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RF Propagation Measurement and Modeling for Wireless Body Area Networking

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EXECUTIVE SUMMARY

This proposal “RF Propagation Measurement and Modeling for Wireless Body Area Networking” is submitted by the Center for Wireless Information Network Studies (CWINS), Worcester Polytechnic Institute, Worcester, Massachusetts in response to the NIST announcement on the Recovery Act Measurement Science and Engineering Research Grant Program. The CWINS is renowned for its seminal research in measurement and modeling of the indoor radio propagations for comparative performance evaluation of emerging wireless high speed communications and localization standards and products. Indoor radio propagation measurement research at the Center has a proven track record of stimulating the economy by impacting the work of the IEEE 802.11 WLAN and IEEE 802.15.3 UWB standardization committees and nurturing start-up companies such as Skyhook Wireless¹. For over two decades, by performing seminal research in indoor radio propagation measurement, building close cooperation with the industry and standardization committees, publishing an international periodical journal and organizing several key workshops and conferences, CWINS has had a unique impact on the growth of the wireless local networking industry. We believe that the CWINS can bring to this NIST program a unique body of expertise and experience in indoor wireless communications that would be highly valuable to the program in areas of RF propagation measurement and modeling in support of emerging high-speed networking applications. Based on our previous experiences, we expect that the result of our research will contribute to the economic recovery by stimulating the growth of commerce in wireless sensor networking industry.

In the past decade wireless sensor networks have emerged as one of the promising industries likely to stimulate the US economy for another round of industrial growth. One of the most promising areas of economic growth in sensor networks is in the pervasive information technology and the so called wireless body area networks (BANs) or body sensor networks (BSNs). To support the growth of this industry, recently the Federal Communication Commission (FCC) has allocated specific bands for Medical Device Radiocommunications Service (MedRadio) and the IEEE 802.15.6 was formed to address standardization for these emerging technologies. Innovations in wireless networks are based on radio propagation measurement science and engineering in the specific environment and frequency of operation of the emerging technologies. As a result, all wireless networking standardization committees devote a substantial effort to measurement of radio propagation characteristics to define suitable channel models useful for performance evaluation of alternative wireless solutions for specific applications.

Measurement and modeling of radio propagation for high speed wireless applications is a challenging field of science and engineering because radio channels suffer from temporal, spatial and direction of arrival fading caused by very complex random variations of the multipath components carrying radio signal from one location to another. Although European, Korean and Japanese academic institutions are actively investigating the propagation characteristics in BANs, there is limited US academic presence in these activities. We envision that our proposed comprehensive research program re-enforces and expands US presence in the measurement and modeling science and engineering research and overcome the lead of research being conducted in Europe, Japan and Korea. Our proposed research program is in synergy with current RF propagation simulation studies from Medical implants at the Pervasive Information Technologies program² of the Information Technology Laboratory at NIST which maintains active participation in the IEEE 802.15 Task Group 6 on BAN³.

¹ The WiFi localization technology of the Skyhook wireless, developed based on the research work of the PI, is adopted by Steve Jobs for the iPhone (<http://www.wi-fiplanet.com/news/article.php/3723366>).

² [http://www.itl.nist.gov/ITLPrograms/Pervasive Information/index.html](http://www.itl.nist.gov/ITLPrograms/Pervasive%20Information/index.html).

³ <https://mentor.ieee.org/802.15/dcn/08/15-08-0519-00-0006-a-statistical-path-loss-model-for-mics.pdf> ,
<https://mentor.ieee.org/802.15/dcn/08/15-08-0351-00-0006-mics-channel-characteristics-preliminary-results.pdf>

The main goal of our proposed research is to develop a comprehensive academic measurement program for characterization of radio propagation for high speed communications and RF localization in and around human body to support the growth of the technology and standardization activities for emerging BAN and sensor networks. The focal point of the research is a comprehensive measurement campaign for body mounted sensors operating in the Industrial, Scientific and Medical (ISM) bands at 902-928 and 2400-2483.5 MHz as well as Ultra Wideband (UWB) frequencies at 3.1-10.6GHz and implant sensors operating in the Medical Radiocommunication Services (MedRadio) band at 401-406 MHz. In this campaign we consider seven line-of-sight (LOS) and non LOS (NLOS) scenarios defined for four type of channels (1) the implant to implant, (2) the body surface to implant, (3) the body surface to body surface, and (4) the body surface to external connection.

Figure 1 provides an overview of our proposed technical approach. For the body mounted sensors we perform extensive measurements on a phantom and verify the results with limited measurement on human subject. Using Ray Optics techniques for large scale radio propagation we analyze the empirical results from body surface measurements. To avoid intrusive measurements for implant sensors inside human body we use the Finite Difference Time Domain (FDTD) simulation of radio propagation inside the body and verify our results using physical measurements obtained from a phantom. Results of measurement campaign are post-processed and analyzed to develop statistical models for behavior of the channels for the seven scenarios. Statistical models will provide for path-loss calculation, statistics of small- and large-scale fading, delay power spectrum or power delay profile, and statistical behavior of distance measurement error for localization applications. We then use the statistical models for measuring the performance of high speed communication and geolocation cooperative sensor networks formed around the body. To measure the physical performance of wireless high speed communications, we use our statistical models to design a real-time testbed using PROPSIM C8 channel emulator and wireless sensors using ZigBee technology. To assess the localization capabilities, we use our empirical models for the ranging error against the Cramer-Rao Lower Bound (CRLB) for geolocation applications. The results of performance measurements provide a guideline for design engineers and standardization committees to design innovative products and standards to stimulate economical recovery.

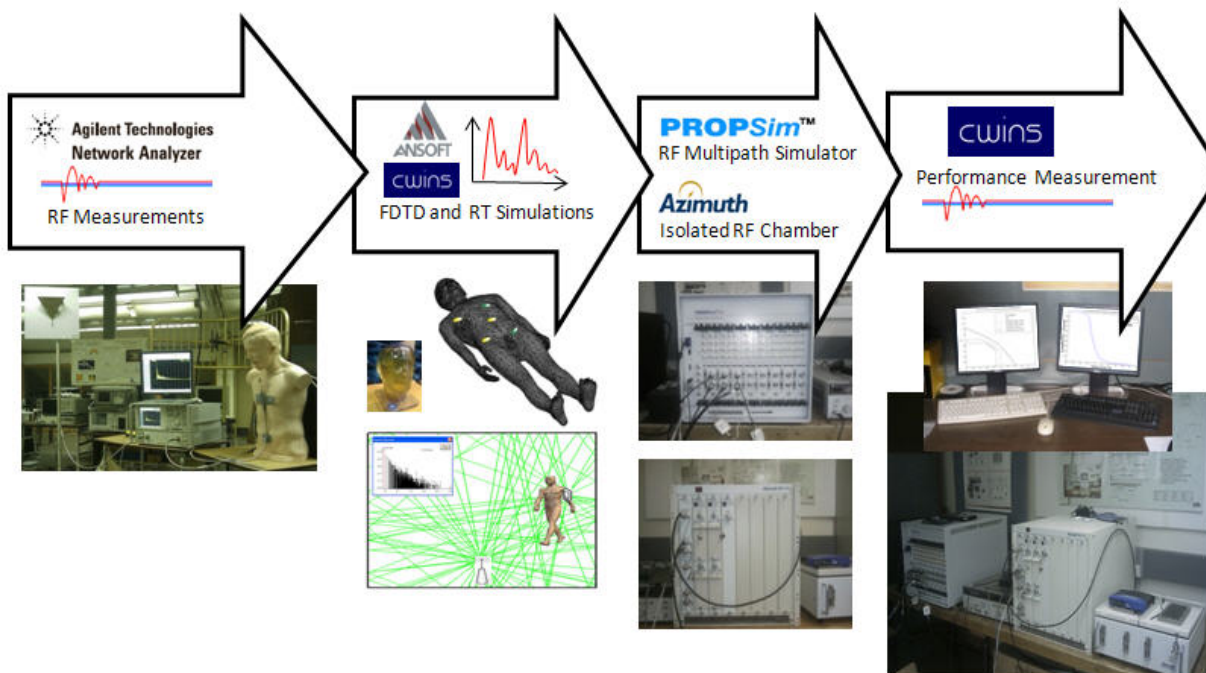


Figure 1: RF measurement process from inception to practice.

