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*Research Article*

# Location-Aware Cross-Layer Design Using Overlay Watermarks

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A new orthogonal frequency division multiplexing (OFDM) system embedded with overlay watermarks for location-aware cross-layer design is proposed in this paper. One major advantage of the proposed system is the multiple functionalities the overlay watermark provides, which includes a cross-layer signaling interface, a transceiver identification for position-aware routing, as well as its basic role as a training sequence for channel estimation. Wireless terminals are typically battery powered and have limited wireless communication bandwidth. Therefore, efficient collaborative signal processing algorithms that consume less energy for computation and less bandwidth for communication are needed. Transceiver aware of its location can also improve the routing efficiency by selective flooding or selective forwarding data only in the desired direction, since in most cases the location of a wireless host is unknown. In the proposed OFDM system, location information of a mobile for efficient routing can be easily derived when a unique watermark is associated with each individual transceiver. In addition, cross-layer signaling and other interlayer interactive information can be exchanged with a new data pipe created by modulating the overlay watermarks. We also study the channel estimation and watermark removal techniques at the physical layer for the proposed overlay OFDM. Our channel estimator iteratively estimates the channel impulse response and the combined signal vector from the overlay OFDM signal. Cross-layer design that leads to low-power consumption and more efficient routing is investigated.

## 1. INTRODUCTION

The growth of wireless packet data applications (e.g., wireless Web access, interactive mobile multimedia applications, and interactive gaming) drives the rapid evolution of next-generation wireless networks. One of the key challenges for next-generation broadband wireless networks is to devise end-to-end protocol solutions across wired and wireless links through cross-layer design. Traditional network protocol design is based on a layered approach in which each layer in the protocol stack is designed and operated independently with interfaces between layers that are static and independent of the individual network constraints and applications. With this approach, information regarding the changing wireless channel condition is often hidden from the higher network layers. In the meantime, the ability for mobile stations to determine their position through automatic means is recognized as an essential feature, since location information is particularly important for network optimization, including energy conservation and location-aware routing. Mobile hosts are typically battery powered and have limited wireless communication bandwidth. Therefore, the transmission power should just be at the right level and this can be achieved if the mobile is aware of its location. As a result, the unique characteristics of wireless networks such as user mobility, fast channel variation, limited link capacity, and limited battery and computational resources in mobile devices, along with the diverse quality of service (QoS) requirements for wireless applications, pose significant challenges in codesigning different layers of network protocols for high-speed mobile communications. Various positioning approaches have been proposed, of which some were even constructed and deployed on a large scale, for example, Global Positioning System (GPS) [1]. GPS is effective and accurate outdoors, but it works very poorly, if at all, indoors and in urban canyon environments [2]. As a result, reliable position location solution is needed for wireless communication devices, particularly for indoor applications. Cellular telephone networks can be used to provide location services, where the mobile receivers are located by measuring the strength of signals traveling to and from a set of fixed cellular base stations. However, owing to the narrow bandwidth and variation of signal strength, position systems based on cellular networks can only achieve very limited accuracy with locationing error often large than few hundred meters [3, 4]. Other positioning alternatives based on ultra wide band (UWB) devices and wireless local area networks (WLAN) can only provide very limited coverage [5].

In this paper, a new OFDM system with overlay watermark for location-aware cross-layer design is proposed and investigated. Orthogonal Frequency Division Multiplexing (OFDM) has been widely accepted as the major transmission technology for next generation wireless communication systems due to its high spectral efficiency, robustness to multipath distortion and simple frequency domain equalization [6]. Accurate channel estimation is indispensable for an OFDM system to achieve coherent demodulation and consequently higher data rate. For OFDM systems operating in a mobile wireless environment, estimation of the time-frequency varying channel requires closely-spaced pilot subcarriers in both the time and frequency domains, resulting in a significant loss in bandwidth efficiency. As an alternative to improve the bandwidth efficiency, pilot symbols can be superimposed upon the data symbols to enable channel estimation without sacrificing the data rate. This idea was first proposed for analog communication in [7] and was later extended to digital single carrier systems in [8]. Recently, the idea of superimposed training has received renewed attention in OFDM systems [9–11]. However, superimposed pilots in the frequency domain will deteriorate the peak to average power ratio (PAPR) problem of the OFDM signals. The high PAPR associated with a frequency-domain overlay pilot signal and the need of cross-layer interface inspire us to consider a time-domain overlay sequence with constant amplitude as a cross-layer signaling and transmitter identification, which can be used to determine the location of the transmitter.

