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Response to Question 7, FCC form 442

Introduction

This project embodies the theoretical development and hardware demonstration of a practical, deployable, zero infrastructure, precision indoor/outdoor personnel location system for use by law enforcement, firefighters, corrections staff and other first responders. The specific impetus for this work is the need to track the location of first responders inside buildings for two reasons: to enhance operational efficiency, but most importantly to avoid loss of life when responders become disoriented and lost inside structures which may be collapsing or on fire. This work is based on a new RF signaling approach that we have named “Multi-Carrier Wide Band” (MCWB) that addresses the problems of indoor multipath interference while ameliorating the interference and spectral allocation problems of impulse ultra-wideband systems. The overall goal of this project is to demonstrate the engineering design of a prototype system which is sufficiently compact, rugged and easy to use that it can be evaluated by first responders.

In the past, several primary factors have obstructed realization of this important capability: insufficient signal strength, lack of precision and multi-path degradation of GPS indoors; FCC spectrum non-compliance of ultra wide band systems; and/or the need for pre-existing infrastructure. Work to date on the proof-of-concept system demonstrated means to provide these capabilities within the bounds of practical constraints and allowed development of design rules for future design efforts. We are now at the stage where indoor/outdoor testing is needed to demonstrate system capabilities and to provide experimental data upon which to base system improvements.

Program of Research

Alternative Approaches

Existing technology for geolocation is largely based upon the DOD's Global Positioning System (GPS) which does not provide the required location accuracy (offering only 10 meter accuracy) nor indoor or urban outdoor performance thanks to its low signal strength and lack of robustness to multi-path conditions.

The FAA has supported the development of high precision (several centimeter precision) augmentation of GPS through additional infrastructure. However, the infrastructure requirements and limitation to outdoor settings remain limitations. Despite the problems associated with using the GPS in these difficult environments, several researchers have attempted to augment, or entirely replace, the GPS with a system of ground- mounted signal sources. These signal sources, or pseudolites transmit signals that are essentially identical to the signals emitted by a GPS satellite. The problem with pseudolite-based systems, however, lies in the fundamental nature of the GPS signal structure itself. There is simply not enough dynamic range and bandwidth available to mitigate problems such as the well-known near-far problem and there is not enough flexibility in the navigation message to allow for large numbers of signal sources. Some researchers have attempted to solve these problems by time sequencing the pseudolite transmissions, but this solution becomes technically cumbersome very quickly and do not make efficient use of channel bandwidth.

Recently several companies, (for example, Time Domain Technologies of Huntsville, AL, Multispectral Solutions of Germantown, MD,) have been exploring the use of Ultra wide band (UWB) technology for precise location. These time domain systems, however, suffer from some technical difficulties in implementation, as well as difficulty in meeting FCC spectrum allocation and power requirements.

Finally, a radically different approach to the indoor positioning problem would make use of inertial navigation, eliminating the need for RF signals. Unfortunately at present this technology is far from feasible with respect to cost, size, power, and precision aspects.

Proposed System

Overview

We propose a new signal alternative to impulse-based, chirp and other spread spectral UWB location technologies that yields the same multi-path robust precise location capabilities while providing a solution to interference and spectrum allocation regulatory problems. Impulse UWB has been generally proposed as a communications and geolocation technology for use in high multi-path environments. This approach has an immediately appealing appearance because of the vivid transparency of its operation: the direct path transmission of its extremely short pulses arrive before any multi-path reflections and hence may be exploited for multi-path elimination and precise round-trip timing. This compelling picture obscures the fact that short pulses are not required for precision location. Furthermore, the intuitive appeal of this approach induces one to overlook the issue of spectral allocation compliance and high levels of interference of other systems caused by front end receiver overload from the high amplitude of the pulses.