1. IDENTIFICATION OF THE SIGNIFICANCE OF THE PROJECT

In the past decade miniaturization and cost reduction of semiconductor devices has allowed design of small low cost computing and wireless communication devices used as sensors in a variety of popular wireless networking applications and this trend is expected to continue in the next two decades. It is expected that a myriad of new applications designed around sensor technologies will emerge to stimulate the US economy for another round of industrial growth. One of the most promising areas of economic growth associated with this industry is the so-called wireless body area networks (BAN) or body sensor networks (BSN) [Yan06]. These networks are expected to connect wearable and implantable sensory nodes together and with the Internet as part of the emerging “Internet of Things” [Rfi06] and support numerous applications ranging from traditional externally mounted temperature meters or implanted pace makers up to emerging blood pressure sensors, eye pressure sensors for glaucoma and smart pills for precision drug delivery. A number of technical challenges regarding size and cost, energy requirements, and wireless communication technology are under investigation and in the heart of these investigations is the understanding of radio propagation in and around the body.

To support the growth of this industry, recently the Federal Communication Commission (FCC) has allocated specific bands for Medical RadioCommunication Services (MedRadio) bands [FCC09] and the IEEE 802.15.6 is formed to address standardization of these emerging technologies. The IEEE 802.15.6 defines the technologies and models for characteristics of the medium for wearable and implanted sensor networks [Aoy08, Kim08, Hag08a, 08b]. Although European [For06], Korean [Hwa08] and Japanese [Yaz07a, b, c, Saw08, Zhe08, Aoy08] academic institutions have research programs in support of measurement of propagation characteristics for BAN applications, the US activity is limited to the NIST participation in the IEEE 802.15.6 channel modeling group [Yaz07d, Say08a,b, Hag08a,b, Say09] without any comprehensive support from US academic institutions.

One of the main focuses of this proposed research program is to reinforce and expand US presence in the measurement and modeling science and engineering efforts for the growth of this industry and its standardization activities. Another focus of this research program is to expand the modeling of the behavior of the channel for communication among sensors to modeling of the channel for calculation of the precision of sensor localization techniques [Als07, Als08, Akg09] which is beyond the current scope of the research in the foreign countries and will provide an edge to the US academic research program. With the completion of this research project, we will have a good understanding of the wireless channel of BAN and BSN for high speed data communication and localization and we overcome the lead of foreign countries in this emerging area of research and commercial developments.

While communication channel models for sensor networks provide for learning the coverage and data rate limitations of sensor devices operating in specific frequencies allocated to the BANs, localization channel models allow us to determine limits on precision of the location estimates for different implant and body mounted sensors. Localization for implant and body mounted sensors is a new area of research that will draw on previous research at CWINS, WPI [Pah98, Pah02, Pah05, Pah06] and ITS, NIST [Sou07, Gen08, Say06a,b] on indoor geolocation. Measurement of the radio characteristics for high speed wireless communications for BAN enables a number of applications mentioned earlier in this section. The measurement of localization characteristics of the BAN would enable another set of interesting applications for implant sensor localization for applications such as localization of wireless endoscopy equipment inside body [Men04] and for body surface mounted applications, localization of surgery equipment inside operation rooms [Hil07].

2. RESEARCH GOAL AND OBJECTIVES

Innovations in wireless networks highly rely on radio propagation measurement science and engineering in the specific environment and frequency of operation as well as bandwidth of the system. As a result, all wireless networking standardization committees devote a substantial effort in measurement of the radio propagation characteristics to define channel models useful for performance evaluation of alternative wireless solution in a particular field of networking. The main goal of this research is to develop a comprehensive measurement program for characterization of radio propagation for high speed communications and RF localization in and around human body to stimulate the innovation and growth of the technology for emerging BAN and BSN applications in various IT sectors of the industry. To achieve our goal we have the following three objectives:

Objective I: Start a measurement campaign and channel modeling research program for body surface mounted sensors operating in the Industrial, Scientific and Medical (ISM) at 902-928 and 2400-24835 MHz bands and Ultra Wideband (UWB) at 3.1-10.6GHz frequencies, in scenarios complementing NIST activities. We use phantoms and physical measurement systems for the basic measurement campaign for this objective and verify the results with limited measurements on human subject⁴. The statistical models developed for body surface to body surface and body surface to external devices and include, path-loss model, models for short- and long-scale fading, and models for clusters of multipath arrival, needed for performance measurement of high speed wireless communications, and models for the behavior of the arrival time of the direct path between the transmitter and the receiver, which is needed for the analysis of geolocation capabilities of the channel. We also analyze the results of empirical measurements using Ray Optics techniques and FDTD simulations.

Objective II: Start a complementary measurement research program for implant propagation to verify the results of NIST research in statistical channel modeling using FDTD simulations in their immersive visualization environment and Medical Implant Communication Services (MICS) 403.5-403.8 MHz bands [Say09] by developing a physical measurement program using a phantom. These models are developed for implant to implant and implant to body surface mounted devices. In our research plan, in addition to complementary measurement of the statistics of path-loss and fading characteristic to verify simulation results at NIST, we will measure the channel characteristics pertinent to high speed wireless networking and RF localization of the implant inside the body.

Objective III: To use our empirical statistical models for performance measurement of different cooperative sensor network topologies formed around human body. This objective is attained by implementation of a real-time testbed with PROPSIM C8 hardware channel simulator and ZigBee sensor modules. We decide on practical topologies with up to eight links and simulate the channel behavior for different links of the network on the eight channel of PROPSIM which connects the ZigBee sensor modules. Each sensor will transmit not only its own signal but also help to transmit the signals from the other sensors, so they form a cooperative communication network. The data rate on every individual link and the data rate achievable by the overall cooperative network as well as variance of the ranging error on each link and the variance of overall localization error will be measured. Results of localization measurements will be compared with the calculation of CRLB for cooperative localization. Calculation using the bounds will then be extended to other technologies developed in other bands and network topologies.

⁴ Pending to IRB approval, which will be obtained by WPI after completion of the review process for the proposed research.

3. MEASUREMENT SCENARIOS

Radio propagation measurements for wireless network applications begin with defining measurement scenarios and frequency bands for an emerging application for which propagation characteristics is not known. For each scenario a measurement campaign is conducted and results of measurements are post processed and analyzed to develop statistical models for the behavior of the channel in different environments. These models are then used for performance measurement of alternative wireless solutions. This entire process for BAN/BSN applications considered in this project is shown in Fig. 1. Seven measurement scenarios considered for BAN/BSN for channel modeling applications in and around the human body are provided in Figure 2(a). We have four different classes of models, CM1 for Implant to Implant, CM2 for Implant to Body Surface and External, CM3 for Body Surface to Body Surface and CM4 for Body Surface to External network connection. These classes are further categorized into scenarios, we have one scenario for CM1, two scenarios for each of the other channel model classes, which forms a total of seven scenarios, summarized in the left top part of Fig. 2(a).

The frequency bands considered in our measurement campaign, shown in Fig. 2(b), are the Medical Radiocommunication Services (MedRadio) bands [FCC09] at 401-406 MHz for measurement scenarios with implant sensors (S1,S2) and ISM and UWB frequency bands for non-implant sensors (S3-S7). The MedRadio bands were recently released by FCC to replace Medical Implant Communication System (MICS) and the Medical Implant Telemetry System (MITS) bands at 402-405 MHz [FCC03]. All these bands are allocated by the FCC for the low power and unlicensed band implant applications. MICS is used for data transmission to help diagnostic or therapeutic functions using external medical processing transceiver and implanted medical devices or between implanted medical devices. MITS which operates in 403.5-403.8 MHz band is used to provide transmission of one way non-voice data on a periodic basis from an active implant to the external receiver. MedRadio is 2MHz wider than MITS and provides a wider flexibility to accommodate new type of devices. The Industrial, Scientific and Medical Band (ISM) at 902-928, 2400-2483.5 MHz are the first unlicensed bands released for wireless local communication in 1985. The Ultra Wideband (UWB) 3.1-10.6GHz bands, released by FCC in 2003, is also an unlicensed band devoted to low power short distance communications [Pah05].

