A Novel Wireless Local Positioning System for Airport (Indoor) Security

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ABSTARCT

A novel wireless local positioning system (WLPS) for airport (or indoor) security is introduced. This system is used by airport (indoor) security guards to locate all of, or a group of airport employees or passengers within the airport area. WLPS consists of two main parts: (1) a base station that is carried by security personnel; hence, introducing dynamic base station (DBS), and (2) a transponder (TRX) that is mounted on all people (including security personnel) present at the airport; thus, introducing them as active targets. In this paper, we (a) draw a futuristic view of the airport security systems, and the flow of information at the airports, (b) investigate the techniques of extending WLPS coverage area beyond the line-of-sight (LoS), and (c) study the performance of this system via standard transceivers, and direct sequence code division multiple access (DS-CDMA) systems with and without antenna arrays and conventional beamforming (BF).

Keywords: Future airport security, Local positioning systems, DS-CDMA, Beamforming schemes, routing algorithms.

1. INTRODUCTION

Historically, positioning was developed for navigational purposes with a wide variety of civilian and military applications, and they fall in to two main categories, global positioning systems (GPS) and local positioning systems (LPS) [1]-[4]. GPS system is a precise, all-weather, 24 hour satellite based positioning system mainly developed for direction finding and navigation [5]. GPS has the following problems: (1) its signal does not penetrate in the buildings, hence, it does not perform at indoor areas, (2) it looses its precision in rich scattering environments such as urban areas, (3) it is mainly suitable for navigation and for tracking or command purposes, it should be merged with a communication system for transmission of position information from the GPS to a center (e.g., command center in defense applications), and (4) it is yet expensive.

Local positioning systems (LPS) fall primarily into two categories [6]: (1) Self Positioning: A mobile device finds its own instantaneous location with respect to a fixed point, e.g., the starting point or a beacon node, and (2) Remote Positioning: A mobile device finds the instantaneous positions of other objects (mobiles) with respect to its own position. In the self positioning LPS, a mobile uses the instantaneous velocity, direction and the elapsed time to calculate its own relative position. Such systems are functional in any indoor or outdoor environment, and are typically used in conjunction with communication control center(s) to perform tracking, monitoring, command and control. However, these systems may loose their location information permanently, if their functionality is lost even for a very short period of time. Moreover, any small error in the computation of location may propagate and lead to a large position error or even loss of position information.

In the search for remote local positioning, different systems have been developed or are under development. For example, radar systems are used to find the position of targets in the surrounding areas via transmission of a short burst of energy and processing its reflection from the targets [7]. The ability of radars to detect the desired targets is hindered by clutters or reflections from undesirable objects and interfering radars, which are inevitable in typical indoor and urban areas, rendering radar systems impractical [8], [9]. Another example is a vision system that uses video signals collected from a camera to recognize targets and estimate positions [10], [11]. Such systems possess major limitations at night and in severe weather conditions such as intense rain, snow and fog (e.g., when they intend to cover the outdoor airport environments), they may suffer from blind spots, and may violate some means of privacy.

In general, the quality of a positioning system is characterized by two important metrics: one is the probability of detection (POD, or \(p_d\)) that represents the ability to detect all targets, and the other is the probability of false alarm (p_{fa}) that indicates the probability of falsely treating noise as the desired target. In both vision and radar positioning systems, the target is a passive target, which incurs expensive signal processing. In addition, detecting a passive target always requires tradeoff between \(p_d\) and p_{fa}; as the former increases, the latter increases as well, resulting in a low overall performance.

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1 The US patent Wireless Local Positioning Systems (WLPS) is pending by Michigan Tech University.
In [12], we introduced an innovative wireless local positioning system (WLPS) with active targets. WLPS consists of (1) a base station in each monitoring mobile, which serves as a non-static or dynamic base station (DBS), and (2) a transponder (TRX) in target mobiles, which acts as active targets. Unique identification (ID) codes are assigned to each target. DBS transmits an ID request (IDR) signal to all targets located in its vicinity, and targets respond to that signal by transmitting their ID codes back to the DBS. DBS recognizes each target by its ID code, and then positions, tracks and monitors those targets. In [12], we mentioned that WLPS has a variety of applications in Defense, collision avoidance and road safety, multi-robot collaboration and coordination, law enforcement, and homeland security.

In this paper, we propose a futuristic view for the implementation techniques of this system for airport security and the benefits created via WLPS for reliable airport (indoor) monitoring. In order to implement the TRXs for airport security, the paper boarding pass should be replaced by either plastic card boarding passes with a TRX installed in it or a wristband that carries a TRX within the area of interest (whole airport or building). However, all security personnel need to locate all TRXs within the area of interest (whole airport or building). To achieve this goal, the position information should be forwarded from a DBS, and via the nearest node, to the neighboring DBS. This is accomplished via multi-hop networks and geographical based routing algorithms [13], [14].