Another technology, developed for high bandwidth communications, which is also multipath robust is COFDM (Coded Orthogonal Frequency Division Multiplexing, or Discrete Multi-Tone). COFDM is the basis for today's variants of DSL signaling for 1-50Mbps data links over the local loop of telephone twisted pair and for innovative zero drop-out radio and TV broadcast services in Great Britain and similar proposals for enhanced cellular systems. In COFDM systems a large number of narrowly spaced carriers are individually modulated at low baud rates with error correction encoded data so that loss of some number of the channels due to time-varying multi-path induced frequency nulls will cause no loss of information. Due to the narrow band nature of each channel, they may be treated as distortionless systems requiring no equalization. Furthermore, bit rate and power levels are dynamically allocated into each channel so as to optimize bandwidth and power efficiency and to provide spectral agility in the face of changing multi-path conditions and interfering signals. A hardware FFT is the core component of transmitters and receivers, replacing local oscillators and mixers with DSP.

We are proposing a broadband COFDM-like signal which we have named Multi-Carrier Wideband (MC-WB). For our purposes, the range of frequencies spanned by this MC-WB signal might be 25 to 200 MHz. The signal consists of widely spaced unmodulated sub-carriers spanning the wide band of operation. See Figure 1 below. These sub-carriers can be made to fall at arbitrary points in the spectrum chosen to avoid other-service interference and fulfill regulatory requirements.

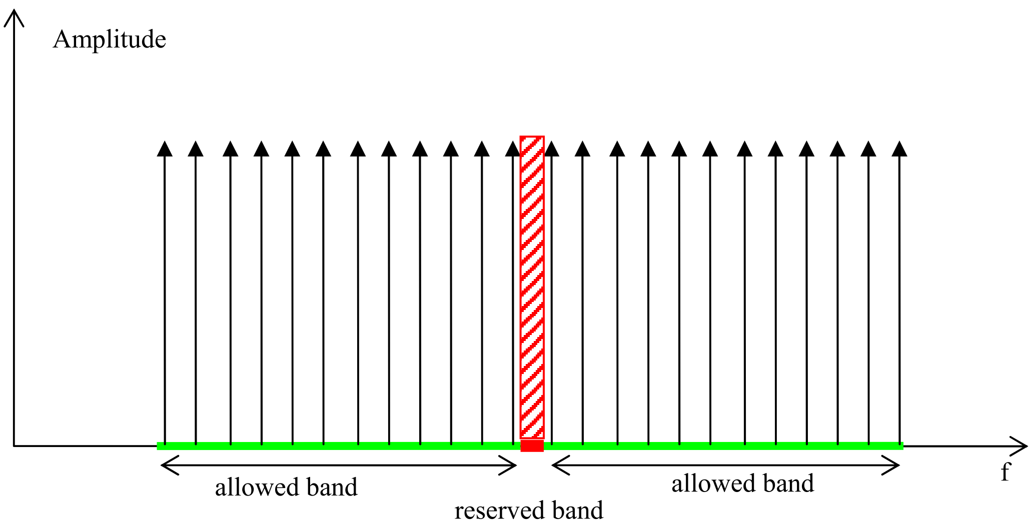

Figure 1 The MC-WB signal consists of unmodulated subcarriers that may be placed to avoid restricted frequency bands.

Precise and multi-path compatible location is obtained by applying novel multi-carrier range recovery techniques derived in work at WPI conducted by us for purposes of wide area automatic target recognition in a project sponsored by DARPA. These algorithms, in a manner resembling the operation of super-resolution spectral estimators, yield the discrete set of dominant signal locations, that is, the transmitter and multi-path reflector locations. These solutions allow the distribution of channel power to be optimized to null out large reflectance paths and hence enhance performance and reduce power levels for the sake of resource conservation and for low probability of interference.

We propose to demonstrate this technology through rigorous analysis, simulation and implementation, and prototype evaluation as detailed in the next section.

Technical Approach

In this section we will explain the technical motivation for the proposed MC-WB system with a series of simplified arguments that contrasts this approach with the Impulse UWB approaches being proposed elsewhere. A real MC-WB system will not be realized in the fashion of this series of explanations but rather in a form that integrates and generalizes upon these concepts.

