed and unlicensed.



Femto Forum graphic

Additionally, in order for wireless operators to offer service over licensed spectrum in an area, they must receive authorization from the FCC. Because licensed femtocells fit this definition, automatic location of the femtocell is critical in ensuring that the femtocell is indeed deployed in a licensed area.

Finally, automatic location can help service providers detect fraud and manage the charging of usage fees across geographic areas with different rates.

- Timing and frequency stability is critical for licensed-spectrum femtocells and for operation of macro cells. Neither will not work without a stable timing source.

These requirements vary based on the technology used by a femtocell to access the telecom infrastructure. For CDMA, WCDMA, and WiMAX, both network synchronization and frequency stability are required; for GSM/UMTS networks, frequency stability is required.

For example, for systems requiring synchronization between the femtocells and the telecom networks, providers are asking for one-microsecond timing accuracy. To maintain frequency alignment with the macro cellular network, femtocells must broadcast at a pilot frequency with an error no greater than 100 parts per billion (ppb), although some efforts are under way to relax this requirement to 250ppb. For WiMAX femtocells, this frequency requirement is much more stringent at 20–40 ppb.

Given the rapid growth in femtocell adoption, consideration must be given to the operational requirements, including managing customer expectations for ease-of-installation — devices that work out-of-the-box with minimal configuration. Customer service calls must be avoided in order to maintain carrier profit margins with this new service.

A widely quoted target for the femtocell bill of materials (BOM) is around $50, with many current devices costing customers more than 50 percent more than that today. Today carriers subsidize femtocells, but tremendous pressure clearly exists to reduce the cost of femtocells.

Femtocell Challenges

Two factors complicate efforts to meet the timing and positioning needs of femtocells: 1) they are generally deployed inside buildings where signal reception is poor, and 2) the service provider has little control over the placement of the femtocell within the customer's home.

Let's take a closer look at these constraints. Poor coverage can be due to a number of factors: the absence of a near-by cell tower leading to signal attenuation over distance, or signal blockage caused by terrain or man-made structures such as buildings, including the customer's residence or office.

Issues arising from placement of the femtocell within the customer's residence are driven mostly by constraints on the location of the DSL or cable outlet, wiring, and/or furniture. Timing and frequency stability solutions that depend on the reliable receipt of RF signals must overcome these constraints. Perhaps the most important of these constraints is building attenuation.

Signal Attenuation Inside Buildings

Fading effects, building attenuation caused by building materials, vary greatly by the frequency of the RF signal. Table 1 below shows a summary of a National Institute of Standards and Technology (NIST) study of RF attenuation caused by building materials.

Note the tremendous difference in attenuation levels across frequencies for building materials, between TV, cellular, and GPS frequencies, and the even greater discrepancy for WiMAX. In passing through a concrete wall of an apartment building, GPS is attenuated 6 dB more than TV, 4 dB more than cellular, but 20 dB less than WiMAX. All steel-reinforced concrete tests were done using eight-inch (203-millimeter) thick slabs.

More detailed building attenuation models have been developed such as the one described in the Working Papers column in the July/August 2008 issue of *Inside GNSS*. These models are helpful in understanding attenuation effects with greater precision.

Timing and Location Solutions

A variety of methods have been explored to provide timing and location for femtocells (See Table 2).

As GPS is already widely used in cellular base stations, many companies are promoting the use of GPS and assisted-GPS (AGPS) as a femtocell timing and location solution. AGPS (or multiple constellation versions of assisted GNSS) replaces missing satellite broadcast data when access is intermittent, difficult, or impossible due to signal obstruction.