In the proposed overlay OFDM system, time-domain orthogonal Kasami sequences [12–14] are used as overlay watermarks for cross-layer signaling and channel estimation training sequence. We propose to modulate the watermark so that a new, low-rate, parallel data pipe is created for the purpose of transporting cross-layer signaling and control information without interruptions to the physical link. Note that there is no redundancy introduced since the overlay watermark will also be used as training sequence for channel estimation. Preambles or training sequences are always required either in frequency or time domain in traditional communications system for channel estimation purpose. For instance, normally more than 10 percent of total bandwidth is used as in-band pilots for channel estimation purpose in conventional OFDM system. In this paper, the in-band pilots of OFDM system is converted as an overlay watermark for channel estimation purposes. It will not introduce extra redundancy since channel estimation preambles are always needed. As an added advantage, the overlay watermark provides an independent data pipe for cross-layer signalling transmission. The use of Kasami watermarks provide the following advantages (i) The availability of a large set of orthogonal Kasami sequences ensures that a unique watermark can be assigned to each individual OFDM transceiver, which may be used for transceiver identification and position location. As a result, position-aware routing algorithms can be used to improve the network efficiency. (ii) A parallel data link can be created by modulating the watermarks for data link controlling purposes. Information related to the adaptive modulation and coding schemes employed can be transmitted over this extra data link. (iii) Simple channel estimation and watermark removal algorithm can be readily employed. The organization of the paper is as follows. The transceiver structure of the proposed OFDM is illustrated in Section 2. To eliminate the impact of the watermark on OFDM signal detection, we also propose an iterative channel estimation and data detection algorithm. Initial channel estimation is obtained from the overlay watermark with the OFDM signal acting as interference. Decision for the transmitted OFDM data is then made based on the tentative channel estimate. The accuracy of the channel estimates is then progressively improved by reestimating the channel by using a new composite channel estimation sequence consisting of the watermark and a tentative OFDM signal derived from the data detection results. Location-aware cross-layer design is investigated in Section 3 with the proposed Kasami watermarks. The design and detection of cross-layer signaling through the modulation of the overlay watermarks are analyzed. A position location technique based on the overlay watermark is investigated. Numerical results are presented in the next section and the paper is summarized in Section 5.

### Notations

$()^H$ and $()^T$ represents the conjugate transpose and transpose; $N$ and $L$ indicate the number of OFDM subcarriers and length of the channel impulse response, respectively; $\mathrm{Tr}\{\}$ denotes the trace of a matrix; $\mathbf{X}$, a vector of size $N$, representing the OFDM data in the frequency domain; $\mathbf{x}$ is the corresponding time domain OFDM signal vector; $\mathbf{y}$ is the received time-domain signal vector; $\mathbf{h}$ and $\mathbf{H}$ are channel vectors in the time and frequency domains with size of $L$ and $N$, respectively; $\mathbf{n}$ is an additive white Gaussian noise (AWGN) vector. Unless otherwise stated, all vectors in the paper are column vectors.

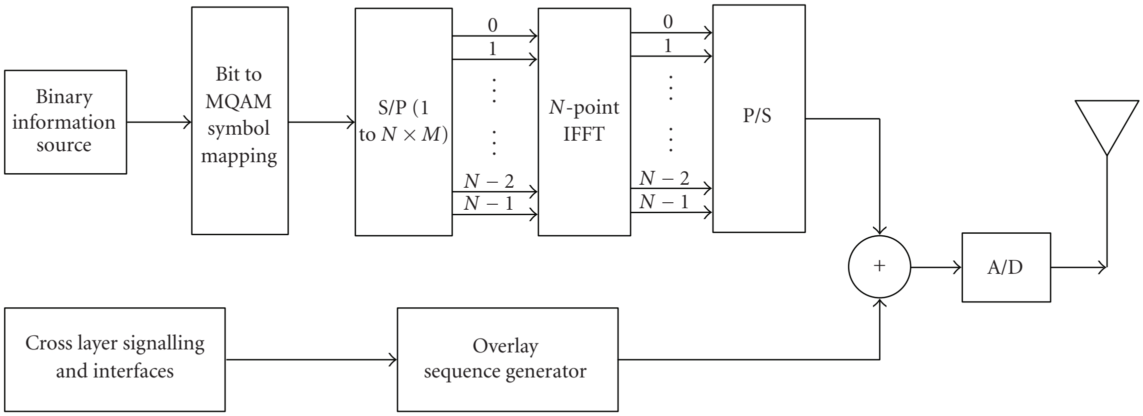
## 2. TRANSCEIVER STRUCTURE FOR OVERLAY OFDM SYSTEMS