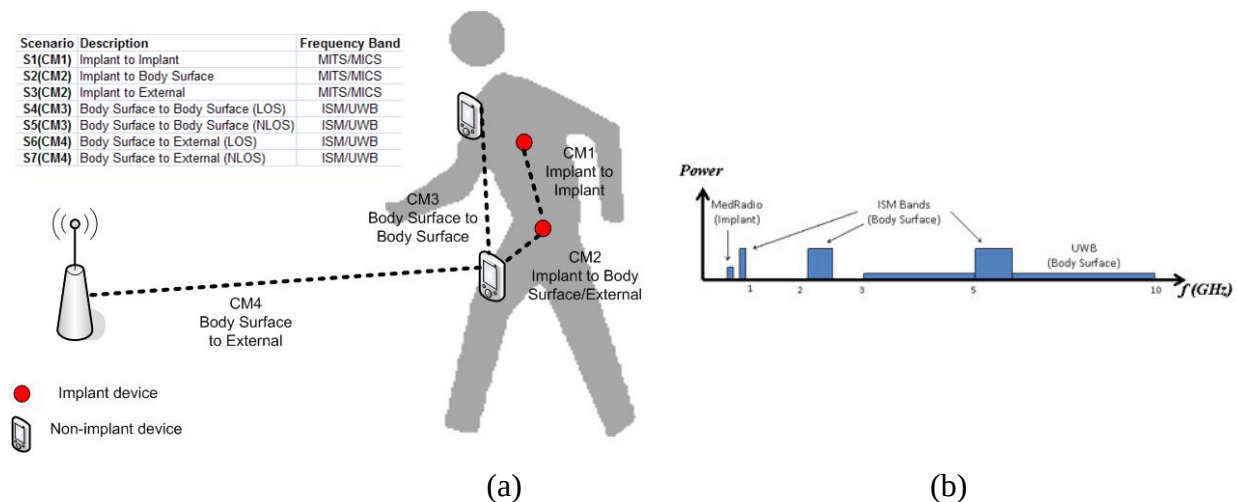


Figure 2: (a) Scenarios and channels for BANs (b) Frequency bands and applications used in the proposed research program.

4. MEASUREMENT ANALYSIS

Measurement and modeling of the radio propagation for high speed wireless communications and localization is a challenging field of science and engineering because radio channel suffers from temporal, spatial and direction of arrival fading caused by very complex random variations of the multipath components carrying radio signal from a location to another. Therefore, in the past few decades a number of statistical models have been adopted to capture certain features of the channel behavior useful for calculation of coverage, determination of data rate limits, and calculation of localization precision. In statistical measurement and modeling of the radio propagation, the radio channel between a wireless transmitter and receiver is described by:

$$h(d, t, \beta, \phi, \tau, \theta) = \sum_{i=1}^L \beta_i^d(t) e^{j\phi_i^d(t)} \delta[\tau - \tau_i^d(t)] \delta[\theta - \theta_i^d(t)] \quad (1)$$

where $h(d, t, \beta, \phi, \tau, \theta)$ is the overall channel impulse response at time t , between a transmitter and receiver that are at a distant d from one another; and $\beta_i^d, \phi_i^d, \tau_i^d$, and θ_i^d are the amplitude, phase, delay, and angle of arrival of the i -th path, and L is the number of paths. Since in wireless applications either terminal is mobile or people move around or in between the transmitter and the receiver these paths and the channel impulse response are also function of time and space. The wireless propagation measurement science and engineering is based on capturing these channel impulse responses, described by (1) in different locations and times before the multipath components change their value substantially and use these measurements to model the statistical behavior of the multipath components in time, space and frequency. Figure 3 shows a sample 2D measurement of the multipath radio channel characteristics using MIMO antennas for a measurement program at CWINS [Tin00, Pah05] and how it maps to a channel impulse response represented by (1). In the rest of this section we discuss the statistical models a propagation measurement program a collection of these impulse responses in different locations and times are used for design of statistical models for particular behavior of the channel.

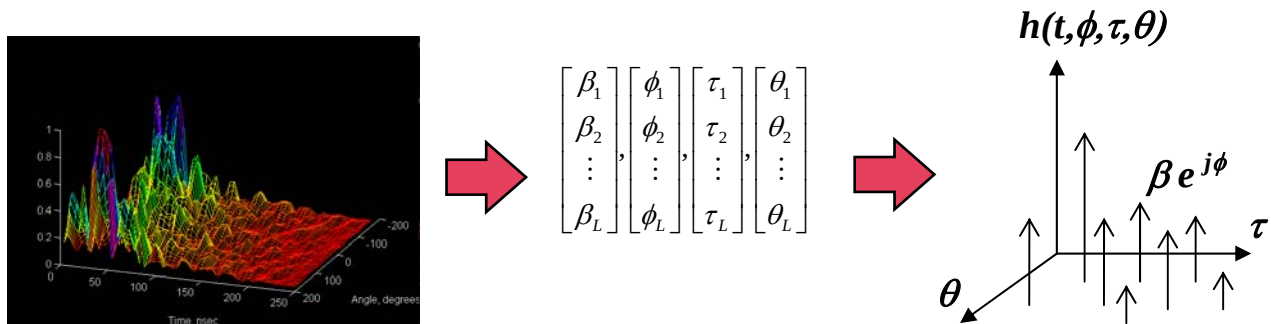


Figure 3: A sample measurement of the multipath propagation characteristics using a 2D wideband channel measurement system [Tin00] and how it turns to different measurement parameters.

4.1 Path-Loss and Fading Characteristics

Path-loss models and fading characteristics of the channels are determined from the empirical data to calculate of coverage and bit error rate performance of a link. Using (1) the instantaneous received power for a given distance between the transmitter and the receiver is given by [Pah05]:

$$P_d(t) = \left| \sum_{i=1}^L \beta_i^d(t) e^{j\phi_i^d(t)} \right|^2$$

Figure 4 represents variations of the received power and variety of characteristics attributed to the modeling of the relation between the received power and distance. As the distance between the transmitter and the receiver increases the path-loss on the average increases. This increase is exposed to slow long-term shadow fading representing the deviation of the average received power from the expected norm determined by path-loss model. In the short-term signal is exposed to multipath fading representing temporal fast variations of the signal strength caused by fast changes in the phase of multipath components in each location. The Doppler spectrum of the received signal represents the frequency spectrum of the variations of the signal in time. Standardization organizations provide models for the path-loss of the channel in dB in a general form of:

$$L(d) = L_0 + L_m + f(d) + \eta \quad (2)$$

where $L(d)$ represents the path-loss at distance d , L_0 is the path-loss in first meter, and $f(d)$ is a function relating the path-loss to the distance and it is determined by finding the slope of the best fit line to the results of measurements at different distances. The parameter L_m is the additional path-loss component due to the measurement system representing antenna gains and polarization, cable losses, and gain of amplifiers. The random variable η is a zero mean Gaussian random variable representing the large scale shadow fading. In the literature, the most commonly used function representing $f(d)$ are single piece line:

$$f(d) = 10\alpha \log_{10} d \quad (3.a)$$

in which α is the distance-power gradient of the channel, and two piece lines:

$$f(d) = \begin{cases} 10\alpha_1 \log_{10} d; & d \leq D \\ 10\alpha_1 \log_{10} D + 10\alpha_2 \log_{10} (d/D); & d > D \end{cases} \quad (3.b)$$

with one break at distance D identifying two regions with separate gradients [Pah05]. Path-loss models and shadow fading characteristics are used for calculation of coverage and fade margin of the channel [Pah02a].

In addition to large-scale shadow fading we have short-scale temporal multipath fast fading. The distribution function of the temporal fast fading is used for calculation of symbol transmission error in digital communications. The third fading characterization function is the Doppler spectrum of the channel that is used to simulate temporal variation of the channel. In all existing models for traditional wireless applications shadow fading is assumed to have lognormal distribution while multipath fading may have Rayleigh, Rician, Weibull, Suzuki, or lognormal distribution. The shape of the Doppler spectrum may change from a u-shape for mobile to a flat or Laplace shape for indoor networks [Pah05]. In channel modeling for a new application we use empirical data to determine path-loss models and the distribution function of the short-and large-scale fading as well as the shape of the Doppler spectrum.

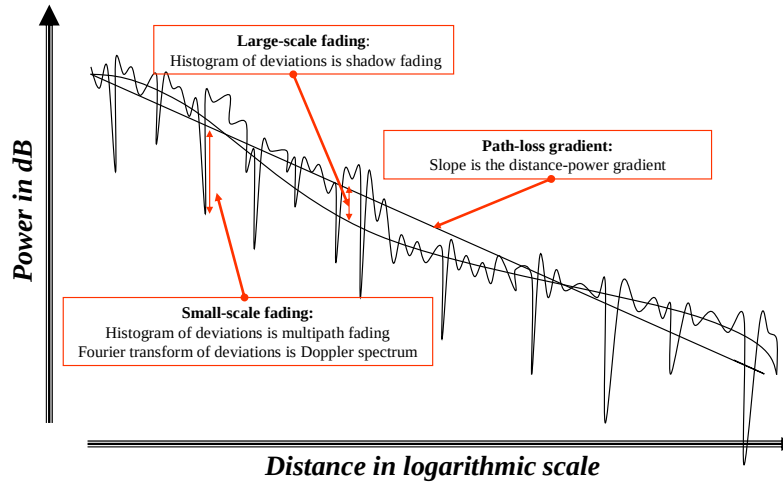


Figure 4: Modeling of the attributes of the received signal strength in wireless channels.