This data includes the orbital location of GPS satellites, timing information, and the approximate location of a receiver. (See, for example, the discussion on AGNSS by Lionel Garin in the GNSS Solutions column in the November/December 2006 issue of *Inside GNSS* and by Jari Syrjärinne and Lauri Wirola in GNSS Solutions in the September/October 2008 issue,

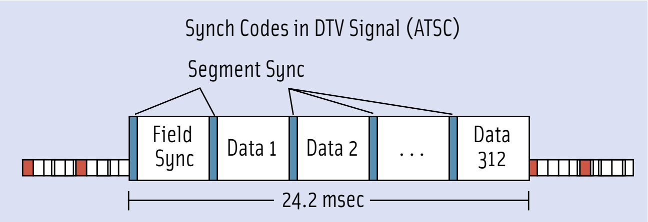


FIGURE 1 ATSC synchronization information

Another approach for femtocell timing comes from network timing solutions such as the Precision Time Protocol (PTP) time-transfer technique defined in the IEEE 1588-2002 standard that allows precise synchronization of networks. However, these solutions require significant network infrastructure to be deployed, don't provide position/location, and, consequently, cannot address E911 issues.

If available, neighboring cell towers may provide timing, but again may not solve an E911 requirement.

Rosum has developed and is promoting a new solution, TV+GPS in which GPS signals are augmented with terrestrial broadcast television signals to provide timing, frequency stability, and E911 location. In the following section we examine TV+GPS in detail and compare it with other solutions.

Using Broadcast TV for Timing and Location

All global standard TV signals include timing information that can be used for precise frequency, synchronization, and location.Rosum's first-generation system, for instance, exploited Advanced Television Systems Committee (ATSC) digital and National Television System Committee (NTSC) analog TV signals used throughout North America and in South Korea.

Rosum has also developed methods using NTSC, DVB-H, DVB-T, T-DMB and other types of TV standards. Broadcast stations in all U.S. markets are currently broadcasting in both analog and digital. Under a congressional mandate,

	Residential		Commercial (Apartment)	
	Wall (Lumber or Brick-Faced Masonry)	Floor (Lumber, Sheetrock)	Wall (Concrete)	Floor (Steel-Reinforced Concrete)
500 MHz (UHF TV)	8dB	16dB	20dB	22dB
900 MHz (Cellular)	11dB	22dB	22dB	27dB
1.6 GHz (GPS)	10dB	20dB	26dB	29dB
3 GHz (WiMax)	29dB	59dB	46dB	50dB

TABLE 1. RF Attenuation by building materials

	TV+GPS	A-GPS	IEEE 1588	Neighboring Tower List
Frequency Stability	Works in all environments - dense urban, suburban, rural, even deep indoors. Minimal DSL bandwidth requirement.	Easy indoor locations only (by the window or simple construction). Other environments require external cable and GPS antenna installation.	Where femtocell is within four hops of the timing server. Can occupy large percentage of the DSL bandwidth.	Applicable only in environments where poor cell coverage is not the cause for femtocell deployment.
Timing Synchronization				
Automatic E911 Location			None	Very rough location only.

TABLE 2. Femtocell Timing and Location Solutions

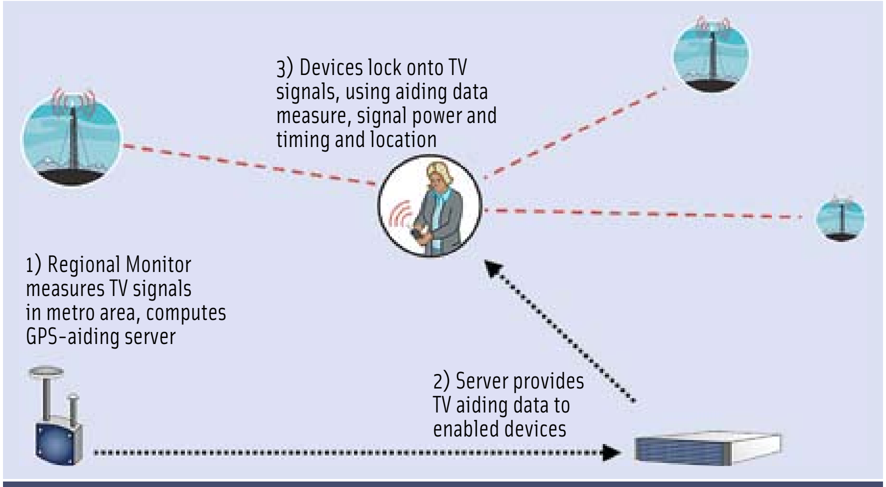


FIGURE 2 Television-based positioning

after February 17, 2009, all full-power television stations will broadcast in digital only.