WLPS introduces a unique application for wireless systems whose performance is degraded via both inter-TRX-interference (IXI) at the DBS receiver as well as inter-DBS-interference (IBI) at the TRX receiver. Multiple access (MA) schemes such as spatial division MA (SDMA) [15], [16] and direct-sequence code division MA (DS-CDMA) [17] can be used to reduce the interference effects. SDMA is possible via antenna arrays with directional beam patterns. Directional beam patterns are formed by applying proper weight vector to the antenna array elements. In DS-CDMA, each user’s bit is multiplied by a sequence of G chips (short pulses of duration Tc), where each chip has amplitude +1 or −1 (here, G is called the processing gain). By careful selection of +1 and −1 values (spreading sequences), the receiver can separate users one from another. To enhance performance via path diversity most DS-CDMA systems employ RAKE receivers, which attempt to separate and linearly recombine the multiple paths.

Here, we study the realization of the DBS receiver via standard transmitters and receivers (i.e., simple modulators and demodulators) as well as receivers with and without antenna arrays and beamforming (BF), and we compare their probability-of-detection (POD), p_d, performance. Assuming a perfect estimation of direction-of-arrival (DOA), we evaluate that a DS-CDMA with conventional BF highly enhances the p_d performance of WLPS.

Section 2 introduces WLPS structure and discusses the interference effects. Section 3 proposes futuristic implementation techniques for airport security. Section 4 discusses the routing techniques that enhance the coverage of the WLPS beyond LoS. Section 5 discusses the DBS receiver structure and theoretical analysis of system performance. Section 6 represents the simulation results and analysis. Section 7 concludes the paper.

2. WLPS STRUCTURE

The two WLPS main parts include: A dynamic base station (DBS) and a transponder (TRX). The DBS transmitter generates an ID code request (IDR) signal every IRT (ID request repetition time) to all TRXs in the coverage area; then, it waits to receive a response back from the TRX within IRT (see Figure 1). TRX transmits a unique ID code as soon as it detects the IDR signal transmitted by DBS. The ID code may be selected from simple pseudo random codes which consist of +1 and -1 (see Figure 1). Hence, the number of bits in the code depicts the maximum capacity of the WLPS. Depending on the application, the ID code can be assigned permanently or can be assigned by DBS.

In a WLPS structure, each DBS communicates with a number of TRX in its coverage area simultaneously. This is the same as usual cellular communication systems. However, in contrast to cellular systems, in WLSP each TRX communicates with a number of DBS simultaneously as well (Figure 2). In addition, as seen in Figure 1, the time of transmission and reception would be different at the DBS. Moreover, the whole DBS and TRX use different transmission frequencies. Thus, the overall system is considered as a time division duplex (TDD)–frequency division duplex (FDD), that is, hybrid TDD/FDD communication system (differ from cellular systems that are either TDD or FDD). This allows WLPS to reduce the interference effects via a proper selection of IRT.
Figure 1 Transmission of IDR and reception from TRX in DBS. Assuming a Pseudo Random ID codes, the number of the bits in the code represents the maximum capacity of the WLPS.

The minimum allowable value for IRT \( IRT_{\text{min}} \) is calculated to avoid range ambiguity or second time around echo \[7\]. That is, if the response to each IDR signal is received in DBS within IRT, mobile range is calculated correctly; however, if it is received after the next ID code request transmission, the range is not correctly calculated. Hence, IRT is a function of the maximum coverage or the maximum range \( R_{\text{max}} \). Considering the maximum uplink antenna array half power beam widths (HPBW) \( \beta \) to be less than 90\(^\circ\), the minimum allowable IRT corresponds to:

\[
IRT_{\text{min}} = 2T_{\text{max}} + T_d + T_g
\]

where \( T_{\text{max}} \) denotes the maximum possible time delay between the TRX transmission and the DBS reception, \( T_d \) is the TRX time delay in responding to the IDR signal, and \( T_g \) is the guard band time corresponds to

\[
T_g = 5T_m + \tau_{\text{DLBS}} + \tau_{\text{TRX}}
\]

Here, \( T_m \) is the wireless channel delay spread, and \( \tau_{\text{DLBS}} \) and \( \tau_{\text{TRX}} \) are the durations of DBS and TRX transmitted signals, respectively. Using simple geometry, \( T_{\text{max}} \) is determined by \( R_{\text{max}} \) and \( \beta \) via:

\[
T_{\text{max}} = \left( \frac{R_{\text{max}}}{2c} \right) \left( 1 + \cos^{-1} \beta \right)
\]

where \( c \) denotes the speed of light. Equation (1) defines a lower limit for IRT (i.e., \( IRT_{\text{min}} \)). Equation (1) refers to a lower limit for the IRT. The upper limit for IRT \( IRT_{\text{max}} \) is a function of the speed of moving TRX and DBS, and the required speed of processing which varies with applications. In general, IRT is selected large enough to reduce the interference effects at the TRX.