4.2 Multipath Modeling and Scattering Function

To further proceed on statistical modeling using measurements of the channel impulse responses, standardization activities assume that the channel is slow time varying Wide Sense Stationary Uncorrelated Scattering (WSSUS). These assumptions allow representation of the statistical behavior of the channel with a single correlation function called scattering function which can be decomposed into two functions, the delay power $Q(\tau)$, and the Doppler spectrum $D(f)$ [Pah05]:

$$S(\tau, f) = R_{hH}(\tau, f) = Q(\tau) \times D(f) \quad (4).$$

Then for any given scenario we need to measure the Doppler spectrums $D(f)$ and the delay power spectrum $Q(\tau)$. For a multipath channel represented by (1) the delay power spectrum is given by:

$$Q(\tau) = \overline{|h(\tau)|^2} = \sum_{i=1}^L \overline{|\beta_i|^2} \delta(\tau - \tau_i) \quad (5)$$

which characterizes the power concentration of arriving paths at different relative delays. The Doppler spectrum for a channel represented by (1) is the power spectrum of the temporal variations of individual paths given by:

$$D(f) = \left| \int_{-\infty}^{\infty} \beta_i(t) e^{j\phi_i(t)} e^{-j\omega\tau} dt \right|^2 \quad (6)$$

4.3 Statistics of Localization Error

Measuring the channel impulse response also allows for empirical modeling of the ranging errors, which can be used for assessment of the geolocation capabilities of the sensor networks formed in and around the body [Pah05]. Localization systems use the time of flight between the transmitter and the receiver

to determine the distance between the two units. This distance is determined from $d = c \times \tau_1$ in which c is the speed of light and τ_1 is the arrival time of the first path in the impulse response. Measurement of the absolute arrival is bounded by the density of multipath arrivals, bandwidth of the measurement system, and the existence of objects between the transmitter and receiver. The error between the measured distance using RF signal and the actual distance is referred to as distance measurement error (DME). In recent years, modeling of the DME has been the subject of a number of research studies for applications in indoor geolocation [Pah05, Ala06 a, b, Als07, 08, Hei08, Asg08]. In general the distance measurement error is given by [Ala06a]:

$$\varepsilon_d = d - \hat{d} = \gamma_w \cdot \log(1 + d) + \xi(d) \cdot \varepsilon_{UDP,w} \quad (7)$$

In which γ_w and $\varepsilon_{UDP,w}$ are non-zero mean Gaussian random variables whose mean and variance are functions of the bandwidth of the measurement system and $\xi(d)$ is a binary random variable with a probability of occurrence that is a function of bandwidth and distance between the transmitter and the receiver. This model is developed based on UWB measurements for different indoor environments. Figure 5 compares the complementary CDF of the distance measurement error obtained from empirical UWB measurements and the overall model described by (7) for the bandwidths of 200MHz and 1GHz.

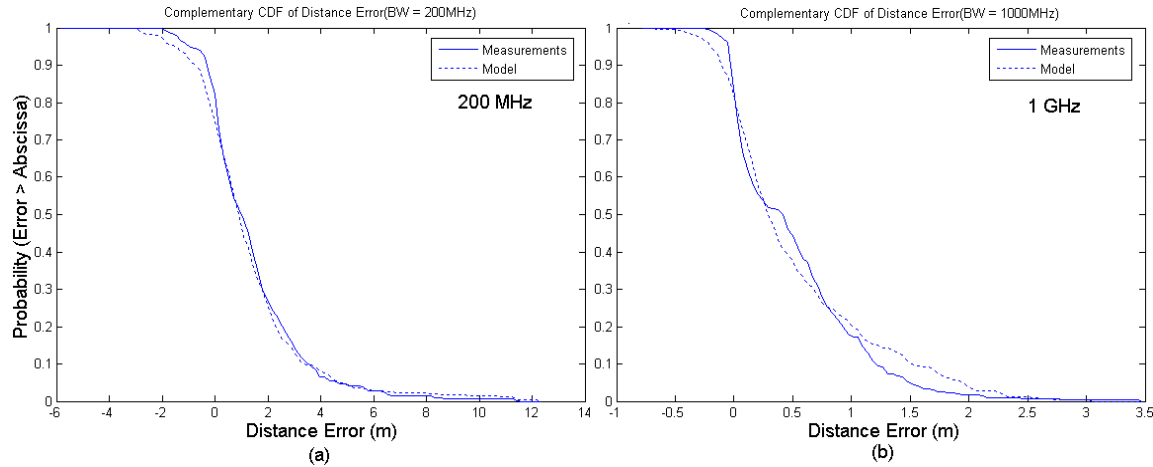


Figure 5: Comparison of DME and the model provided by (7).

Bound for Sensor Node Localization: Assuming n randomly deployed sensor nodes which we know the exact location of a small fraction of them and the variances of the DME of the links connecting the neighboring nodes, a lower bound on the error covariance matrix of the sensor node locations can be obtained by applying the Cramer-Rao Lower Bound (CRLB). As shown in [Sav05] if we represent the coordinates of the nodes in a sensor network by vector $\alpha = [x_1, y_1, \dots, x_n, y_n]$ and the estimate of α by the vector $\hat{\alpha} = [\hat{x}_1, \hat{y}_1, \dots, \hat{x}_n, \hat{y}_n]$, the error covariance matrix of this estimation process is given by:

$$C = E\{(\hat{\alpha} - \alpha)(\hat{\alpha} - \alpha)^T\}. \quad (8)$$

The CRLB provides a lower bound of C and it is given by:

$$CRLB = [J(\alpha)]^{-1} \quad (9)$$

where

$$J(\alpha) = E \left\{ \left[\nabla_{\alpha} \ln f_x(X; \alpha) \right] \left[\nabla_{\alpha} \ln f_x(X; \alpha) \right]^T \right\} \quad (10)$$

is the Fisher Information Matrix (FIM). The parameter X in (10) is an $(M \times 1)$ measurement vector formed by stacking the available distance measurements $\hat{d}_{ij} = d_{ij} + \varepsilon_{ij}$ where ε_{ij} is the DME between nodes i and j . Our empirical results using UWB measurements in [Ala06] show that this DME is a normally distributed random variable with a probability density function of $f_x(X; \alpha) = N(\mu(\alpha), \Sigma)$, where $\mu(\alpha)$ is a vector of true distances between two nodes and Σ is the measurement covariance matrix. Since the results of empirical measurements in [Ala06] show that the measurements are uncorrelated but not necessarily identical, Σ is a diagonal matrix with the diagonal elements calculated from $\Sigma_{ii} = \sigma_i^2$ where $i = \{1, \dots, n\}$ and $J(\alpha)$ is given by

$$J(\alpha) = [G(\alpha)]^T \Sigma^{-1} [G(\alpha)]. \quad (11)$$

The vector $G(\alpha)$ contains the partial derivatives between two sensor nodes. The final CRLB is obtained by the inverse of the FIM given in (9). More details of this CRLB derivation can be found in [Sav05]. In our work we use results of empirical modeling of the DME to calculate this bound in a realistic environment with non uniform error between the nodes. The performance of a given sensor node localization algorithm can then be evaluated against this CRLB.

5. RESEARCH PLAN

Our research plan draws on the CWINS expertise and facilities. The Center is renowned for its seminal work in measurement and modeling of the indoor multipath channel behavior [Pah00]. The pioneering radio propagation measurement and modeling research at the center [Gan91a,b] has influenced IEEE 802.11 WLAN and IEEE 802.15.3 UWB WPAN recommended radio propagation channel models. The frequency domain wideband channel measurement system using a network analyzer, first introduced at CWINS [Pah89, How90, How91], is today's most common method for measurement of radio channel characteristics in local, personal and body area networks. The Center also has a pioneering record in application of Ray Optics methods [Hol92, Yan94, Ali02, Hei04], FDTD techniques [Pah95, Asg08] and antenna design [Fer02, Mak06, Mak09] for local indoor radio propagation measurements. In the past decade the Center has contributed in seminal work in UWB radio channel measurement and modeling for indoor geolocation [Pah98, Ala06a,b, Als07, Als08, Asg08]. The core of CWINS' facilities includes Faraday RF isolation facilities, radio measurement systems up to 40GHz, assorted antenna systems in variety of wireless frequency bands, Ansoft and proprietary FDTD and Ray Tracing software for antenna design and radio propagation studies, and real-time hardware multi-channel RF propagation simulator.

