Spatial Behavior of UWB Channel Pertinent to Indoor Geolocation

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Abstract— This paper describes the results of frequency-domain dynamic channel sounding in a typical office environment for studying the spatio-temporal channel behavior pertinent to indoor geolocation. It consists of detailed characterization of complex frequency responses of ultra-wideband (UWB) signals having a nominal center frequency of 5.5GHz and bandwidth of 5GHz. The effects of distance, threshold for picking paths, bandwidth, and occurrence of none-line-of-sight (NLOS) on multipath parameters such as number of multipath-components (MPCs) and path persistency are presented. Furthermore, a novel model for the dynamic behavior of number of MPCs is proposed.

I. INTRODUCTION

Recently, indoor geolocation technologies has been attracting tremendous attention. Applications are envisioned for indoor location sensing in commercial, public safety, and military settings. The well known GPS system [1] falls short of expectations when it comes to indoor areas. For indoor environments, the fine time resolution of ultra-wideband (UWB) signals enables the potentiality of accurate distance measurement of the direct path (DP) between a number of reference sources and the people or assets of interest. However, the rich multipath environment often causes the received signal strength (RSS) of indirect paths being greater than that of the direct path, sometimes resulting in undetected direct path (UDP) conditions [2]. Once the DP is not available or shadowed, substantial amount of errors will be introduced into the ranging measurements hence leading to large localization errors when combined from multiple sources [3]. The existence of these UDP conditions and how they affect the ranging/positioning accuracy can be found in [4], [5].

The measurement accuracy in UDP conditions can be improved in some cases by exploiting the geolocation information contained in the indirect path measurements, which can be found in [3], or exploiting multipath signals by using them as additional measurements within a nonlinear filter [6]. Both of these approaches will need the help of other indirect paths rather than only the DP component. The intuition for using multipath is that even in the absence of DP, there will be multipath components that might show stable and persistent behavior and hence can be related to the DP to aid in more precise localization. Therefore, the dynamic behavior (persistency) of paths which is time varying due to the motion of the mobile terminal (MT) and changes in the surrounding objects is an important issue in mitigating the UDP error. To explain path persistency, we will consider the following channel model [2] :

\[ h(t, \theta) = \sum_{k=0}^{N-1} \alpha_k p(t - \tau_k, \theta - \theta_k) e^{j\phi_k} \]  \hspace{1cm} (1)

where N is the number of multipath components (MPCs), \(p(t)\) is the pulse (with a certain bandwidth \(\omega\)) transmitted, and \(\alpha_k, \tau_k, \theta_k, \phi_k\) are the amplitude, propagation delay (TOA), angle of arrival(AOA) and phase of the kth MPC respectively, which can be considered as traceable features of the paths. Persistency is basically the lifetime of a particular path during which its traceable features exhibit differential changes in accordance with the receiver’s differential motion. If we can track the paths that exhibit persistent behavior even when the DP is not present, then we can use this additional information to properly adjust the ranging measurements for true distance [3].

The objectives of this paper are twofold. Firstly, to study the dynamic behavior of indoor propagation channels in order to provide information for dynamic spatio-temporal channel parameters modeling. Secondly, to present the results on the effect of bandwidth, path detection threshold and NLOS occurrence on multipath parameters.

REFERENCES

Abstract—An RF-based system is being developed for tracking of first responders and other personnel in indoor environments. The system assumes no existing infrastructure, no pre-characterization of the area of operation and is designed for spectral compliance and rapid deployment. The RF 3D location system, based on a recently developed multicarrier signal fusion algorithm, has previously demonstrated sub-meter positioning accuracy of a transmitter, even in difficult indoor environments with high multi-path, with all receivers placed outside the building. However, the current version of the system requires a set of 12 to 16 antennas be distributed outside three to four sides of the building in order to obtain the necessary diversity of information necessary to precisely resolve 3D location. This is undesirable as a practical application of a Precision Personnel Location (PPL) system requires rapid deployment of any antenna nodes at a time when almost all manpower at the fire scene is dedicated to rapid and safe entry into the building and fire suppression activities. Thus, the act of antenna deployment must be extremely fast, easy and forgiving. This paper reports on the development and evaluation outcomes of an approach that permits 3D location based upon deployment of two antenna arrays on any one face of the building.