TV-positioning technology comprises three elements: a mobile device incorporating a TV tuner and a baseband TV measurement module that receives TV signals and calculates timing, frequency, and location; an aiding server; and a regional monitor unit that measures certain clock characteristics of TV signals and sends time correction data to the aiding server.

The TV signals typically can be used at a range of up to 50 to 100 kilometers from the transmitter depending on terrain. Regional monitor units sited at surveyed locations are equipped with a stable clock source (i.e., GPS), which enables accurate timing measurements and the creation of aiding information.

In ATSC systems, we exploit the synchronization field (field sync), a special segment made of a pseudorandom noise (PN)-code of length 511 and three additional PN-codes of length 63. (See **Figure 1**.) Additionally, each 828-symbol segment is preceded by a four-symbol binary pattern that acts as a segment synchronization (segment synch) sequence. NTSC analog signals have several synchronization features as well that can be used, such as horizontal and vertical synchronization pulses.

In order to compute an accurate location of a femtocell or other device, the precise timing of the TV synchronization code must be known. A reference unit — or, optimally, a network of such units — at known positions are used independently to monitor the TV station clock offsets, which may then be communicated to the device for calculation of its own position.

With the receiver/transmitter time and frequency biases now known, signal-processing algorithms can compute frequency, timing, and ranges and solve for a position in a comparable fashion as with GPS.

In the United States, TV signals broadcast over 4,500 channels occupy nearly half of the spectrum between 30 MHz and 1 GHz. A new, mobile version of ATSC will likely lead to creation of additional transmitter sites to support mobile receivers.

Technical Advantages of TV Signals

Broadcast TV signals have numerous characteristics that make them desirable for use in location and timing.

TV signals are strong, with broadcast power levels of hundreds of kilowatts or megawatts, providing a positioning link margin 50 dB greater than GPS. (Positioning link margin is the ratio of the lowest usable power level and the outdoor power level and represents the amount of building attenuation that can be suffered and still have usable signals.)

In comparison, for GPS, the outdoor design level is -130 dBm, and currently a state-of-the-art high-sensitivity AGPS receiver can use GPS signals down to -160 dBm, yielding a power margin of 30dB. For TV, outdoor power levels are typically -45 dBm, and Rosum has shown ranging to be effective with signals down to -125 dBm — a margin of 80 dB. Thus, TV signals can tolerate 50 dB more attenuation and still be usable as a ranging signal.

Moreover, TV signals are broadcast at low frequencies, which allows them to penetrate buildings well — further widening the positioning link margin advantage. As previously mentioned and reflected in Table 1, TV transmissions are attenuated less than cellular, GPS, and WiMAX.

The wider bandwidth of TV signals helps mitigate multipath effects. Broadcast analog and digital TV standards are either 6 MHz or 8 MHz wide, which compares favorably with GPS at 1 MHz bandwidth, UMTS/GSM at 5 MHz, CDMA at 1.2 MHz, and EvDO at 5 MHz.

TV signals, which are broadcast across every metropolitan area on Earth, have stable timing and are highly reliable. In the United States, broadcasters have Emergency Alert System obligations that commit them to maintaining service even during disasters.

New mobile TV networks (DVB-H, T-DMB, ATSC-M/H, and others) are being deployed, and these new signals can be used in addition to existing broadcast TV networks.

TV location and timing information can be combined with other signals at the ranging level to create hybrid solutions that outperform single-technology solutions. Combined with other location signals (such as AGPS), TV location and timing can further improve the performance of those solutions.