The overall research plan starts with the design of the measurement environment with appropriate antennas and tools. The measurement systems is then used in a measurement campaign of characteristics of radio propagation in and around the human body using our frequency domain channel measurement system, FDTD simulation software, and Ray Optics analysis. Statistical models for the radio propagation characteristics pertinent to high speed communications and geolocation applications use the results of the measurement campaign. These models are then used for performance assessments using real-time channel simulation environment and calculation of bounds on cooperative communications and localization for body area sensor networks.

5.1 Research Plan for Objective I: Body Surface Measurements

Understanding the nature of signal propagation is key to the design of efficient and low-power, low-cost communication systems for medical applications. The first objective of this research program is to start a measurement and modeling program for body surface mounted sensor networking applications. The existing body of propagation measurements around the body for wireless high speed BAN applications has been conducted by Europeans, Japanese and Koreans. Authors in [Ryc04] derive a channel model for the 400, 900 and 2400 MHz bands using FDTD methods and show the impact of creeping waves for around body propagation. In [Fort06] and [Gou08], authors propose UWB channel and path loss models based on actual measurements in the 3-6 GHz bands. [Yaz07, Min08, Saw08]. More specifically [Yaz07] discusses the effect of human body UWB antennas and its propagation characteristics. [Min08] and [Saw08] present the channel modeling efforts for body to external signal propagation and provide results of measurements for path-loss and time-delay characteristics for these scenarios. These measurement programs are fragmented and they do not pay attention to around body localization applications such as locating surgery equipment during knee operation which has shown commercial importance in the recent years [Hil07]. The objective of our research is to start a measurement science and engineering program to overcome the lead of research by other countries and as such our plan include a comprehensive measurement program for wireless high speed communication and localization applications.

Our body surface measurement campaign is performed at 902-928 and 2400-24835 MHz ISM bands and 3.1-10.6 GHz UWB frequencies for body surface to body surface as well as body surface to external antenna. We use phantoms and physical measurement systems for the basic measurement campaign for this objective and verify the results with limited measurements on human subject. The measurement campaign is conducted using our frequency domain channel measurement system using a network analyzer. Figure 6(a) shows a sample measurement using our current frequency domain measurement system for body surface to external antenna using a half body manikin. The heart of this measurement system is the 40GHz Agilent Technologies E8363B Network Analyzer purchased in 2004 by NSF funding. The antenna used on the body of manikin is a cone UWB antenna designed by IWT, Virginia and the triangular antenna posted on the beam is an UWB base station antenna designed by PJ Microwave division of Elektrobit, Oulu, Finland. These antennas have been acquired through DoD and NSF research grants. The UWB measurement shown in the computer screen is the channel impulse response obtained from inverse Fourier transform of the measured frequency response at 3-8GHz.

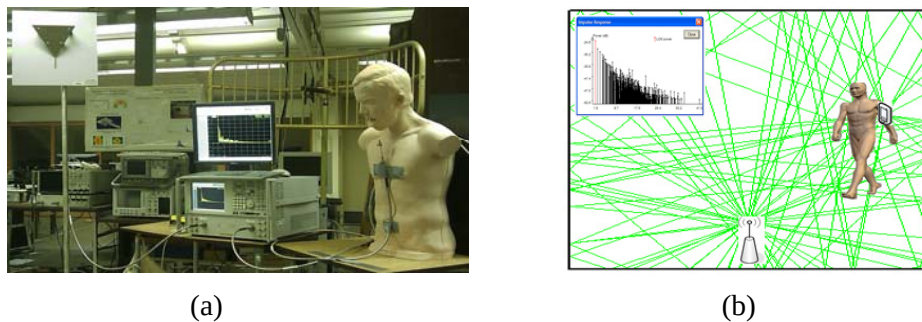


Figure 6: (a) The UWB frequency domain measurement system (b) propagation analysis using principles of Ray Optics.

Another tool we will use for our measurement and modeling plan for objective 1 is the Ray Tracing (RT) tool. Figure 6(b) shows the general idea behind this approach. Ray Tracing provides a ray optics approximation to propagation analysis and it can be used for larger areas where FDTD solution to propagation analysis is not practical [Pah05]. At CWINS we use physical measurements to calibrate the RT software and then we use RT to obtain massive measurements for modeling of the behavior of the

channel [Pah06]. CWINS owns 2D and 3D proprietary RT software [Hol92a, Yan94] which will be exploited in this program. The advantage of Ray Optics approach is that we can find more compact solutions explaining behavior of path arrivals [Ali02].

Channel measurement and modeling for body surface mounted sensors is divided into Body-to-Body and Body-to-External experiments which are further divided into line-of-sight (LOS) and Non-LOS (NLOS) scenarios. In LOS scenarios there is a direct un-obstructed path between the transmitter and the receiver. In NLOS scenarios the body is blocking the signal from direct connection path between the transmitter and the receiver. Figure 7 shows the results of four measurement experiences using the system shown in Fig. 6(a) for body surface to body surface and body surface to external experiences for LOS and body obstructed NLOS conditions. In LOS experiences we can clearly see the direct path which is also the strongest path. In NLOS experiences direct path is not the strongest path and overall channel impulse response has a clearly different pattern of behavior. Considerable changes in multipath profiles suggest needs for separating LOS and NLOS channel models for these scenarios application.

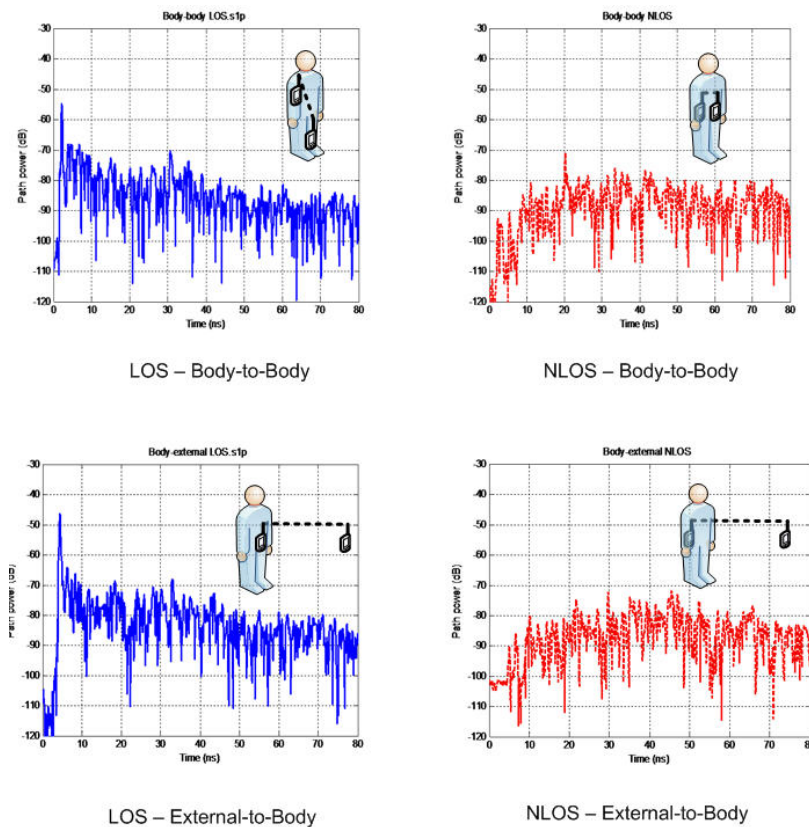


Figure 7: Channel impulse response in four different orientations of the body.

In the body surface areas a number of scenarios can be defined depicting relative movements of body limbs towards one another. We define these channels in cooperation with NIST and considering progress on the IEEE 802.15.6 radio propagation modeling group.