The positioning performance of the PPL system with the new antenna system will be compared to performance from the previous incarnation of the PPL system with widely distributed antennas. In the case of the new antenna system, outcomes will be shown for both the cases of Bayesian inference based upon additional sensor information and without this sensor information. The previously described [1]–[5] WPI PPL system has demonstrated 3D accuracies of better than 1 m in indoor tests. We will show that the new version of the system does not perform at the level of precision as that with a diverse antenna distribution, however, at a level sufficient to still significantly aid in search and rescue missions.

I. INTRODUCTION

The Worcester Polytechnic Institute (WPI) Precision Personnel Location (PPL) system, being developed at WPI, is an RF based system for locating first responders inside of a building. More specifically, the goal is to have a system that is accurate within +/- one meter, portable, rugged, and rapidly deployable with no site preparation or on-site calibration procedures [2]. In recent years, the system has been expanded to consider fire, police, military, and even robotic vehicles in both urban and wilderness settings.

Figure 1 is an artist’s rendition of the PPL concept. The locator units worn by personnel emit a Multi-Carrier Wide-Band (MC-WB) signal that is received by multiple antennas located outdoors, around the building at known positions. The receiving antennas are connected to our transceiver units, which send the spectrum of the received signal to a central computer through a wireless network. The computer processes the data from all of the received antennas, and calculates the location of the firefighter based on the time-difference-of-arrival (TDOA) like algorithm involving a signal fusion approach.
incorporating no pre-installed infrastructure, rapid deployability, medium (not ultra-wide) bandwidth, flexible and spectrally compliant signals, and low cost personnel tags [2]. Previous papers have described: development and performance of new signal processing and location techniques for the amelioration of the extreme multi-path conditions such as found in typical commercial and industrial structures [1]–[5], which usually frustrate all attempts to achieve precision location; incorporation of physiological monitoring sensors and real time display; automated solution of outdoor sensor positions for rapid deployment; synchronization technology for wirelessly connected transceiver nodes [6]. This paper describes a next generation of the PPL fast-deployment antenna system and requisite sensor and algorithmic support for solution of 3D indoor location from antennas located on only a single side of a building. An approach has been developed in which signals are captured from antennas mounted on two extension ladders that can be transported easily by fire truck and then quickly extended and leaned against a building face. However, due to the poor geometry this presents for 3D precision location within the context of the present TDOA-like multicarrier solution technique and especially when challenged within the high multipath indoor environment, large errors in the direction perpendicular to the antenna plane are experienced. To ameliorate this degradation of location precision, a new data fusion system has been developed that uses Bayesian inference to introduce additional, not necessarily precise or low variance information, to obtain a refined global solution. The flexible Bayesian inference engine allows additional information to be obtained from sources as diverse as low-cost inertial sensors and simple radio ranging sensors.

The following sections will describe the current WPI location algorithm(σART), pure RF signal based tests of both the unrestricted and rapid deployments, additional sensor information introduced in this paper, and the results of the rapid deployment system information fused with these additional sources of information. [7]

II. CONCLUSION

The importance of precision indoor positioning with no pre-installed infrastructure is well understood, and this paper presents significant progress toward that goal. Previously this research group constructed a system using RF-only technology with diversely distributed antennas which successfully demonstrated the concept of the new positioning approach while realizing that deployment requirements of the fire fighting environment and severe deployment restrictions would additionally need to be addressed. This paper explained these deployment requirements, the problem posed by them, the solution implemented, and the performance of a system enhanced by fusion of information from three sources.

While the Rapid Deployment/Fusion outcomes are less precise than the unrestricted deployment approach, the floor is always correctly identified (with half meter precision). The floor occupied by the subject to be rescued is considered, by firefighters, to be the single most valuable piece of information to promote timely rescues. The Y direction information has approximately 2 meter maximum error (4 ladder case), which can be probed with classic swinging firefighter’s “pipe” or ax handle. The larger (2-4 meter) X direction errors can be accommodated with rapid linear search, which is faster than searching the circular area swept by this same distance. Thus this paper documents what must be considered a successful demonstration of firefighter location technology with a rapid deployment system.