### 2.1. Transmitter for overlay OFDM system

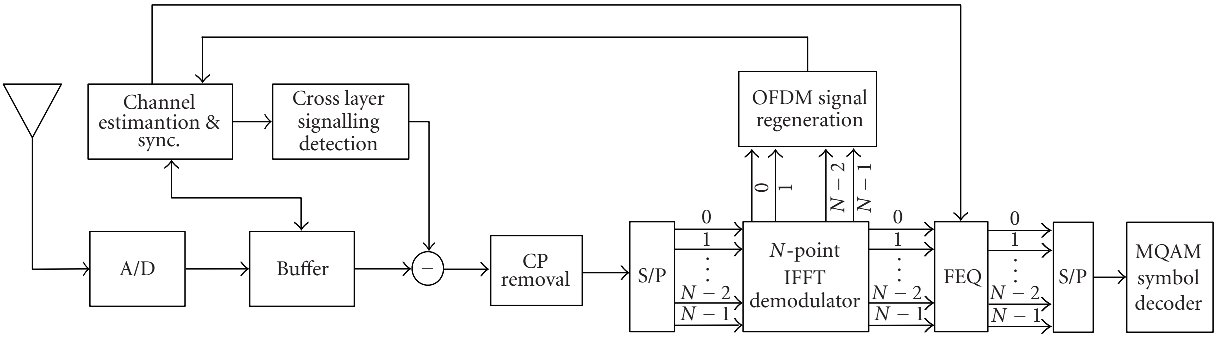
The transceiver block diagram of the proposed overlay OFDM system is depicted in Figure 1. Each time-domain OFDM symbol $\mathbf{x}$ in the transmitter side of proposed overlay system is represented by an $N$-point complex sequence through an inverse discrete Fourier transformation (IDFT) of the subchannels data $\mathbf{X}$ as follows:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi(nk/N)}, \quad n = 0, 1, 2, \dots, N-1. \tag{1}$$

The signal in (1) consists of $N$ complex sinusoids modulated by the complex data symbols $X(1), X(2), \dots, X(N-1)$.



(a) Transmitter



(b) Receiver

Figure 1: The transceiver block diagram for the OFDM system with overlay watermark.

The watermark signal is superimposed on the OFDM symbol before the cyclic prefix is added. Since the addition and elimination of the cyclic prefix has no impact on the statistics of the signal as well as the subsequent analysis, these steps are omitted from the discussion throughout the paper. The superimposed watermark vector $\mathbf{p}$ is added to the OFDM signal according to

$$\mathbf{s} = \mathbf{x} + \mathbf{p}, \tag{2}$$

where $\mathbf{p} = [p(0), p(1), \ldots, p(N-1)]^T = \alpha\mathbf{p}_{\text{kasami}}$, $\alpha$ is a gain control parameter that determines the power of the superimposed watermark, and $\mathbf{p}_{\text{kasami}}$ represents a complex vector whose real and imaginary parts are two orthogonal Kasami sequences. The duration of the Kasami sequences and hence the watermark is identical to one OFDM symbol.

### 2.2. Receiver for overlay OFDM system

A slow varying multipath channel model is adopted in this paper. The received signal can be expressed as

$$y(n) = \sum_{l=0}^{L-1} h_l s(n-l) + n(n). \tag{3}$$

After the removal of cyclic prefix, the received signal vector $\mathbf{y} = [y(0), y(1), \ldots, y(N-1)]^T$ can be written as

$$\mathbf{y} = \mathbf{X}_M\mathbf{h} + \mathbf{P}\mathbf{h} + \mathbf{n}, \tag{4}$$

where $\mathbf{h} = [h(0), h(1), \ldots, h(L)]^T$ is the channel vector, $\mathbf{n} = [n(0), n(1), \ldots, n(N-1)]^T$ is an AWGN vector with variance $\sigma_n^2$,

$$\mathbf{X}_M = \begin{bmatrix} x(0) & x(N-1) & \cdots & x(N-L+1) \\ x(1) & x(0) & \cdots & x(N-L+2) \\ \vdots & \vdots & & \vdots \\ x(N-1) & x(N-2) & \cdots & x(N-L) \end{bmatrix} \tag{5}$$

is the data matrix derived from $\mathbf{x}$, and

$$\mathbf{P} = \begin{bmatrix} p(0) & p(N-1) & \cdots & p(N-L+1) \\ p(1) & p(0) & \cdots & p(N-L+2) \\ \vdots & \vdots & & \vdots \\ p(N-1) & p(N-2) & \cdots & p(N-L) \end{bmatrix} \tag{6}$$