The TRX receiver is subject to inter-DBS interference (IBI), since more than one DBS may transmit IDR signals in the coverage area of a TRX. Large selection of IRT reduces the probability-of-overlap or collision of the DBSs transmitted signals at the TRX receiver. In addition, a number of TRXs in the DBS coverage area respond to the IDR signal of one DBS simultaneously, causing inter-TRX-interference (IXI) at the DBS receiver. Figure 3(a) represents the IXI effect at the DBS receiver. Both IXI and IBI are a function of the probability-of-overlap, \( p_{\text{ovl}} \), of the received signals from TRXs and DBSs respectively. Probability-of-overlap has a profound effect on the performance of the receiver, is a function of the number of mobiles or transmitters (DBS or TRX), \( K \), in their coverage area, and corresponds to

\[
p_{\text{ovl}} = 1 - (1 - d_c)^{K-1},
\]

where, \( d_c = \tau / T, \tau = \tau_{\text{DLBS}} (\tau_{\text{TRX}}) \) is the duration of DBS (TRX) transmitted signal (see Figure 1), and \( T = T_{\text{DLBS}} (T = T_{\text{TRX}}) \).
where, $I_{\text{RT\ min}}$ refers to minimum allowable $I_{\text{RT}}$ ($I_{\text{RT\ max}}$ denotes the maximum allowable $I_{\text{RT}}$, or the selected $I_{\text{RT}}$ value). Figure 4 represents this probability as a function of the number-of-transmitters (TRX or DBS) for different values of duty cycle.

In general, large selection of $I_{\text{RT}}$ reduces IBI effects at the TRX receiver and highly enhances its POD performance. However, the large selection of $I_{\text{RT}}$ does not affect the IXI, since all of the signals are received by DBS receiver within the $T_{\text{max}}$ time frame, which is mainly a function of the maximum coverage range [see Figure 3(a)]. It is also worth mentioning, each TRX located in the coverage area of more than one DBS may generate ID codes in response to more than one DBS within each $I_{\text{RT}}$. This leads to both IXI as well as range ambiguity [see Figure 3(b)]. Range ambiguity can be resolved via changing code assignments (MA codes, ID codes or both) for different DBS. In addition, in Equation (4), the parameter $d_c$ is a function of $\tau_{\text{TRX}}$ and $\tau_{\text{DBS}}$, so as the probability-of-overlap and the POD performance of WLPS.

In general, selection of $\tau_{\text{DBS}}$ and $\tau_{\text{TRX}}$ depends on the POD, desired system capacity (in terms of the number of TRX/DBS accommodated), bandwidth, positioning accuracy and maximum coverage range, and may vary with WLPS application. The duration of the transmitted signal by the DBS ($\tau_{\text{DBS}}$) and TRX ($\tau_{\text{TRX}}$) should be much smaller than the $I_{\text{RT}}$ to reduce $p_{\text{ovl}}$ among signals received by receivers of TRX and DBS, respectively. A smaller $p_{\text{ovl}}$ decreases both the IBI (at TRX) and IXI effects (at DBS), which in turn enhances the POD performance, positioning accuracy and user capacity of the WLPS system. On the other hand, as indicated in Figure 1, the system maximum capacity expressed by the maximum number of TRX (DBS) determines the number of bits within each ID code, which is to be transmitted over a period of $\tau_{\text{DBS}}$ ($\tau_{\text{TRX}}$). The required bandwidth, is inversely proportional to $\tau_{\text{DBS}}$ and $\tau_{\text{TRX}}$ for a given capacity. A large selection of $I_{\text{RT}}$ allows $\tau_{\text{DBS}}$ to be selected much larger than $\tau_{\text{TRX}}$ without sacrificing $p_{\text{ovl}}$ at the TRX receiver. Hence, WLPS bandwidth is mainly determined by the value of $\tau_{\text{TRX}}$ (see Section 6, simulation results).
Large IRT values lead to low $p_{out}$, and to reduce IBI effects at the TRX receiver, a simple structure consists of an omni-directional antenna and a standard (or CDMA) receiver suffices. However, to reduce IXI effects, DS-CDMA along with BF are employed for DBS receiver. The DS-CDMA suppresses the interference via orthogonal codes, and BF reduces the IXI via SDMA. Hence, the TRX needs a simple demodulator and a DS-CDMA transmitter (which leads to a very simple structure), and, antenna arrays and BF techniques are not required at the TRX, and its complexity, cost and size are minimal. (For some applications with a larger selection of IRT, DS-CDMA receiver is suggested for TRX.) However, the DBS would have a more complex structure at its receiver. Figure 5 represents the structure of DBS. DBS receiver calculates the position of active targets (TRX) via both the time of arrival (TOA) and DOA information. DBS receiver estimates the signal TOA with respect to the time of transmission of IDR signal in order to find the distance of the mobile. It uses antenna arrays to find the DOA via various schemes [16].