The new hardware (with mobile transceiver capability) which enabled the tests described in this paper also unlocks other opportunities that surpass in potential the basic fusion system just described. We are continuing active research aimed at further improving the precision of X, Y and Z estimates in the rapid deployment configuration.

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REFERENCES

On Wideband Modular Design of Small Arrays of Planar Dipoles

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Abstract-A new approach to the design of small size wideband arrays of planar dipoles situated over a ground plane is introduced. While these arrays are intended for use in the VHF-UHF region of the spectrum, they can be easily scaled for operation at higher frequencies. The modular design results in increased impedance bandwidth (≥ 2.5:1), as well as higher directive gain at the low frequencies. The design of these arrays also includes an analytical model for the power combiner. We will also compare two different approaches to implementing the balun. The simulation results for a 2x1 array and a 4x1 array will confirm our hypothesis.

I. INTRODUCTION

In this paper we propose a new approach to design small broadside arrays comprised of identical square radiators attached side to side. The individual radiator (the unit cell) has the size $\sim \lambda/2 \times \lambda/2$, where $\lambda$ is the wavelength at the center frequency. We believe that the individual radiator may be designed in such a way that the 2x1 array, 3x1 array, 2x2 array, 4x1 array, 3x2 array, 3x3 array, 4x2 array and the 4x4 array of these identical radiators may have the same impedance bandwidth of $\sim 2.5:1$, over the same band of frequencies. At the center frequency, the array gain will always approach a value predicted by the array area rule [1]-[3], for any considered array geometry. While single antenna systems do achieve bandwidths far greater than 2:1, there is a degree of complexity in their design and construction. Some of the common examples of such antennas are the spiral [4], [5] and the log-periodic antennas [6]. Furthermore, the arrays so designed will have a superior gain at lower frequencies. The present modular approach may be used for low-cost larger-volume small broadside array design.

II. UNIT CELL BASED FINITE ARRAY CONFIGURATIONS

A. Unit Cell Structure and 2x1 Array

The unit cell serves as the basic building block for all the arrays and is shown in Fig. 1. It comprises of a resonant dipole of total length $2L$, and width $W$ placed over a finite ground plane of dimensions $S_x \times S_y$ at a height $h$. A conical impedance matching structure is included to control the impedance match between the feed point and the dipole. A wide blade dipole is chosen since it is easier to impedance match to such dipoles (thick dipoles if considering cylindricals) [7], [8].

As mentioned in the introduction, we investigate whether bandwidth improvement can be obtained by using one more identical unit cell either along the x or the y axes. Our goal is to at least achieve a bandwidth of 2.5:1. The bandwidth definition used is shown below,

$$B = \frac{f_u}{f_l}$$  \hspace{1cm} (1)

where, $f_u$ and $f_l$ represents the upper and lower frequencies which satisfy the $S_{11} < -10$ dB criterion. The 2x1 array is shown in Fig. 2, along with the port numbering scheme. In this case we have two ports, but due to symmetry we only need the reflection coefficient data from either port. The antennas are excited uniformly and are not intended to have scanning capability. The simulation is performed in ANSOFT HFSS. It is clear from Fig. 3 that we can indeed achieve a larger bandwidth. The 2x1 array is capable of an impedance bandwidth of 2.5:1 as compared to the single antenna, which provided about 35 % fractional bandwidth. The bandwidth shown in in Fig. 3 is calculated on the basis of the reflection coefficient measured at one port when all other ports are terminated into 50Ω impedance. We are currently in the process of using the full active S-parameters for optimizing and calculating the bandwidth. The active S-parameters will allow for a more accurate modeling of the array performance.

![Fig. 1. Top view of unit cell consisting of a resonant dipole above a ground plane (dotted line as border). Conical matching section can be seen extending to the feed for impedance matching purpose.](image-url)
B. Power Combiner Model

Arrays inherently require a power combining/dividing network to function. Typically such power combining networks are based on the common Wilkinson power divider [9]. However, since the antenna impedance is frequency dependant, we have to optimize the array performance by including the impedance transformation through the power combiner/divider. An analytical model for the impedance transformation will be introduced that calculates the input impedance at the input port of the 2-way power combiner, $Z_{in}$, with the array elements as the load as follows:

$$Z_{in} = \frac{2Z_0^2(Z_1 + Z_2 + Z_3)}{Z_1R_d + 4Z_1Z_2 + Z_2R_d} \tag{2}$$

where, $Z_1$ and $Z_2$ represent the active antenna impedances, $Z_0$ is the characteristic impedance and $R_d$ is the dissipation resistor within the Wilkinson combiner.