Tasks for completing Objective I:

- Define a measurement plan in cooperation with NIST for a frequency domain measurement campaign on body surface in 900 and 2400MHz ISM bands as well as 3-10GHz UWB frequencies
- Perform limited measurement on human subject to verify results of measurement on the phantom

- Perform mass measurements using the phantom
- Develop statistical models for path-loss and fading characteristics for different scenarios and frequency bands
- Develop wideband models for multipath arrival for different scenarios and frequencies bands using empirical data
- Explain the results of empirical modeling using Ray Optics theory
- Design models for the localization error in different bands and measurement scenarios

5.2 Research Plan for Objective II: Implant Measurements

The second objective of our proposal is to start a complementary physical measurement research program for implant propagations using a phantom to verify results of NIST's research in this area using FDTD simulations [Say09]. The NIST simulations are performed in 300KHz Medical Implant Communication Services (MITS) bands at 403.5-403.8 which is a part of Medical Implant Communication System (MICS) bands at 402-405MHz [FCC03]. We will pursue our measurements in the newly released Medical Radiocommunication Services (MedRadio) bands at 401-406 MHz [FCC09], which is replacing the MICS and rather than using 300KHz MIT band modeling we use the entire 5MHz MedRadio band for modeling. As a result, in addition to complementary measurement of the statistics of path-loss and fading characteristic to verify simulation results at NIST, we will measure the multipath channel characteristics pertinent to high speed wireless networking and RF localization of the implants in the entire 5MHz MedRadio band. Similar to the NIST program we include implant to implant and implant to body surface channels.

The calculation engine of the existing simulation environment in NIST for modeling of the implant propagation is the Ansoft's FDTD propagation simulation software [Yaz07d, Hag08a,b]. Finite Difference Time Domain provides direct numerical solution of the Maxwell's propagation equations, however, defining the boundary conditions for calculations and details of the simulation for the inside of the body can possibly cause inaccuracies. On the other hand results of this research does not fully agree with those reported by Korean researchers for analysis of the implant propagations [Kim08]. The research community needs to verify the results using other approaches [Say09]. In our research program, we propose using a phantom for radio propagation studies for verification of the results of implant modeling obtained by FDTD. We use WPI's Ansoft based FDTD for simulation of the propagation in sample implant locations available in the phantom for physical measurements to compare the results. The FDTD simulator provides a 3D human body graphics for a three-dimensional full-wave electromagnetic field simulation (HFSS) using a FDTD with resolutions as low as 2 mm. Figure 8(a) provides a sample 3D simulation of our software with two implanted and three surface mounted sensors. Using our FDTD simulation, propagation characteristics of the channel between any two sensors in time and frequency can be simulated and compared with similar results of physical measurements obtained from implant devices inside the phantom body.

Different phantom setups have been implemented to measure radio propagation inside the body and test the performance of designed antenna for body area applications. In [Joo06] Finnish researchers use fiberglass shell phantoms filled with tissue simulating liquid. The liquid is a typical sugar and water based liquid commonly used in the antenna propagation measurements inside the head from mobile terminals. The phantom head shown in Fig. 8(b) is currently used at WPI for this purpose. In [Alo06] researchers in UK have used a similar full-human phantom with plastic shell, shown in Fig. 8(b), with animal organs holding an implant antenna inside, to characterize and simulate human tissues for measurements of implant propagations. In [Soo04],

tissue stimulant material composed of TX-151, sugar, salt, and water was used to verify the results of spiral and serpentine antenna performance. In [Kim04] Korean researchers use a human tissue-simulating liquid made from deionized water, salt, and cellulose to verify the performance of planar inverted-F antenna (PIFA). In [Hig07] researchers in UK used the implant placed inside a Perplex body (30cm diameter cylinder), and measure the signal strength as a function of the distance.

In our proposed research we have allocated \$50K to purchase a new body phantom to complement our existing phantom head. We have studied different options and need to finalize our decision with NIST. We propose purchasing a custom liquid filled phantom, similar to the one used in the UK [Alo06], but designed by Phantom Laboratory, Salem, NY. Phantom Laboratory has custom designed similar phantoms for other applications [Jon02]. In this project they will manufacture a full-bodied liquid filled phantom for our research that can place a small antenna in a know locations within the body. They manufacture a liquid filled torso and limbs formed from CAB plastic and using end plates machined from polycarbonate. The phantom would have a large access port on the torso which would allow items to be inserted within the phantom. The arms and legs will have simple pivot joints at the shoulders, elbows, hips and knees. There would also be a couple of ports on the limbs to enable antenna to be inserted in a couple places into the limbs. The Phantom Laboratory will work with CWINS in the development of a antenna retaining system which will allow accurate positioning without distorting the antenna signal. Phantom Laboratory can fix a grid on the interior of the back of the phantom. Antenna support posts could then be placed into the grid enabling reproducible positioning. If this approach did not work, they can use exterior ports and support rods located is specific places to position reproducibly the antennae. This project in Phantom Laboratory will involve general concepts identification and test designing, test phase which will include construction and testing of basic concepts and phantom manufacturing. Phantom laboratory has an estimate of \$50K to complete this cooperative design.

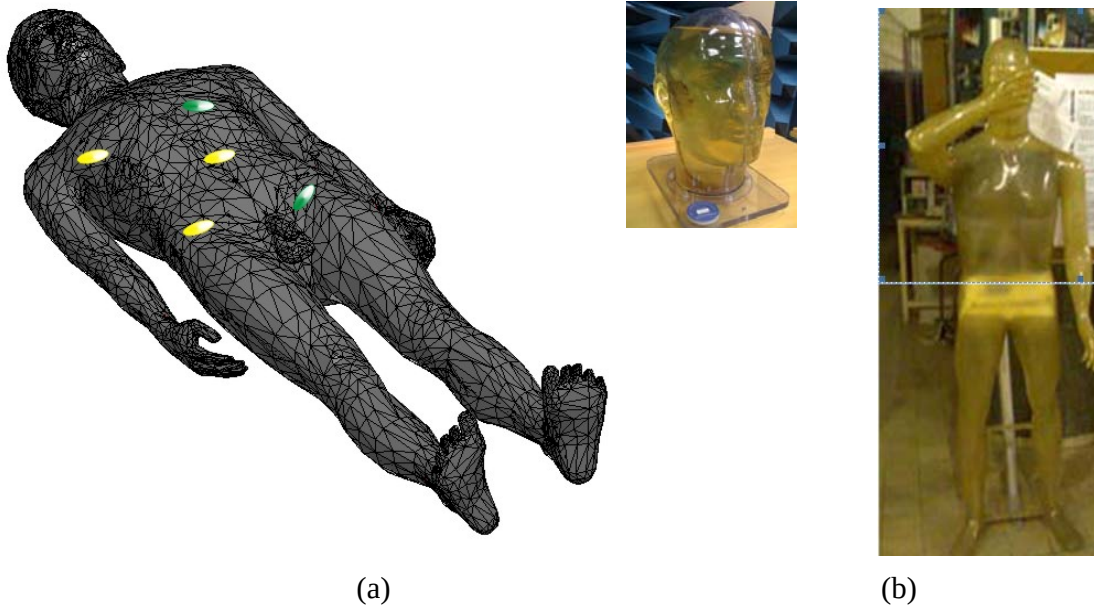


Figure 8: (a) HFSS simulation of radio propagation inside human body using FDTD. (b) Head and full-body phantoms for measurement of radio propagation inside human body.

Tasks for completing Objective II:

- Implement a testbed for intrusive measurements using a phantom
- Verify results of existing statistical models for path-loss and fading characteristics using FDTD for 300KHz MITS band with the results of measurements using the phantom
- Use phantom measurements and FDTD simulations to design multipath models for high speed wireless using full-band operation at MedRadio bands of 401-406MHz
- Measure and model the ranging error for implant RF localization in MedRadio bands

5.3 Research Plan Objective III: Performance Measurement

The third objective of this research program is to use the results of measurement and modeling of the radio propagation in the first two objectives for performance measurement of high speed wireless communications and RF localization sensor networks formed around the body. This objective is attained by implementation of a real-time testbed using CWINS' IWT ZigBee sensor set and PROPSIM C8 real-time channel simulator, programmed to implement statistical models designed in objectives 1 and 2. Different sensor network topologies can be simulated by this testbed and used for real-time performance measurement. The real time testbed allows an interference controlled and repeatable environment for performance measurement, which is ideal for comparative performance evaluations. Detailed example of such testbed for application in indoor geolocation and WiFi performance evaluation are available in [Hei05, Met06, Ass07]. For the wireless high speed communication network part of the research we follow the body area network architecture presented in [Che09], where the node that sends information and the relay nodes are separated. The implant nodes only send the information and body surface nodes act as relays. We study formations which minimize the power consumption of the implant and maximize the bandwidth utilization of the channel.