3. AIRPORT SECURITY VIA WLPS: A FUTURISTIC VIEW

Here, we propose a futuristic view of WLPS implementation for airport security and the benefits created via WLPS for reliable airport (indoor) monitoring. As we mentioned earlier, WLPS consists of two main components, DBS and TRX. DBS should be carried by monitoring parties, which are basically the security guards. The DBS transmitter requires an omnidirectional antenna; however, its receiver needs an antenna array. Assuming a carrier frequency of 3GHz and a standard antenna array with half-wavelength element spacing and 4 elements, the antenna array dimension would be in the order of 15 cm which can be mounted at the security guards’ belts as shown in Figure 6(a).

The TRX will be carried by the all passengers, airport employees as well as the security guards. Different categories of these codes can be selected for each category of people in the airport area that makes them recognizable. The TRX can be mounted at reusable plastic cards, or wristbands (see Figure 6(b)). Both the plastic card and the wristband will act as the passengers’ boarding pass as well. The latter is a more reliable approach since it can be locked (e.g., by a magnetic lock) made to not be detached from the wrist (unless for example via a magnetic device). The wristband can also be used as a safety monitor and flight information system. A sensor can be installed in the wristband to monitor the heartbeats. The heartbeat signal: (a) confirms that the wristband is in its place, and (b) maintains the safety of the holder. For example, if a security guard’s life carrying the same TRX is seriously in danger (e.g., because he has faced an assault), a control center would be notified automatically. In addition, the gate and flight information can be directed to the wristband and passengers would be notified about any change. The wristband (or the card) can be used for automatic gate check in as well.

Figure 6 Implementation of (a) TRX (two options), and (b) DBS, for Future Airport Security.
In WLPS, the DBS can find the location of all TRX via multihop localization techniques as discussed in the next Section. In this case, a top view of the position of the TRX can be provided to the airport security control center (See Figure 7). In contrast to security cameras, this system provides visual location information to the security control center, with all information regarding all individuals in all weather conditions, while it does not suffer from blind spots, and does not violate some means of privacy. In addition, via mounting a simple TRX on the airplanes, a visual location of the airplanes can be provided which facilitates both the process of safety, security and ground traffic control. Some Static Base Stations (SBS) might be required to facilitate the process of multihop localization when a LoS node is not available [e.g., for multi-level localization, see Figure 7 and 8(c)].

4. ROUTING ALGORITHMS AND MULTIHOP LOCALIZATION

In WLPS, all DBSs as well as a control center should be capable of monitoring all TRX within the airport environment (indoor or outdoor), including the TRX outside the LoS of a particular DBS. However, if the TRXs and DBSs are not in the LoS of each other, they cannot maintain localization directly. The purpose of multi-hop localization is to localize all TRXs within an airport via localizing the immediate DBS neighbors. Here, all security personnel carry both DBS and TRX. Hence, each DBS of security personnel can locate the position of TRX of other security personnel. We define security personnel carrying DBS and TRX systems as nodes in the multi-hop localization system. Hence, each node can find the position of another node.

In a multi-hop wireless system, the position and orientation of one node can be estimated in the local coordinate system of another node, if they are immediate neighbors, as shown in Figure 8(a). However, if two nodes are not neighbors, they cannot locate each other directly. To define the geometrical relationship between any two nodes, a route from a source node to a destination node need to be determined. The routing algorithm process consists of two stages. First the route is discovered via a localized triangulation scheme called Delaunay triangulation [13]; and then, a kinematics model for the transmission of the information is formed.

The route discovery and the kinematics model are defined using a graph model, as shown in Figure 8(a). In the graph model, the geometric relationship between one node and its neighbors is defined via Delaunay tessellation. The nodes are denoted by $R_i, i=1,2,\ldots,n$. The Delaunay triangulation defines the link properties between one-hop neighbors, which are represented by a set of edges $E=\{e_{ij}(t), i,j=1,2,\ldots,n, i \neq j\}$ (see Figure 8(b)). In Figure 8(a), the nodes that are directly connected to $R_i$ are called the one-hop neighbors of $R_i$. The inter-node distance $e_{ij}$ is estimated by the onboard DBS. Figure 8(a) depicts a Delaunay tessellation scenario for an airport terminal.