is the watermark matrix obtained from $\mathbf{p}$. Here we assume the watermark vector $\mathbf{p}$ (and hence $\mathbf{P}$) is known to the receiver. Note that the polarity of the imaginary part of the watermark has to be determined when the watermark is modulated for data transmission; see Section 3. Given the transmitted signal vector $\mathbf{s}$ and the channel $\mathbf{h}$, the conditional likelihood function of the received signal can be expressed as

$$\Lambda(\mathbf{y} \mid \mathbf{x}, \mathbf{h}) = \frac{1}{\left(\pi\sigma_{\mathbf{n}}^2\right)^N} \exp\left\{ -\frac{1}{\sigma_{\mathbf{n}}^2}\left[\mathbf{y}-\mathbf{X}_M\mathbf{h}-\mathbf{P}\mathbf{h}\right]^{\mathbf{H}}\left[\mathbf{y}-\mathbf{X}_M\mathbf{h}-\mathbf{P}\mathbf{h}\right]\right\}. \tag{7}$$

The goal of the receiver is to find the data **x** and the channel **h** that maximizes this conditional likelihood function. With a brute force implementation, the complexity associated with this joint optimization is huge. Here we propose a much simpler iterative algorithm, as shown in Figure 1(b). Below is a description of this iterative procedure.

First, consider (4). This equation can be rewritten as

$$\mathbf{y} = \mathbf{A}\mathbf{h} + \mathbf{n}, \tag{8}$$

where the $N \times L$ matrix **A** is derived from the composite signal **s** in (2) as follows:

$$\mathbf{A} = \begin{bmatrix} s(0) & s(N-1) & \cdots & s(N-L+1) \\ s(1) & s(0) & \cdots & s(N-L+2) \\ \vdots & \vdots & & \vdots \\ s(N-1) & s(N-2) & \cdots & s(N-L) \end{bmatrix}. \tag{9}$$

When the OFDM signal **x** is known to the receiver, then the above matrix is also known and hence can be treated as a training sequence for channel estimation purpose. In this case, the conditional likelihood function of the received signal becomes

$$\Lambda(\mathbf{y} \mid \mathbf{h}) = \frac{1}{\left(\pi\sigma_{\mathbf{n}}^2\right)^N} \exp\left\{-\frac{1}{\sigma_{\mathbf{n}}^2}[\mathbf{y}-\mathbf{A}\mathbf{h}]^{\mathbf{H}}[\mathbf{y}-\mathbf{A}\mathbf{h}]\right\}. \tag{10}$$

The maximum likelihood (ML) channel estimate, $\widetilde{\mathbf{h}}$, is the value of **h** that maximizes the argument of the above exponential function, that is,

$$\widetilde{\mathbf{h}} = \min_{\mathbf{h}} \left\{[\mathbf{y}-\mathbf{A}\mathbf{h}]^{\mathbf{H}}[\mathbf{y}-\mathbf{A}\mathbf{h}]\right\}. \tag{11}$$

Since the right-hand side of the above equation, denoted by $\Lambda_L(\mathbf{y} \mid \mathbf{h}) = [\mathbf{y}-\mathbf{A}\mathbf{h}]^{\mathbf{H}}[\mathbf{y}-\mathbf{A}\mathbf{h}]$, is a convex function over **h**, the ML channel estimate satisfies

$$\left.\frac{\partial\Lambda_L(\mathbf{y} \mid \mathbf{h})}{\partial\mathbf{h}}\right|_{\mathbf{h}=\widetilde{\mathbf{h}}} = 0. \tag{12}$$

This implies that the ML channel estimate $\widetilde{\mathbf{h}}$ is, in principle, given by

$$\widetilde{\mathbf{h}} = \left(\mathbf{A}^H\mathbf{A}\right)^{-1}\mathbf{A}^H\mathbf{y}. \tag{13}$$

Unfortunately, the matrix **A** in (9) is not known initially to the receiver, since each element of the matrix is the superimposition of the unknown OFDM signal sequence and the watermark. To circumvent this problem, the receiver resorts to obtaining an approximation of **A** based on the tentative data estimates derived from the rather crude initial channel estimates provided by the superimposed watermark. The iterative receiver then progressively provides more reliable information on matrix **A**. As a result, the accuracy of the channel and data estimates will also be improved accordingly. We list below the procedure of this iterative channel estimator.