TV positioning had been shown to be E911-compliant, even with aggressive third-party FCC OET-71 testing (discussed later), using 50 percent indoor and 50 percent outdoor test sites.

Frequency and Timing Accuracy

TV+GPS can provide highly accurate frequency stability of better than 100

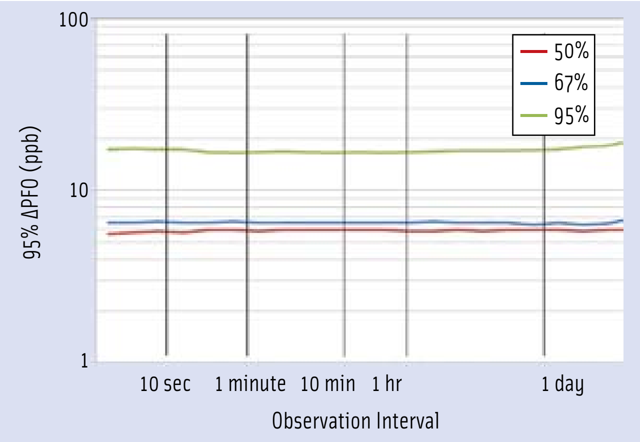


FIGURE 3 DTV Pilot Stability

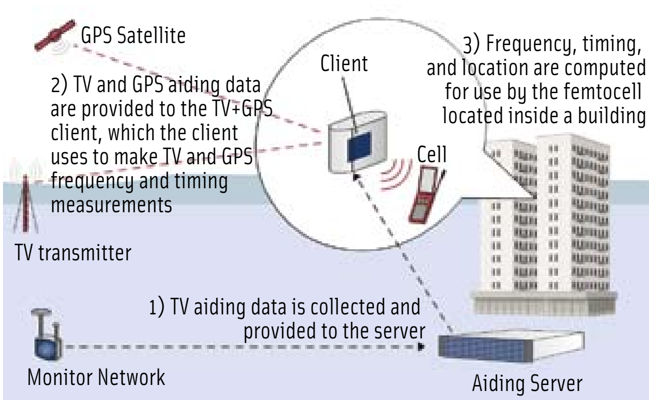


FIGURE 4 TV+GPS architecture

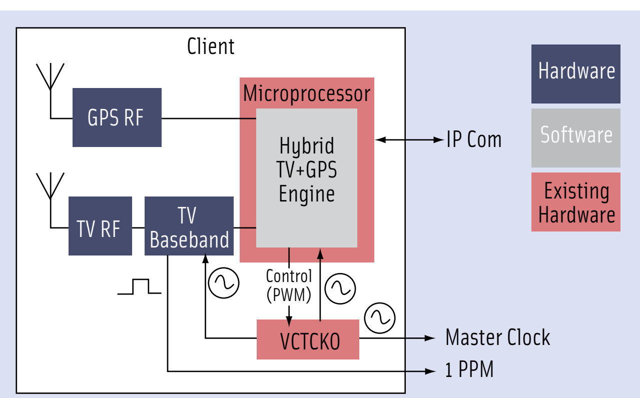


FIGURE 5 TV+GPS client

ppb, commonly 10 ppb. Data collected from TV reference monitors show the inherent stability of broadcast TV signals. **Figure 3** shows the one-day pilot and one-hour symbol stability from the 74 broadcast DTV signals in the San Francisco, New York City, and Washington, D.C., metropolitan areas.

The excellent stability of the DTV pilots, showing a median variance (over both short 10-second and longer one-day intervals) of 6 ppb, is the source of the frequency stability provided by TV+GPS. By observing the pilot signals at the TV+GPS client and comparing the measurements with that of the Reference Monitors, TV+GPS can adjust the local clock to maintain the required 100 ppb frequency stability.