Consider a purely periodic (that is, unmodulated) series of UWB monopulses, a signal with a periodic line spectrum. Obviously, if the pulses are sufficiently separated, we can determine the time of arrival over a direct path versus a reflection by choosing the first arrival pulse in any time interval. Now, instead of transmitting the original pulse sequence, first pass it through a linear transfer function with some complex variation of amplitude and phase as a function of frequency - with an impulse response that is much longer than the pulse periodicity. This very non-impulsive time function still has a line spectrum, but, has no distinct edges for naive recovery of time of arrival information. However, passing the sum of direct and multipath signals through an inverse filter will recover the original and reflected pulses from which direct and multipath delays can again be extracted. Obviously the desired information was not stored “in the edges" but rather in the amplitude/phase information associated with each carrier that comprised this signal.

The above can also be expressed with a frequency domain sampling picture. A single monopulse in time suffices to probe the time delay information we need. This signal has a continuous UWB spectrum. If we periodically sample this spectrum (producing a signal with a periodic line spectrum) we can reconstruct the original monopulse signal to within a repetition in the time domain (time aliasing). However, applying generalized sampling theory we can also quickly come to the conclusion that we can aperiodically sample the frequency domain (placing “carriers" almost arbitrarily) and still recover the original monopulse (with aliasing) from the now non-impulsive time domain function by appropriate sampling reconstruction. Thus we have more latitude in designing our signal than was apparent in our first picture.

Next consider the fact that we need not begin or end the process with an impulsive signal. As we said, the precise geolocation information is in the nuances of the amplitude and phase spectrum at the receiver and multipath contributions need not disrupt the identification of direct path information even though these signals entirely overlap. An excellent illustration of this fact is exposed by the operation of synthetic aperture sonar. The signal received by a linear array of displaced microphones can be processed to obtain (with great resolution) the direction of arrival (DOA) of a signal from a continuous wave source. Additional sources in the same field (perhaps reflectors) simply produce additional solutions when appropriate DOA processing techniques (akin to super-resolution spectral estimation) are employed. Now consider that two such arrays not lying in the same line provide two direction solutions that identify the location of the source in a plane and that three arrays identify a point in space.

Now, as attractive as this DOA based array processing solution appears to be on the surface, it suffers from an implementation problem. The solution for source directions from spatially distributed signal samples is simple only in the case of certain very constrained sensor geometries. Uniformly spaced linear arrays of sensors permit very simple (low computational cost) processing. Non-uniform but linear arrays can be accommodated with a fairly low cost preprocessing step. Other acceptable geometries include uniformly spaced groups of identical but otherwise randomly arranged sets of sensors and arbitrarily placed sets of linear arrays of sensors.

However, the general case of arbitrarily spaced sensors, while admitting a theoretical solution, requires solution of a global optimization problem that puts this approach outside the realm of practical application in an ad hoc network of randomly located nodes of any significant size.

The solution to this problem, the major innovation leading to this proposal, arises from a non-intuitive transformation of the system. The traditional DOA solution involves solution for the wave number (direction information) in the spatial-Fourier domain of signals from spatial domain samples. Now suppose we exchange the spatial domain for the time domain and exchange Fourier and non-Fourier domains. By these two transformations, we may instead solve for time offset (range information) of signals from frequency domain samples in the associated time-Fourier domain.

The beauty of this realization is that it allows a single sensor which acquires samples in the frequency domain, (which may be spaced uniformly or in arbitrarily spaced groups of uniformly spaced samples,) to be used in place of an extended physical array. Hence no problems of random ad hoc node placement arise. Parallel to the case of the DOA solution, from a set of frequency samples we may solve for the range of a source and each reflector of that source's signal. From three or more such measurements we may locate the point of emission in three-space.