Based on the graph model, a route can be established between two nodes, as shown by the thick line in Fig. 8(a). After the route is discovered, the relative position between the source node and the destination node would be established. The position and the direction of a node is defined in its local inertial coordinate system, as shown in Fig. 8(b). The relative position between the local coordinate systems of neighboring nodes is used to specify the relative position of the source and destination nodes. Similar to the kinematics of articulated robot manipulators, the kinematics between two nodes is established using a localized definition of the relationship between two neighboring nodes. The localized kinematics is represented by a transformation matrix between two nodes. For example, the relationship for $R_i$ and $R_j$ can be defined by transformation matrices $T_{ij}$ and $T_{ji}$ which are represented by the distance between the two nodes, $e_{ij}$, and their relative orientation, $\theta_{ij}$. One-hop nodes can communicate to compute their relative direction. $\alpha_{ij}$ denotes the orientation of the node $R_i$ in the local coordinate system of node $R_j$. Based on the localization between one-hop nodes in the system, the resulted transformation matrix $T_{ij}$ is:
Base on the transformation matrix between two neighboring nodes and a route, the relative position of any two nodes in the system can be determined. Static base station (SBS) can be used to facilitate the process of multi-hop routing in the positions that the security guards (nodes) are not present. The same technique can be applied to multi-floor airport terminals or buildings. In this case, a static node (SBS) can be used to facilitate the process of routing from a node in one floor to a node in another floor (see Figure 8(c)).

5. DBS REALIZATION

As discussed in Section 3, in general, the interference effect IIXI (IBI) at the DBS (TRX) receiver can be mitigated via (a) making $d_c$ large enough, and (b) MA schemes. Large selection of IRT reduces the $d_c$ and consequently the IBI at the TRX receiver; however, the selection of IRT does not have any effect on the IIXI at the DBS receiver. Hence, while a simple receiver may ensure a high TRX POD performance, the DBS performance is improved just via MA schemes. Here, we see that a combination of two MA schemes, DS-CDMA and SDMA leads to a very high DBS POD performance. We start with the theoretical investigation of performance for standard receives and then we continue the discussion for MA schemes. The theoretical results discussed here can be equivalently applied to both TRX and DBS receivers.

### a. Standard Receiver System

Assuming a standard receiver at the DBS (TRX), the transmitted signal from the TRX (DBS) corresponds to:

$$s'(t) = g_x(t) \sum b'[n] \cdot g_c(t-nT_c) \cos(2\pi f t)$$

where $N$ denotes the number of bits per ID code (that represents the maximum capacity of the WLPS), $b'[n]$ denotes the $n^{th}$ bit of user $k$’s ID, $T_c = \tau / N$ represents TRX ID and bit duration, respectively; and, $g_x(t)$, $g_c(t)$ are rectangular pulses with the duration of $\tau_{\text{TRX}}$ ($\tau_{\text{DBS}}$) and $T_b$, respectively. Assuming a frequency selective channel, the received signal $r(t)$ at the DBS is a mixture of signals from different users and different paths, which is given by:

$$r(t) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} \sum_{n=1}^{N} \alpha_k^l b'[n] \cdot g_x(t-\tau_k^l-nT_c) \cdot g_c(t-\tau_k^l) \cdot \cos(2\pi f t + \phi_k^l) + n(t),$$

where $K$ denotes the total number of users, $L_k$ is the number of paths for user $k$, $\alpha_k^l$, $\tau_k^l$, $\phi_k^l$ denote the fading factor, time delay, and random phase for $k^{th}$ user’s $l^{th}$ path, respectively. After the demodulator, the $n^{th}$ bit output for $j^{th}$ user’s $l^{th}$ path corresponds to:
\[
y'_j[n] = \int_{t_{n-1}}^{t_n} r(t) \cos(2\pi f_j t + \phi_j) \, dt
\]

Equation (7) can be decomposed into four components correspond to:

\[
y'_j[n] = S'_j[n] + jX[I'_j[n] + jXSI'_j[n] + N'_j[n]]
\]

Assuming all users have the same number of paths and bit energy is uniformly distributed in paths, e.g., \( E'(\alpha'_j) = 1/L \), the powers of the four components of (8) correspond to:

\[
P_i = \frac{1}{L}, \quad P_{s_i} = \frac{d_i \cdot (K-1)}{2}, \quad P_{s_{wi}} = \frac{d_i \cdot (1-1/L)}{2}, \quad P_s = \frac{1}{2\tau_{st}}
\]

where \( \tau_{st} \) is the average SNR, \( d_i \) denotes the duty cycle, which is \( \tau_{as} / \tau_{rt} \) (\( \tau_{as} / \tau_{rt} \)). Finally, the SINR in \( j^{th} \) user’s \( l^{th} \) path is:

\[
r_j = \frac{1}{d_i (K-1)/2 + d_i (1-1/L) + 1/2\tau_{st}}
\]

b. Standard Receiver with Antenna Arrays and Conventional Beamforming (BF)