Within the TV+GPS client, the TV tuner provides approximately 4 ppb accuracy of the DTV. Taking the median DTV pilot stability of 6 ppb from Figure 3 gives 10 ppb stability in the system, far more precise than the 100 ppb requirement for UMTS and the 20 ppb requirement for WiMAX.

The reference monitors provide precise knowledge of the DTV pilot frequency offset, symbol rate offset (SRO), and time of transmission. Detailed knowledge of the SRO enables coherent integration of the DTV timing signal, providing 43 dB of processing gain for the TV+GPS solutions and usable signals far below the viewing level required for DTV. Based on the ranging measurements, the TV+GPS solution provides accurate location and network synchronization.

For CDMA and WiMax femtocells, where network synchronization is required, TV+GPS provides a one pulse per second (1 PPS) synch signal. The initial position fix determines location and time, and this time is used to synchronize the 1PPS. Further periodic ranging measurements can be made thereafter to maintain the required network synchronization.

TV+GPS System Architecture and Components

Figure 4 shows the overall architecture of the hybrid GPS+TV-based positioning and timing solution. To ensure that the location solution is the best available in all environments, a hybrid TV+GPS solution has been developed that integrates ranging information from TV and AGPS sources.

The TV+GPS client (see **Figure 5**) resides in the femtocell, employs a high-sensitivity AGPS solution, and uses its knowledge of local time to further assist and enhance the performance of A-GPS. The femtocell requests aiding data from an *aiding server*. This aiding data comes from the *reference monitor network*.

TV+GPS Data Processing

The TV+GPS client uses the aiding data to detect and measure the timing of TV and GPS signals, which are then used to compute frequency, timing, and location for the femtocell. The solution uses detailed knowledge of the pilot frequency offset (PFO – the deviation from the FCC nominal broadcast frequency) and the frame rate offset (FCRO – deviation from the standard-specified 24.2-millisecond frame duration) to find and lock onto the signals and to measure their precise frequency and timing.

Local femtocell PFO measurements are compared with reference monitor PFO measurements to discipline the local femtocell oscillator. A 100 ppb frequency stability is specified in the 3GPP standard; as mentioned, TV+GPS can commonly provide a much more accurate level of 10 ppb.

By measuring the timing of TV and GPS signals from three or more towers or satellites, TV+GPS can compute ranges to those points and then can compute the location of the femtocell device even in very challenging indoor environments. Because the TV aiding data is referenced to GPS at the monitor, TV and GPS ranges are combined easily.

TV+GPS Performance

TV-based positioning has GPS-level (single-digit meter) accuracy in environments with clear line-of-site visibility to regional TV towers. The results shown in **Figure 6** are 4.7-meter median accuracy, one sigma (67 percent of the time).

The greatest value of using TV for positioning and timing, however, manifests itself in obstructed or indoor environments. Most wireless users spend the bulk of their day indoors, and over half of wireless emergency calls are made from inside buildings.

Emergency caller location identification requirements vary by country, and even in the United States the requirements for femtocells remain unclear. As of this writing, the FCC has not ruled specifically on the E911 requirements for femtocells.

FCC E911 Phase 1 delivers the location of the cell site with the emergency call, which would seem to apply to an emergency call made over a femtocell. Further, FCC rulings on VoIP 911 suggest that femtocell customers will be protected by E911 laws. Recent activity in the 3GPP standards body also suggests a desire by certain members to provide E911 services to femtocell customers. Despite interest in providing E911 functionality for consumer safety, the limitations of indoor performance on GPS and network technologies are widely understood, and currently, the FCC requires no in-building testing for E911 calls.

The Network Reliability and Interoperability Committee (NRIC) VII, an FCC working group, recommended that up to five percent of wireless E911 test calls be made from within an enclosed structure such as a building or parking garage. (NRIC said it chose the 5 percent value was chosen because no data currently exists that defines the actual number of wireless E911 calls made from indoors and "because of practical limitations of location technologies currently deployed."