Multi-Carrier Signal Structure

As described in the previous papers [1, 2], the new method is based upon transmission of a continuous multi-carrier signal of the form

$$s_c(t) = \sum_{m=0}^{M-1} A_c e^{2\pi j(f_0 + m\Delta f)t + \phi_m} \qquad (1)$$

comprising M sinusoidal carriers with frequency spacing Δf and arbitrary phases ϕ_m. For simplicity we will consider only the case of baseband signal generation at the transmitter and a direct conversion (similarly baseband) receiver. Discrete Fourier Transform (DFT) processing may be used to implement this architecture. Let N be the number of time samples that are generated by the transmitter's inverse DFT (IDFT) and then repeatedly transmitted to form the continuous output waveform and f_s be the sampling rate. Of course, the DFT may be implemented via a Fast Fourier Transform (FFT) algorithm.

Furthermore, we will consider only the case of real signals and hence describe our signal by

$$s(t) = s_c(t) + s_c^*(t) \qquad (2)$$

$$= \sum_{m=0}^{M-1} A\cos(2\pi(M_0 + mK)\delta ft + \phi_k) \qquad (3)$$

where we can express the parameters of the previous equations in terms of the sampled signal system as $\Delta f = K\delta f$ and $f_0 = M_0\delta f$, where $\delta f = \frac{f_s}{N}$ is the DFT frequency sample separation.

If this signal is received at reference sites, with distances d_k from the source giving rise to propagation delays $\tau_k = d_k/c$, then each carrier component is shifted by a phase shift which depends both upon τ_k and the carrier's frequency.

If we assume that the reference sites have synchronized clocks, while the source clock has some unknown offset t_0, this offset induces another unknown phase shift dependent on carrier index $\psi_m = 2\pi(f_0 + m\Delta f)t_0$.

Let's now assume that the sampled received signal plus noise at the k_{th} reference is of the form

$$r_k(n) = s_k(n) + n_k(n) \tag{4}$$

for $n = 0..N-1$ with DFT

$$R_k(m) = S_k(m) + N_k(m). \tag{5}$$

The phase difference between adjacent carriers for the signal received at reference k, $S_k(M_0 + mK)$ for $m = 0..M-1$, corrected for the known phases ϕ_m (Eq. 1) satisfies

$$\Delta\theta_k = \Phi_{mk} - \Phi_{m-1,k} - \phi_m + \phi_{m-1} \tag{6}$$

$$= -2\pi\Delta f \tau_k + \psi_m - \psi_{m-1} \tag{7}$$

$$= -2\pi\Delta f \tau_k + m\Delta\psi \tag{8}$$

modulo 2π.

Finally, the difference of the phases obtained as above for carrier m at two sites, q and r, is $\theta_{qr} = \Delta\theta_r - \Delta\theta_q$, from which we can recover the Time Difference of Arrival (TDOA) of the signals at those sites,

$$\Delta\tau_{qr} = \frac{-\theta_{qr}}{2\pi\Delta f} = \frac{d_2 - d_1}{c} \tag{9}$$

where c is the velocity of the wave in our medium.

Now, since our signal is periodic, with period $T = \frac{1}{\Delta f}$, the solution suffers a time (range) aliasing ambiguity. However, thanks to the limited spatial scope of the location problem we defined, by choosing Δf sufficiently small, we can make our TDOA solution unambiguous throughout a ranging cell which is defined by the locus of points within distance $R = \frac{c}{\Delta f}$ of any receiving site.

Thus the problem of TDOA estimation for this signal reduces to the estimation of the value of phase change between adjacent carriers in the received signal, $\Delta\theta_k$ that best fits the given noisy data. That is, the phasor amplitudes of the M carriers (after compensation for the known phases ϕ_m) have the form $Be^{2\pi j\Omega m}$ and we seek the frequency sample phase progression coefficient $\Omega = \Delta\theta_k$. This problem is effectively a sinusoidal frequency estimation problem applied to the phasor valued signal spectrum.

The problem of estimating the frequencies of multiple, arbitrarily spaced, sinusoidal signals from a noisy linear combination has a long history. Modern analytic and computational methods are now known collectively as Modern Spectral Analysis [3]. The approach implemented in this work follows the State Space Estimator approach first outlined by Rao and Arun [4].