BF techniques reduce the signal from other users and other paths as long as they are in different direction from the desired user and path. In this case, with the same transmitted signal as Equation (1), the received signal at the DBS with antenna arrays shown in Figure 9 corresponds to:

\[
\tilde{r}(t) = \sum_{k=0}^{M} \sum_{l=0}^{L} \alpha_k^l \, \tilde{V}(\theta_k^l) \cdot b^l[n] \cdot g_k(t - \tau_k^l - nT_i) \cdot g_s(t - \tau_s^l) \cdot \cos(2\pi f_j t + \phi_j) \cdot \tilde{n}(t)
\]

where \( \tilde{V}(\theta_k^l) \) denotes the array response vector and corresponds to:

\[
\tilde{V}(\theta_k^l) = \begin{bmatrix} 1 & \exp\left(-\frac{2\pi d \cos(\theta_k^l)}{\lambda}\right) & \ldots & \exp\left(-\frac{2(M-1)\pi d \cos(\theta_k^l)}{\lambda}\right) \end{bmatrix}
\]

Here, \( d \) denotes the spacing between antenna elements, \( M \) is the total number of antennas, \( \lambda \) denotes the carrier wavelength, \( \theta_k^l \) is the direction of \( k^{th} \) user’s \( l^{th} \) path. After BF, the \( n^{th} \) bit output for \( j^{th} \) user’s \( l^{th} \) path corresponds to:

\[
y'_j[n] = W(\theta_k^l) \cdot \int_{t_{n-1}}^{t_n} \tilde{r}(t) \cdot \cos(2\pi f_j t + \phi_j) \, dt
\]

where \( W(\theta_k^l) = V^\dagger(\theta_k^l) \), and \( H \) denotes Hermitian transpose. In this case, the powers of the four components of (8) correspond to:

\[
P_i = \frac{M^2}{L}, \quad P_{s_i} = \frac{B \cdot d_i \cdot (K-1)}{2}, \quad P_{s_{wi}} = \frac{B \cdot d_i \cdot (1-1/L)}{2}, \quad P_s = \frac{M}{2\tau_{st}}
\]

where

\[
B = \frac{\sum_{m=0}^{M} (m+1)J_m(2\pi d_m/\lambda) + \sum_{m=0}^{M} (2M-m-1)J_m(2\pi d_m/\lambda) + \sum_{m=0}^{M} (2M-m-1)J_m(2\pi d_m/\lambda)}{\lambda}
\]

and \( J_0 \) represents the zeroth order Bessel function of the first kind. Therefore, the SINR in \( j^{th} \) user’s \( l^{th} \) path is:

\[
r_j = \frac{M^2}{B \cdot d_i \cdot (K-1)/2 + B \cdot d_i \cdot (1-1/L) + M / 2\tau_{st}}
\]

c. The DS-CDMA System

The transmitted DS-CDMA signal by the \( k^{th} \) TRX (DBS) corresponds to:

\[
S_k^l(t) = g_s(t) \sum_{n=0}^{M} b^l[n] \cdot g_k(t - nT_i) \cdot d^l(t - nT_c) \cdot \cos(2\pi f_j t)
\]

where \( d^l(t) = \sum_{n=0}^{N-1} C_i^l \, g_c(t - iT_c) \), \( C_i^l \in \{-1,1\} \), denotes the spreading code, and \( G \) is the processing gain (code length), \( T_c = \tau / N \cdot G \) represents TRX chip duration and, \( g_c(t) \) is a rectangular pulse with the duration of \( T_c \).
The received signal corresponds to:
\[
r(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{n=0}^{N} C_{k}^{l} \cdot b_{i}[n] \cdot g_{c}(t - \tau_{k}^{l} - nT) \cdot g_{l}(t - \tau_{k}^{l} - nT) \cdot \cos(2\pi f_{c} t + \phi_{k}^{l}) + n(t)
\]  
(18)

After dispreading, the \textit{n}th bit output for \textit{j}th user’s \textit{l}th path corresponds to:
\[
y_{i}^{j}[n] = \int_{t_{i}^{j} + 1}^{t_{i}^{j} + 1 + T_{c}} r(t) \cos(2\pi f_{c} t + \phi_{k}^{l}) a^{j}(t - \tau_{i}^{j} - nT) dt
\]
(19)

Again the received signal is a combination of four parts in Equation (3) with powers correspond to
\[
P_{i} = \frac{G}{L}, \quad P_{in} = \frac{B \cdot D \cdot (K-1)}{2}, \quad P_{o} = \frac{B \cdot D \cdot (1-1/L)}{2}, \quad P_{o} = \frac{G}{2r_{i}}
\]
(20)

where \(D = d_{i} \cdot (N^{2} - 3N + 3) \cdot d_{i}^{2} / 2 \). Thus, the SINR in \textit{j}th user’s \textit{q}th path is:
\[
r_{s} = \frac{G}{D \cdot (K-1)/2 + D \cdot (1-1/L) + G/2r_{i}} \cdot \frac{1}{L}
\]
(21)

d. DS-CDMA Merger with SDMA

With the same transmitted signal as in (17), the received signal at the DBS (TRX) for the antenna array (see Figure 9), which is a mixture of signals from different users and different paths, is given as:
\[
\tilde{r}(t) = \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{n=0}^{N} C_{k}^{l} \cdot \tilde{V}(\theta_{k}^{l}) \cdot b_{i}[n] \cdot g_{c}(t - \tau_{k}^{l} - nT) \cdot g_{l}(t - \tau_{k}^{l} - nT) \cdot \cos(2\pi f_{c} t + \phi_{k}^{l}) + n(t)
\]
(22)