In our testbed we simulate different sensor network topologies with up to eight links for sensors placed around the body. Each body mounted sensor will transmit not only its own signal but also help to transmit the signals from the implant sensors, so they form a cooperative communication network. The sensor network also uses relative location of sensors from each other for cooperative localization using CWINS patented algorithm described in [Als06, Sil09]. In this cooperative communication and localization network, there will be implant, body surface and external sensors located in different areas of the body. The data rate on every individual link and the data rate achievable by the overall cooperative network as well as variance of the ranging error for all links and variance of localization error for the overall cooperative network will be measured. Results of localization precision measurements will be compared with the calculation of Cramer Rao Lower Bound (CRLB) for cooperative localization. In wireless localization area, the CRLB is used to evaluate the accuracy of the localization. The CRLB of single link and the overall cooperative network will be developed. The measured data will be compared with the CRLB and the performance gap will be found. Using results of our research we further examine two localization applications. These applications are localization of an implant inside the body and localization of knee surgery equipment during a body surface operation.

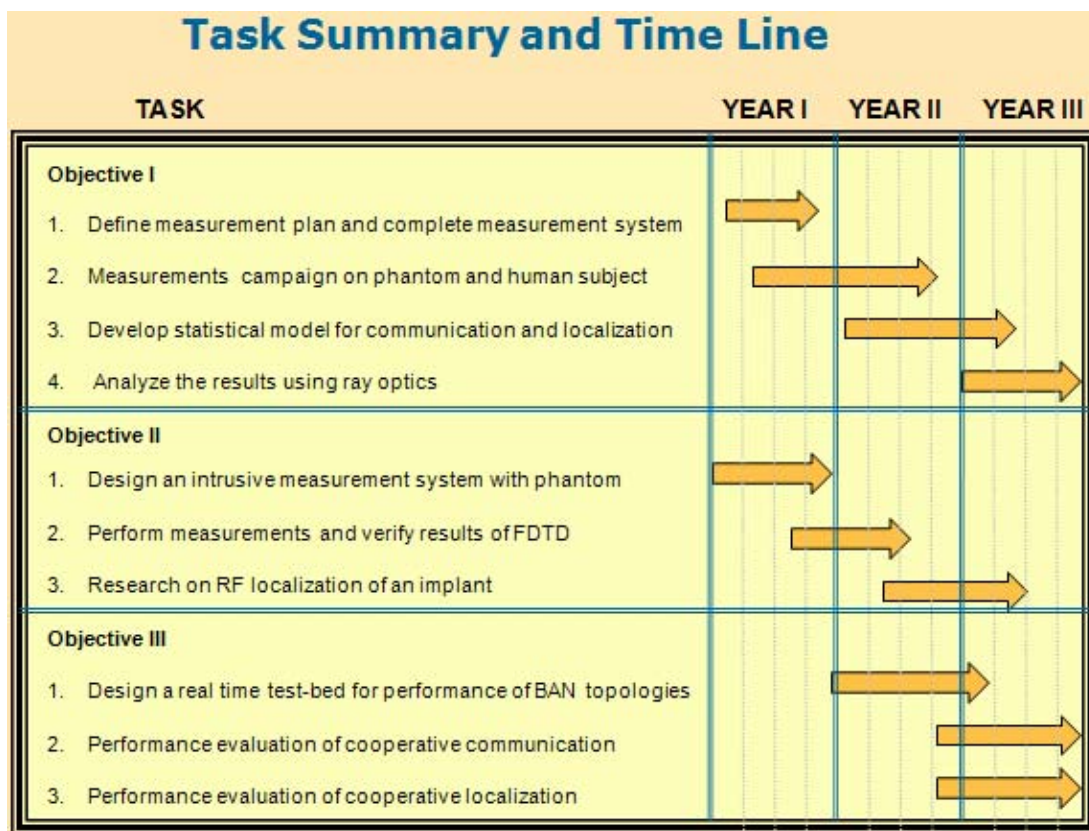
Tasks for completing Objective III:

- Define topologies with eight links for cooperative BANs with implant, body mounted and external nodes
- Design a real time testbed using PROPSIM C8 and eight IWT Zig-Bee sensors
- Measure the performance of high speed wireless data communication for different cooperative BAN topologies
- Measure the performance of wireless localization in different cooperative BANs topologies and compare the results with the CRLB

- Exploit the result of research for two applications, finding the location of implant inside the body and tracking the location of surgery equipment for the knee surgery.

6. TASK SUMMARY AND MANAGEMENT PLAN

Management Plan: The PI of the project, Prof. Kaveh Pahlavan, Professor of ECE and director of CWINS, is the overall architect and responsible for technical management of research team. He is also the technical leader for radio propagation measurement and modeling program. Professor Sergey Makarov, Professor of ECE, is responsible for numerical analysis for radio wave propagation inside the body and design of patch antennas for body mounting implant antennas. Dr. Allen Levesque, Adjunct Research Professor, is responsible for communication between the CWINS group, the NIST group, and standardization committees. Dr. Ning Yang, Adjunct Assistant Research Professor, is responsible for derivation of performance measurement for cooperative communication and localization. Ferit Akgul will act as a post doctoral fellow in measurement and modeling. Two other PhD students divide their time to help the senior faculty to carry on the research.



7. PERSONEL AND THEIR QUALIFICATION

Research proposed in this project will be conducted at the Center for Wireless Information Network Studies (CWINS), Electrical and Computer Engineering department, Worcester Polytechnic Institute, Worcester, Massachusetts. The Center was established at WPI by PI of this project in 1985 as the first modern research program in wireless information networks in the US. Fairly soon the Center became internationally renowned for its pioneering research work in indoor radio propagation measurement and modeling and performance evaluation of wireless local area networks (WLANs) [Pah00]. The Center is also known for its promotion of the WLAN industry through active participation in several start up companies such as WINDATA and R&D groups in larger companies such as Digital Equipment Corporation, Motorola and Raytheon, interactions with IEEE 802.11 WLAN standardization committee,

and organizing the first IEEE Workshop on WLAN. The Center's pioneering work in measurement and modeling of the indoor multipath channel behavior [Gan91a,b] has influenced IEEE 802.11 WLAN and IEEE 802.15 WPAN recommended radio channel models. The frequency domain wideband channel measurement system using a network analyzer, first introduced at CWINS [How90,91], is today's most common method for measurement of radio channel characteristics in local, personal and body area networks. The Center also has a pioneering record in application of Ray Optics methods [Hol92a, Yan94] and FDTD techniques [Pah05, Asg08] to indoor radio propagation studies. In the past decade the Center has pioneering work in UWB radio channel measurement and modeling for indoor geolocation application [Pah98, Als04, 06, 07, 08, Hei05]. Since 1991 collaboration with University of Oulu, Nokia, Elektrobit and several other companies and organizations in Finland created a close association between the Center, the University of Oulu, and the Finnish industry that leads the wireless network industry in commercial applications. This connection helped the Center to stay informed of the leading edge in commercially important issues for the wireless industry.

In over two decades of research experience in indoor radio channel measurement and modeling for high speed wireless communications and indoor geolocation CWINS' research has been sponsored by a number of government agencies such as NSF, DARPA, DoD, US Army, US Air Force in the US and TEKES and Finnish Air Forces in Finland. The Center's research has also received a number of research sponsorships from the industry that include: GTE Laboratories, DEC, WINDATA, 3COM and BBN in Massachusetts, JPL, Savi Technologies, RadioLAN in California, Aironet in Ohio, United Technology Research Center in Connecticut, Honeywell in Arizona, Rockwell Collins in Iowa; Nokia, LK-Products and Elektrobit in Finland, and NTT in Japan.