Hardware Implementation

Figures 2 and 3 show the block-level designs of the transmitter and receiver, respectively. Both are quite simple from the RF point of view, minimizing the RF hardware and taking a "software radio" approach to the maximum extent possible. The RF signals are formed by double sideband modulation of a set of sinusoids (as described above) which are themselves produced by a D/A converter. The transmitted bandwidth is thus nominally twice the bandwidth of this set of sinusoids, and this wider RF bandwidth is fully utilized by the receiver processing in performing the range determinations.

The hardware represented by Figures 2 and 3 will be designed and implemented with a modular structure, using separate boards for the digital interface, mixed signal (A/D or D/A) and RF stages. Hence both transmitter and receiver will consist of three boards. All of the hardware will be custom-designed, using commercially available components and modules (mixers, amplifiers, etc.).

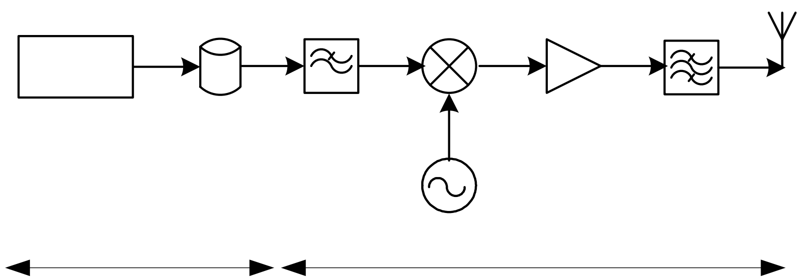

Figure 2 Transmitter block diagram

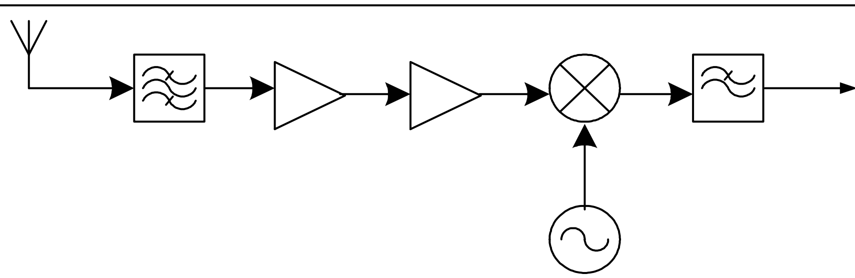

Figure 3 Receiver block diagram.

An extensive suite of test equipment is available to characterize system performance and to verify compliance with applicable regulations (power level, RF bandwidth, out-of-band emissions, etc.) Following is a list of the major pieces of RF test equipment:

- Agilent Vector Signal Analyzer, 89600S, 13.2 GHz
- Agilent Spectrum Analyzer, E4445A, 13.2 GHz

- Agilent 8722 Network Analyzer (50 MHz – 40 GHz)
- Agilent Vector Signal Generators, E4438C (quantity 2), 3 GHz
- Agilent Signal Generator, E4426B, 3 GHz
- Agilent Digital Oscilloscope, 54832D (quantity 2), 4 GS/sec

Overall Project Implementation

The activities of the overall Precision Personnel Locator project which relate directly to this license application include the following:

- **Signal theory** Complete theoretical development of multi-carrier wideband (MC-WB) precise location performance analysis including dilution of location precision due to noise, interference, node geometry and critical electronic characteristics (clock jitter, etc.) versus signal structure (number and spacing of channels, sub-band size and gaps, power level.)
- **Top-level design** Choice of frequency bands, power levels, detailed signal structure. Apportionment of processing tasks to software, custom hardware, commercial hardware, general purpose computing. User Interface design.
- **Algorithm design** Construct a MATLAB based software simulation of the entire end-to-end system for purposes of
  - theory verification,
  - implementation of the signal processing in the PC based portable prototype units,
  - being the basis for the DSP code that will be needed in a future embedded system realization or software radio implementation.
- **Simulation** Software simulation while RF design takes place.
- **Hardware requirements specification** Translation of theoretical performance behavior into hardware requirements for front end signal to noise ratios, local oscillator phase stability, sampling clock jitter, analog to digital converter resolution, etc.
- **RF hardware** Evaluation and selection of commercial off-the-shelf RF modules for implementation of the transmitters and receivers. Design and test omnidirectional wide/multiband antennas.
- **High-speed digital design** Design and construct custom digital logic for MC-WB signal generation and reception.
- **Interface design** Design and construct custom digital signal capture system and receive to computer interface electronics.
- **Real-time DSP** Conversion of algorithms into real-time implementation.
- **Prototype system construction** Construct several portable hardware/software prototypes based upon off-the-shelf RF components and laptop PC based processing/display.