The \textit{i}th bit output of BF for \textit{j}th user’s \textit{l}th path is given as:
\[
z_{i}^{j}[n] = \tilde{W}^{j}(\theta_{i}^{l}) \int_{t_{i}^{j} + 1}^{t_{i}^{j} + 1 + T_{c}} \tilde{r}(t) \cos(2\pi f_{c} t + \phi_{k}^{l}) a^{j}(t - \tau_{i}^{j} - nT) dt
\]
(23)

The powers of the four components in Equation (8) correspond to
\[
P_{i} = M \cdot G / L, \quad P_{in} = \frac{B \cdot D \cdot (1-1/L)}{2}, \quad P_{o} = \frac{B \cdot D \cdot (K-1)}{2}, \quad P_{o} = \frac{M \cdot G}{2r_{i}}
\]
(24)

Therefore, the SINR in \textit{j}th user’s \textit{q}th path correspond to
\[
r_{s} = \frac{M \cdot G}{D \cdot (K-1)/2 + D \cdot (1-1/L) + MG/2r_{i}} \cdot \frac{1}{L}
\]
(25)

e. Path Diversity Combining

Finally, for all of the receivers discussed in parts a – d, we apply Maximal Ratio Combining (MRC) across the path diversity components.
Therefore, the final instantaneous SNR expression can be written as:

\[ r_e = \alpha_e \cdot (\alpha'_e + \alpha''_e + \ldots + \alpha''''_e) \]  

(27)

In (27) the parameter \( r_e \) is as defined in (10), (16), (21), and (25), corresponding to the receivers introduced in subsections a – d respectively. The Bit-Error-Rate for all of the receivers discussed in parts a – d corresponds to:

\[ P_e = \int Q(2\tau_e) f(\tau_e) d\tau_e = 0.5 \left( 1 - \frac{\tau_e}{L + \tau_e} \sum_{i=1}^{2L} \frac{1}{2^i (1 + \tau_e / L)} \right) \]  

(28)

For frequency-selective channel, \( L \) is greater than one. For flat-fading channel, \( L \) equals to one. If all bits are detected correctly, the ID of the desired user is detected correctly. Therefore, the probability of detection is given as:

\[ P_d = (1 - P_e)^k \]  

(29)

6. SIMULATIONS

In this section, we evaluate the POD performance and capacity (in terms of number of users) of WLPS system under multi-TRX, multi-path environment, via simulations and we compare the results with the theoretical result of (29). For simulation purposes we assume:

1) The ID code has 6 bits (\( N = 6 \));
2) The DS-CDMA code has 64 chips (\( G = 64 \));
3) Channel delay spread for a typical street area is 27nsec [18];
4) Carrier frequency = 3GHz,
5) \( \tau_{\text{rx}} = 1.2 \mu \text{sec} \), and \( \tau_{\text{trx}} = 24 \mu \text{sec} \);
6) Maximum coverage range = 1000m;
7) The antenna array is linear with 4 elements, and \( d = 0.05 \text{m} \) element spacing (HPBW = 27\(^{\circ}\));
8) Four multipaths lead to 4 fold path diversity;
9) The TRX distance is uniformly distributed in [0 1]km;
10) The TRX angle is uniformly distributed in [0 \( \pi \)];
11) TRX TOA is uniformly distributed in [0 \( T_{\text{max}} \)], \( T_{\text{max}} = 3.3 \mu \text{sec} \);
12) Uniform multi-path intensity profile, i.e., bit energy is distributed in each path identically;
13) Binary Phase Shift Keying (BPSK) modulation; and
14) Perfect power control and TOA estimation.

Based on the assumed setup, the minimum IRT, \( IRT_{\text{min}} \) is 9.83\( \mu \text{sec} \) [c.f., Eq. (1)]. We select a larger value \( IRT = 24 \mu \text{sec} \) in order to reduce the IBI effects. With the assumed \( \tau_{\text{trx}} \) and \( \tau_{\text{trx}} \), the required bandwidth of a DS-CDMA (standard) transmitter is 320MHz (5MHz) for TRX, 16MHz (250kHz) for DBS, which is much smaller than the TRX bandwidth. Hence, the WLPS bandwidth is mainly determined by the TRX transmission bandwidth, as expected. In addition, using these parameters, the duty cycle for DBS and TRX receivers correspond to \( d_{\text{trx}} \equiv 0.1 \) and \( d_{\text{trx}} \equiv 0.001 \). Figure 4 depicts \( p_{\text{trx}} \) as a function of the number of transmitters (TRX or DBS) for various values of the duty cycle that is a function of \( IRT \).