C. Peak Broadside Gain

For a large array that is uniformly excited, and possesses no grating lobes, the peak directive gain is given in [1–3] and restated here as:

$$G_d = \frac{4\pi NA}{\lambda^2} = \frac{4\pi N_x S_x S_y}{\lambda^2} \tag{3}$$

where $G_d$ is the peak directive gain of the array, $N$ is the total no. of elements in the array (with $N_x$ elements along the $x$ direction, $N_y$ elements along the $y$ direction), $A$ represents the array area, $S_x$ and $S_y$ are the inter element separation within the array. It is our firm belief that small arrays such as the ones being considered in this paper will outperform the theoretical limit given in Eq. (3) at the lower frequencies. We intend to provide the comparison for the 2x1 and the 4x1 arrays.

III. Conclusion

Modular design of small arrays has the potential to provide bandwidths of at least 2.5:1 together with higher and uniform gain over the operating bandwidth. Modeling the effects of the power combiner on the active array impedances allows for better accuracy in optimization which should translate to improved performance when implemented in hardware. Current work is focused on design optimization and the hardware implementation.

REFERENCES

Group Device Pairing: Secure Communication Bootstrapping for Wireless Body Area Networks

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Abstract—Body Area Networks (BAN) is a key enabling technology in E-healthcare such as ubiquitous health monitoring. An important security issue is to bootstrap secure communication within BAN during the setup phase, including establishing trust relationship among a group of sensor devices and generate necessary secret keys to protect the subsequent wireless communications. Due to the ad hoc nature of the BAN and the extreme resource constraints of sensor devices, providing secure, fast, efficient and user-friendly communication bootstrapping is a challenging task. In this paper, we propose a lightweight scheme for secure communication bootstrapping in BAN. A group of sensor nodes, having no prior shared secrets before they meet, establish initial trust through group device pairing (GDP), which is an authenticated group key agreement protocol where the legitimacy of each member node can be visually verified by a human. Various kinds of secret keys can be generated on demand after deployment. The GDP supports batch deployment of sensor nodes to save setup time, does not rely on any additional hardware devices, and is mostly based on symmetric key cryptography, while allowing batch node addition and revocation. We implemented GDP on a sensor network testbed and evaluated its performance. Experimental results show that that GDP outperforms several state-of-the-art schemes.

I. INTRODUCTION

In recent years, wireless body area networks (BAN) have emerged as an enabling technique for E-healthcare systems, which will revolutionize the way of hospitalization [1]. A BAN is composed of small wearable or implantable sensor nodes that are placed in, on or around a patient’s body, which are capable of sensing, storing, processing and transmitting medical data via wireless communications. The BAN is used in a wide range of applications, such as ubiquitous health monitoring (UHM) and emergency medical response (EMS). A typical structure of the BAN and its relationship with the E-healthcare system is depicted in Fig. 1. Usually for each patient, a controller acts as the gateway node between the BAN and the communication infrastructure.

A fundamental security problem during the setup phase of a BAN is to associate a group of sensor devices to the correct patient (sensor association), without which wrong or faked medical data maybe treated as genuine. Essentially, this requires secure communication bootstrapping for BAN, which aims at initializing secure wireless communication among a group of sensor nodes. In particular, the sensor nodes must authenticate with each other and form a group with the controller. They cooperatively generate a secret key which is only known to the group, so as to protect the subsequent communications. The primary requirements in this process are fast, efficient, and user-friendly. Here the unique challenge is, the sensor nodes may not share any prior common security contexts since they come from different vendors and may have never meet each other before. This means secure communication must be established out of an insecure channel. Previous works were mostly based on “device pairing” [2], where two devices sharing no secrets are securely paired together. However, current device pairing algorithms are either designed for pairing two devices [2], or are too slow to be used [3] in BAN bootstrapping.