- **Operational verification** Staged testing of the various hardware and software modules with design feedback, troubleshooting and necessary modifications.
- **Controlled tests** Conduct indoor location performance tests with the multi-node system.
- **Results analysis** Compare field tests with analytic and simulation results. Identify system imperfections that lead to any observed degradations of performance.

Program Objectives

The overall objective of this project is both simple and ambitious:

- Theoretical development and proof-of-concept demonstration of a Precision Indoor Positioning System with 0.3m accuracy and requiring no pre-installed infrastructure

The following presents the operational characteristics underlying this Objective:

- Performance Characteristics
  - No site preparation or manual on-site calibration procedures,
  - Portable, rugged, easy-to-use computerized system control unit,
  - Self-configuring, fault-tolerant, distributed software systems.
  - Location precision: +/- 1 ft
  - Maximum range: 2000 ft
  - Simultaneous users: 100
  - 3-D position information (multi-level emergencies being common)
  - Rugged and miniature low-power user equipment with no controls,
  - Guidance information available to rescue teams
  - Capable of integration with stored databases: geographic and structural
  - Requires no interaction with wearer during normal use
  - Integrated with present first-responder equipment
  - Optional basic physiologic/environmental information capture and transmission

Frequency Bands and Power Requested

Frequency Bands and Signal Bandwidths

It is important to determine experimentally the effects of signal bandwidth and to relate this to the theoretical and simulation results. Hence bandwidths from 25 to 200 MHz are desired. Also important to the test program is determination of the effects of propagation characteristics through building materials in various frequency bands. For physical reasons (antenna size on the low end and attenuation on the upper end) the overall frequency range of 400 MHz to 3 GHz is of interest. Within this range, the operational bands requested are listed below, together with their licensed uses:

1. 410 - 470 MHz (Fixed, Mobile, Space Research, Satellite, Radiolocation, Amateur)
2. 512 - 608 MHz (Broadcast television)
3. 614 - 698 MHz (Broadcast television)
4. 1240 - 1350 MHz (Radiolocation, Radionavigation, Amateur)
5. 1755 - 2000 MHz (Mobile and Fixed)
6. 2390 - 2450 MHz (Amateur, Radiolocation, ISM)

It would be highly desirable to operate in both of the broadcast television bands, 512 - 608 MHz and 614 - 698 MHz since our signal structure could avoid the gap between 608 and 614 MHz and treat the entire frequency range as providing 186 MHz of bandwidth. We recognize that the range from 1300 to 1350 MHz is restricted but because of the potential value of this frequency range, we submit a request for experimental authorization.

As is described above, the RF signal to be employed here (a set of unmodulated sinusoids) spans a broad frequency range, but actually occupies a near-zero amount of that total bandwidth (deviations from zero-width spectral lines are only due to residual oscillator jitter and time windowing of the overall signal). The spectral space not occupied by our signal is available to other users. At the power levels requested for this experimental work, interference with other services, including those services on the same frequencies as our sinusoids, should not exist, and will be monitored. An important part of the experimental work is the determination of system performance vs frequency span and other parameters such as SNR. In this application “bandwidth” is used in the common sense of frequency range spanned by our set of signals, and wide bandwidths are requested. Our requested signal bandwidths for each band range from 60 MHz (occupying the entire band) to 100 MHz.