As we mentioned earlier, the IBI at the TRX receiver can be considerably reduced by selecting the \( IRT \) large enough; however, this selection will not affect IIX at the DBS receiver. Hence, a TRX receiver can just be implemented by a simple transceiver (or DS-CDMA) systems without employment of BF, while a DBS receiver needs a combination of DS-CDMA and BF. A small \( d_{\text{trx}} \equiv 0.001 \) at the TRX receiver leads to a small \( p_{\text{trx}} \), which leads to small IBI and high probability of detection. In contrast, a large \( d_{\text{trx}} \equiv 0.1 \) at the DBS receiver leads to a high \( p_{\text{trx}} \) that results in high IIX. Both BF and CDMA techniques help to reduce the IIX effects at DBS.

The probability of detection \( p_d \) of the DBS receiver is depicted in Figure 10(a). This figure compares \( p_d \) vs. the number of TRX for a standard transceiver and a DS-CDMA transceiver, with or without antenna arrays and BF. It shows that in general the \( p_d \) decreases as the number of TRX increases, which is a direct result of IIX. As to the impact of BF, the use of BF does not affect much the capacity (in terms of number of TRX) for a standard receiver (the lower two curves), but
it considerably enhances the capacity of the DS-CDMA system (the upper two curves). Merging DS-CDMA with BF is thus highly promising for enhancing the $p_d$ performance of WLPS systems. In Figure 10(a) the solid lines represent the theoretical results having a good match with the simulations.

The $p_d$ results for TRX receiver using standard receiver is shown in Figure 10(b). Although simple, a standard TRX receiver typically achieves good $p_d$ performance. Further improvement is possible by selecting a larger $IRT$ value, or a smaller $DBS$ value. For example, occupying the same bandwidth as DS-CDMA, a standard receiver should choose $\tau_{DBS}$ ($\tau_{TRX}$) to be $1/64^{th}$ of that of a DS-CDMA system. (In this case, the same number of path diversity as the DS-CDMA receiver (i.e., 4 fold diversity) is achievable.) This corresponds to $d_{TRX} \equiv 0.000015$ ($d_{DBS} \equiv 0.0015$), which leads to a very small $p_{ovl}$ at the TRX (DBS) receiver and very high $p_d$. This fact has been shown in Figure 10(a), (b) for DBS and TRX, respectively.

Figure 10(b) shows that, with similar bandwidths, a DS-CDMA system with duty cycle 64 times higher than a standard receiver leads to (almost) the same performance curve. The two top curves (theoretical results) in Figure 10(a) for standard and DS-CDMA receivers with BF are sketched in Figure 10(c). It is seen that standard receiver outperforms DS-CDMA receiver for DS-CDMA with high duty cycles ($d_c \cong 0.1$ leads to a high $p_{ovl}$ as shown in Figure 4). In this case, the standard receiver leads to a capacity more than two times of DS-CDMA receiver at the $p_d = 0.99$. For the TRX receiver, $p_{ovl}$ statistics with $d_c \equiv 0.000015$ is depicted in Figure 4. This low probability leads to the high TRX standard receiver POD performance shown in Figure 10(b). However, it is seen that DS-CDMA receiver outperforms standard receiver for DS-CDMA with low duty cycles ($d_c \cong 0.001$ leads to a low $p_{ovl}$ as shown in Figure 4). For airport security where the data rate is not critical, the $IRT$ can be chosen larger than 24msec for even better TRX standard receiver POD performance.

Figure 10 Simulation results for (a) DBS, and (b) TRX receivers. (c) and (d) are the two top curves in (a) and (b), respectively.
7. CONCLUSIONS

This paper presents the application of a novel WLPS for indoor security. WLPS two main components are DBS and TRX. The security personnel are equipped with both the DBS and the TRX while the passengers and employees are equipped with just a TRX. The TRX can be made from standard receiver and DS-CDMA transmitter with a very simple structure and minimal cost and complexity. The DBS can be made from simple transmitter (modulators) while it needs a complex receiver to ensure high probability-of-detection (POD). We studied the POD performance at the TRX and DBS. We observed a high IRT leads to a high TRX performance while the DBS performance is highly enhanced via a merger of DS-CDMA and SDMA. We studied the techniques of enhancing the coverage area beyond the LoS via multihop localization techniques. The WLPS may use SBS in order to facilitate non-LoS (e.g., multi-floor) localization. We proposed a futuristic view for the implementation of the TRX. WLPS creates a visual localization view of all personnel, passengers and staff at the airport. WLPS can be used for both airport indoor and outdoor areas. It highly enhances the safety of the airports, supports the safety of security guards, and facilitates the process of information flow (e.g., gate and flight information) to the passengers, airport employees and security guards simultaneously. The applications of WLPS are not just limited to airport security. It has broad applications in collision avoidance and road safety, law enforcement, defense, and multi-robot collaboration and coordination.

REFERENCES