Kaveh Pahlavan, is a Professor of ECE, a Professor of CS, and founding Director of the Center for Wireless Information Network Studies, Worcester Polytechnic Institute, Worcester, MA. He is also a visiting Professor of Telecommunication Laboratory and Center for Wireless Communications, University of Oulu, Finland. His area of research is location aware broadband sensor and adhoc networks. He has contributed to numerous seminal technical and visionary publications in wireless office information networks, home networking, and indoor geolocation science and technology. He is the principal author of the Wireless Information Networks (with Allen Levesque), John Wiley and Sons, 1995, 2ed Ed. 2005 and Principles of Wireless Networks – A Unified Approach (with P. Krishnamurthy), Prentice Hall, 2002. Before joining WPI, he was the director of advanced development at Infinite Inc., Andover, Mass. working on data communications. He started his career as an assistant Professor at Northeastern University, Boston, MA. He is the founder and Editor-in-Chief of the International Journal on Wireless Information Networks, the first journal in modern wireless networks established in 1994 and a member of the advisory board of the IEEE Wireless Magazine. He was the founder, the program chairman and organizer of the IEEE Wireless LAN Workshop, Worcester, in 1991, 1996, and 2001; organizer and technical program chairman of the IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications, Boston, MA, in 1992 and 1998; co-chair of the International Workshop on Ultra Wideband Systems, Oulu, Finland, 2003; co-chair of the International Workshop on Wireless Adhoc Network, Oulu, Finland, 2004; and the chairman of the IEEE International Conference on Mobile Adhoc Sensor Systems, 2005. He has also been selected as a member of the Committee on Evolution of Untethered Communication, US National Research Council, 1997 and has lead the US review team for the Finnish R&D Programs in Electronic and Telecommunication in 1999 and NETs project in 2003. For his contributions to the wireless networks he was the Westin Hadden Professor of Electrical and Computer Engineering at WPI during 1993-1996, was elected as a fellow of the IEEE in 1996 and became the first non-Finn fellow of the Nokia in 1999. From May to December of 2000 he was the first Fulbright-Nokia scholar at the University of Oulu, Finland. In the past few years Prof. Pahlavan's research work was the core for more than 25 patents by Skyhook Wireless where he acts as the chief technical advisor. Skyhook Wireless localization technology is used in iPhone and Dell's new Mini 10 Netbooks. The centre maintains a well-documented web site at <http://www.cwins.wpi.edu>.

Sergey N. Makarov earned his B.S./M.S./Ph.D./Dr. Sci. degrees at the State University St. Petersburg (Leningrad), Russian Federation – Faculty of Mathematics and Mechanics. Dr. Makarov joined Institute of Mathematics and Mechanics at State St. Petersburg University in 1986 as a researcher and then joined the Faculty of State St. Petersburg University where he became a full professor in 1996. In 2000 he joined the Faculty of Department of Electrical and Computer Engineering at Worcester Polytechnic Institute, MA where he became a professor in 2008. His current research interests include practical antenna design, computational electromagnetic, and RF evaluation of material properties. He is the director of the Center for Electromagnetic Modeling and Design at WPI. This center focuses on the EM modeling of antennas and new engineering materials for antennas including dielectrics, semiconductors, and semiconducting materials.

Allen Levesque is a Research Scientist in WPI's Center for Wireless Information Network Studies (CWINS). He is currently conducting research in indoor wireless networking and advising MS and PhD graduate students in their own research. He is a Registered Professional Engineer in Massachusetts, and a Fellow of the IEEE. He received the BSEE degree from WPI and the MSEE and PhDEE degrees from Yale University. He joined CWINS in 1999, following a 36-year career in several divisions of the GTE Corporation, where he held a variety of positions as researcher, project leader, line manager, and Senior Staff Scientist. His professional work has focused on communications technology, with application to both military and commercial communication systems development. Just prior to his early retirement from GTE Labs, he managed GTE's research team under a Cooperative Research & Development Agreement with the U. S. Army Research Laboratory. He has authored about 40 conference and journal papers in the field of communications and has co-authored three texts, one in error-control coding, and two (with Prof. Pahlavan) in wireless communications.

Ning Yang is a Research Scientist at the Center for Wireless Information Network Studies (CWINS) of WPI. He currently is conducting research in wireless cooperative network and indoor geolocation. He is advising graduate student in their own research. He received the Ph.D. in EE degree from Northeastern University, MSEE degree from Virginia Tech, and the BS degree in Biomedical Engineering and Instrumentation from Tianjin University, China. He is a Senior Member of IEEE and has 14 years of industrial experience. His research interests are space time coding, MIMO system, forward error control coding, multiuser detection for CDMA systems, and digital signal processing.

Ferit Ozan Akgul received his B.Sc. degree from Middle East Technical University, Turkey, in 2002 and his M.S. degree from Koc University, Turkey, in 2004 both in electrical engineering. During his master's, he studied efficient resource allocation for high speed multicarrier CDMA data systems, specifically EV-DO. He also worked on the integration methodologies for WLAN and CDMA system using joint resource allocation and routing. Currently he is a Ph.D candidate at CWINS/WPI where he works as a research assistant on RF based indoor geolocation and indoor channel characterization with a particular focus on multipath aided precise indoor ranging. His interests include algorithms, statistical modeling, and performance evaluation of TOA-based ranging/positioning systems. He is the author of one book chapter, and numerous peer reviewed journal and conference papers. He served as a TPC member for Globecom07, Chinacom08 and Chinacom09 and was a reviewer for IEEE Transactions on Wireless Communications, IET Communications, EURASIP Journal on Advances in Signal Processing, and Elsevier Neurocomputing Journal as well as numerous conferences. He is expecting to graduate in Fall 2009 and expecting to work as a postdoc upon the completion of his studies.

8. INSTITUTIONAL CAPABILITIES

This project will be conducted by faculty affiliated with the Department of Electrical and Computer Engineering (ECE) at the Worcester Polytechnic Institute (WPI). The ECE department possesses 30,000 square feet of space (exclusive of classrooms) in a recently renovated building, with in excess of 8,000 square feet devoted to research laboratories. The server room is located on the first floor of Atwater Kent Laboratories, and consists of about 1,000 square feet of space. The fiber optical links directly connect to

the campus network at 10 Gbps, and both gigabit Ethernet switches and terabyte network storage are available. WPI's network hosts the Goddard's GigaPoP Internet-2 connection, and wireless access and point-to-point connections inside the campus. The Department of Electrical and Computer Engineering staffs an electronics shop with three full time technicians, and the expected array of equipment and parts. This equipment is supplemented with the ECE Departments' facilities that include a well-equipped electronics shop with complete maintenance facilities and staff (2 MS-level engineers, 2 full-time technicians) as well as a beerwolf cluster for high performance computing.

This project will be carried out at the Center for Wireless Information Network Studies (CWINS) at Worcester Polytechnic Institute (WPI). The basic equipment in CWINS has been acquired through three NSF equipment grants with WPI cost sharing (for approximately \$700K), one DoD DURIP equipment grant (for approximately \$250K), and a number of industrial contributions (order of \$300K). The core of CWINS' equipment includes RF facilities for radio propagation measurements, modeling and real-time performance evaluation studies.

Followings are the summary of the existing equipment available to CWINS laboratory that can be useful for RF measurement and modeling program proposed in this project:

- RF Measurement Equipment
 - Agilent E8363B Network Analyzers up to 40GHz
 - Agilent E4407B Spectrum Analyzer up to 26GHz
 - Agilent 8600C Digital Oscilloscope up to 20GHz
 - HP-8753B Network Analyzer 6GHz
 - HP-85047A S-Parameter Test Set
 - HP 8672A Synthesized Signal Generator
 - HP 8082A Pulse Generator
 - Agilent E4419B Power Meter
 - Agilent E3644A Adjustable Power Supply
- State-of-the-art Channel Measurement System
 - UWB measurement systems
 - IWT - Custom Made UWB Cone Antennas
 - PJ Microwave – Base station UWB Triangular Antennas
 - WPI designed UWB flat bow-tie antennas
 - RF Labs - Lab Flex 335 UWB Cables
 - Mini-Circuits – ZVE-8G UWB Power Amplifier
 - IWT – Custom Made UWB Low Noise Amplifier
 - Collection of high performance antenna systems from 100MHz-2.4GHz
- Proprietary Software
 - CWINS proprietary 2D and 3D measurement calibrated Ray Tracing software
 - CWINS proprietary WLAN RF Placement Tool
 - CWINS proprietary Super-resolution software for post-processing
- EM Modeling Software
 - Ansoft HFSS with Capability to simulate inner body propagations
 - Ansoft Maxwell 3D
 - CST Studio
 - In house and SuperNEC MOM software
- Real Time Channel Simulator
 - PROPSIM C8 Real Time Channel Simulator with Proprietary Ray Tracing Interface
- Isolated Environment
 - Azimuth 801W isolated laboratory test environment
 - Azimuth Mini Test Head WLAN Traffic Analyzer
 - Faraday RF isolated rooms
- Sensors for Real-time Measurements
 - 12 IWT Axon Modules ZigBee Sensor Network Set
 - Ekahau RFID WiFi localization tags
 - WiFi Access Points with connectors to PROPSIM channel simulator
 - Axis 9010A Bluetooth access point and Palm Bluetooth cards

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