PSAP	Environment	Overall Accuracy			Compliant?
		Mean	67%	95%	
Nashua, NH	Rural-Suburban	23m	31m	66m	yes
Needham, MA	Rural-Suburban	27m	33m	63m	yes
Santa Clara, CA	Suburban-Urban	28m	36m	65m	yes
Washington, DC	Dense Urban - Urban	37m	49m	86m	yes
Edison, NJ	Suburban-Urban	38m	50m	83m	yes
FCC Requirement			50m	150m	

TABLE 3. FCC E911 Compliance Testing Results

An industry organization, the Alliance for Telecommunications Industry Solutions (ATIS) recommended in its report, *Location Technology Performance Data - Define Topologies & Data Collection, ATIS 0500011,* that indoor test calls be made from locations that are representative of macro environment. In dense urban areas, for example, 25 percent of indoor test calls should be made from "underground parking lots of shopping centers, inside elevators, and inner offices of high rise buildings."

Rosum has undertaken third-party FCC compliance testing based on both the FCC Office of Engineering and Technology bulletin OET-71 and ATIS 0500011 standards, which included 50 percent indoor testing. In these real-world environments, Rosum's TV positioning technology was shown to provide accurate outdoor and indoor positioning as summarized in **Table 3**.

Conclusion

Femtocells represent a tremendous market opportunity for telecommunications service providers, and a great boost in cellular network performance for consumers. Customers, however, expect that femtocells will work where they put them in their homes and that their 911 calls will receive proper treatment.

A number of solutions are being evaluated for femtocell timing and location, including using A-GPS, cell tower signals, and network timing. However none of these addresses both the timing and automatic location requirements adequately.

TV+GPS hybrid timing and location can meet the FCC's E911 requirements needed to enable this important developing market.

FIGURE 6 Line-of-Sight Positioning Accuracy (diameter of circle: 100 meters)

The core of TV-positioning is the tremendous power advantage provided relative to GPS and superior building penetration. Hybridizing with A-GPS adds to that advantage.

In addition to the reciprocal technical advantages of their hybridization, TV and GPS are highly complementary in their geographical availability. In dense urban areas with large buildings and very challenging indoor settings, TV transmitter geometry is excellent. In remote areas where few TV towers exist, urban canyons and large multi-story steel-reinforced concrete buildings are rare; so, GPS provides the timing and location data.

At the signal processing level, precise timing derived from TV signals can be used to enhance AGPS performance.

Manufacturers

FemtoSynch is the trade name for the TV+GPS product from **Rosum Corporation**, Mountain View, California, USA. In its FemtoSynch client, Rosum uses an AGPS receiver from **ST-NXP Wireless,** Plan-les-Ouates, Switzerland.

Additional Resources

[1] 3rd Generation Partnership Project (3GPP), "3G Home NodeB Study Item Technical Report," September 23, 2008. Report available at <http://www.3gpp.org/ftp/Specs/html-info/25820.htm>

[2] Alliance for Telecommunications Industry Solutions, "Location Technology Performance Data - Define Topologies & Data Collection, ATIS-0500011," February 2007

[3] National Institute of Standards and Technology, "NIST Construction Automation Program Report No. 3, Electromagnetic Signal Attenuation in Construction Materials," October 1997

[4] http://www.ctia.org/advocacy/research/index.cfm/AID/10323

[5] http://www.fcc.gov/pshs/services/911-services/voip/Welcome.html

[6] Network Reliability and Interoperability Committee (NRIC) VII, February 15, 2005, Focus Group 1A. "Near Term Issues for Emergency/E9-1-1 Services"

[7] Discussion of the FCC's E911 rule can be found at <http://www.fcc.gov/pshs/services/911services/enhanced911/Welcome.html>.

[8] More details about the FCC's E911 Phase 2 rules at <http://www.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet71>

[9] For detailed treatment of the femtocell/carrier interface architectures, please see the FemtoForum (www.femtoforum.org), UMA (www.umatoday.com), and 3GPP (www.3gpp.org) websites.

Authors

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