RF Power

Maximum average transmitted power in any of these bands will be +10 dBm. Transmit antennas will be dipole, monopole, or wide beam patch antennas with at most a +3 dB directivity gain, yielding a maximum ERP of +13 dBm. The minimum bandwidth to be used is 30 MHz, yielding a maximum power density of -62 dBm/Hz.

Power control will be used to limit the amount of power radiated to that needed for the test, but never more than stated above. It is expected that many tests will be conducted with transmitted power of approximately -35 dBm. With this power the transmitted field strength will be below the thermal noise ambient at a distance of approximately 50 meters from the transmitter in a free space environment. This assures that signal strength exterior to the WPI campus will be less than the thermal noise level. As real-world conditions (interior and exterior walls between transmitter and receiver, with attenuation values between 1 and 30 dB per partition) are added to the test environment, their attenuation will require power increase from -35 dBm. However, power monitoring will be used to insure that signal strength levels exterior to the building under test are no greater than are needed to maintain an appropriate received signal to noise level.

Station Identification

We request an exemption from the requirement for station identification. If required to do so, we will add this capability. Adding the necessary modulation for identification on each of our originally unmodulated sinusoids would of course substantially increase the occupied spectral area during the identification period.

Contributions to the Radio Art

The approach to RF spectrum utilization of this project represents a potentially significant new way to address the inherent large bandwidth requirements for precision positioning systems while minimizing the impact on other services. Unlike direct-sequence spread-spectrum and conventional ultrawideband systems, the signals used here may ultimately be designed to lie between other signals. This is made possible by the fact that each carrier signal is unmodulated, and hence nominally of zero bandwidth. Of course in practice a non-zero bandwidth must be provided for each carrier to allow for oscillator frequency tolerance and slight spectral impurities. Such unmodulated signals would be of no use for data communication, but the positioning problem is very different from the communications problem. In the positioning problem, effectively the modulation (in phase) is provided by the relative position difference between transmitter and receiver rather than by data to be transmitted.

Provisions to prevent interference

The test transmissions will be conducted on the WPI campus using minimal power levels. Figure 5 shows the WPI campus. The building circled in yellow (the "Atwater Kent Building") will be the site of most of the experiments. The campus area under WPI's direct control is outlined in yellow. Also, the area outlined in green is parkland with no residential or commercial sites. Hence, a buffer zone of at least 150 m will exist. Should a larger zone be needed for some experiments to prevent off-campus interference, the site of the tests may be moved to the center of the WPI campus.

All regulations with respect to Experimental Operations (in particular, those with regard to ceasing transmission in the event of any interference) will be complied with. A cell phone number of the person able to immediately cease transmission will be provided to the FCC and any other appropriate agency. The band in use will be constantly monitored. In particular, if television or amateur bands are being used, they will be monitored with typical reception equipment. An important aspect of the experimental work is the determination of needed transmitter power for acceptable system performance in the highly variable attenuation environment of the building interior-to-exterior paths. Our system architecture places the transmitters on the persons to be tracked inside the buildings, thereby minimizing field strength on the building exteriors, and hence minimizing interference potential. Also, the separate two-way data communications channel will permit adaptive transmit power adjustment.

Figure 5 Area of experimentation, the WPI campus.

References

[1] D. Cyganski, J. A. Orr, W. R. Michalson, "Performance of a Precision Indoor Positioning System Using a Multi-Carrier Approach. *Proceedings of ION NTM 2004*, January 26-28, 2004, San Diego, CA."

[2] D. Cyganski, J. A. Orr, W. R. Michalson, "A Multi-Carrier Technique for Precision Geolocation for Indoor/Multipath Environments," *Proceedings of ION GPS/GNSS, 2003*, Sept. 9-12, 2003, Portland, OR.

[3] S. M. Kay, "Spectrum Analysis - A Modern Perspective," *Proc. IEEE*, vol. 69, no. 11, pp. 1380-1419, Nov. 1981.

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