Therefore, in this paper, we propose a novel scheme group device pairing (GDP), where a group of sensor devices bootstrap secure communication through establishing a common, authenticated group key based on no prior shared secrets. We leverage device pairing and group key agreement techniques in an unique way, so that the sensor devices authenticate themselves to the whole group in one batch, which takes less than 30 seconds. During this process, a human user can visually make sure (by watching simultaneous LED blinking patterns) that the authenticated group of devices include and only include the intended devices that s/he wants to associate together to a patient. Other salient features of GDP include computationally efficient, user-friendly, and also error-proof. In addition, GDP neither requires a public key infrastructure (PKI) nor additional hardware, which makes it suitable for commercial BAN applications. We implement GDP on a 10 node sensor network testbed. Experimental results show that group sensor association can be done within 30 seconds with low overhead, and is intuitive-to-use.

II. GDP: SECURE COMMUNICATION BOOTSTRAPPING FOR BAN

In our proposed scheme, group device pairing is performed among the sensor nodes and the controller to setup a shared group key, so that the controller can securely associate the correct group of nodes to the patient it belongs to. In GDP, the key idea is to authenticate the protocol transcript of a group key agreement scheme by simultaneously comparing
LED blinking patterns for a group of nodes. Using the derived group key, nodes can establish pairwise secret keys between each other to protect the subsequent wireless communications within the BAN.

The GDP is carried out only for a group of size less than \( n_{\text{max}} \) where \( n_{\text{max}} \) is a parameter. If the size of the intended group \( N = |\mathcal{G}| > n_{\text{max}} \), the user randomly picks \( n_{\text{max}} \) nodes from \( \mathcal{G} \) in a batch to form several subgroups and multiple GDP runs are needed. Each GDP run consists the following four phases:

- Counting and initialization. In this phase, the user picks sensor nodes and counts their number, which is input into the controller. The member count information is used to protect against member masquerade attacks.
- Executing the unauthenticated group key agreement protocol. In this phase, a traditional, participatory group key agreement protocol is executed, where each member device contributes a key share based on which the group key will be derived. We use the one in [4] (UDB) due to its security and efficiency.
- The authentication steps. In this phase, the protocol transcript of UDB is authenticated. We leverage the commitment schemes where the information to-be-authenticated is first committed and then revealed, so that it cannot be maliciously altered by others. The result of this phase is the derivation of a short authentication string (SAS) which is synchronously displayed by the LEDs of all member devices, which should be consistent and can be visually verified by a human. During this phase, only two rounds of broadcast communication is needed for each device.
- Key derivation and confirmation. In this final phase, the group key is derived and confirmed by exchanging a few more messages among the group members.

### III. Evaluation

#### A. Implementation

We implemented GDP on a sensor network platform consisting of 10 Tmote-Sky nodes, each with 8MHz TI-MSP430 microcontroller, 10KB RAM and 48KB Flash (ROM). We let one of the sensor nodes be the controller. We convert the GDP to its elliptic curve cryptography (ECC) version. To provide 80-bit key security, we derive a 160-bit group key; so the size of the finite field used is 160-bits. Also, the length of the SAS is \( \rho = 16 \).

#### B. Results

In the following, we choose \( n_{\text{max}} = 10 \).

1) **Time required for sensor association**

We plot the time for one GDP run \( T_{\text{gdp}}(N) \) against the group size \( N \) in Fig. 2. The \( T_{\text{gdp}} \) is almost constant when \( N \) increases. This is because all nodes display LED blinking patterns simultaneously, while the computations are quite fast. We also decompose \( T_{\text{gdp}} \) in Table I. We then compare GDP with Scheme I, where pairwise device pairing is applied multiple \( (N) \) times. From Fig. 2, \( T_{\text{sc}}(N) \) is linear with \( N \). For \( N = 20 \), this is 475s. Obviously, when \( N \geq 3 \) the time of GDP is far less than Scheme I (and also [5]).

2) **Energy Consumption**

We plot the average EC for each sensor node in GDP against the group size \( (N \leq 10) \) in Fig. 3. The EC of GDP is small; although it is a little higher than that of Scheme I, since it uses extra ECC point multiplication and addition operations, the difference is small (below 50 mJ). Also we break down the EC of GDP in Table I.

3) **Usability**

The result is summarized in Table II.

#### REFERENCES