Initial channel estimates will be derived solely from the embedded watermark signal. That is, the OFDM signal will be treated as noise. This is because OFDM signal at any time instant is the summation of $N$ independent subcarriers. When the number of the subcarriers is large enough, the OFDM signal can be approximated as Gaussian distributed random variable. Due to the Gaussian nature of the OFDM signal, the combined effect of the channel AWGN and the OFDM signal, $\mathbf{w} = \mathbf{X}_M\mathbf{h} + \mathbf{n}$, will still be Gaussian. The received signal is now expressed as

$$\mathbf{y} = \mathbf{P}\mathbf{h} + \mathbf{w}. \tag{14}$$

It is straightforward to verify that the variance of the effective noise **w** is

$$\sigma_w^2 = \sigma_n^2 + \sigma_x^2, \tag{15}$$

where $\sigma_x^2$ is the variance of the OFDM signal. Similar to (13), the initial channel estimate is given by

$$\widetilde{\mathbf{h}} = \left(\mathbf{P}^H\mathbf{P}\right)^{-1}\mathbf{P}^H\mathbf{y}. \tag{16}$$

One of the key ideas of the proposed iterative channel estimator is that, instead of using only the embedded watermark as the training sequence, the tentative estimated OFDM sequence in the time domain will also be used for that purpose. With this approach, the performance of the estimator is expected to be significantly improved, since now, the power of the training sequence is increased. To improve the channel estimate, the iterative receiver subtracts $\mathbf{P}\widetilde{\mathbf{h}}$ from the received vector **y** to obtain the new observation $\mathbf{y}' = \mathbf{y} - \mathbf{P}\widetilde{\mathbf{h}}$. After converting $\mathbf{y}'$ to $\mathbf{Y}' = \mathrm{DFT}(\mathbf{y}')$ via DFT, individual subchannels are gain/phase compensated by dividing the components of $\mathbf{Y}'$ by the corresponding components in frequency domain channel estimates $\widetilde{\mathbf{H}}$. Decisions on the data in individual channels are then made. These data estimates $\widetilde{\mathbf{X}}$ are then used to generate the estimated OFDM signal in the time domain $\widetilde{\mathbf{x}}$ using IDFT. At this point, the channel estimator employs $\widetilde{\mathbf{s}} = \widetilde{\mathbf{x}} + \mathbf{p}$ as the effective training sequence to update the channel estimates. A similar matrix $\widetilde{\mathbf{A}}$ will be constructed using $\widetilde{\mathbf{s}}$ to get the improved channel estimation according to $\widetilde{\mathbf{h}} = (\widetilde{\mathbf{A}}^H\widetilde{\mathbf{A}})^{-1}\widetilde{\mathbf{A}}^H\mathbf{y}$. This process will be iterated for the improved performance of the receiver.

## 3. CROSS-LAYER DESIGN WITH THE OVERLAY WATERMARKS

In this section, cross-layer signaling and interface design using the embedded watermarks are investigated. In addition to the basic function of the overlay watermark as a training sequence for channel estimation, channel quality information, adaptive rate control information, and network timing information can be transmitted by modulating the watermarks. This "free" physical signaling pipe, which is in parallel to the OFDM signal, provides interfaces between different network layers directly. Interruption to the physical layers can be reduced since the cross-layer interactive information can be transmitted with the new link. Note here that only the bottom three layers of the OSI model under investigation here are depicted. The physical layer defines all the electrical and physical specifications for the communications devices, and is responsible for OFDM data transmission. The data link layer responds to service requests from the network layer and issues service requests to the physical layer. The network layer performs network routing, flow control, segmentation/de-segmentation, and error control functions.

### 3.1. *Cross-layer signaling detection*

We propose in this subsection a technique for transmitting medium access layer (MAC), layer controlling information as well as other protocol information via the superimposed watermark. Specifically, we propose to modulate the imaginary part of watermark with the incoming control data. Assuming that antipodal signalling is employed in this low data-rate digital pipe, then the received time-domain signal in (4) becomes

$$\mathbf{y} = \mathbf{X}_M\mathbf{h} + \mathbf{P}_r\mathbf{h} + jD\mathbf{P}_i\mathbf{h} + \mathbf{n}, \tag{17}$$

where $D$ is the data bit ($-1$ or $+1$) containing cross-layer signaling, and $\mathbf{P}_r$ and $\mathbf{P}_i$ represents the real and imaginary parts of the matrix $\mathbf{P}$ in (6). Assuming perfect timing and frequency synchronization are achieved, a simple demodulator for the control data bit $D$ is

$$\widetilde{D} = \operatorname{sign}\left(\operatorname{Re}\langle \mathbf{y}\cdot \mathbf{P}_i\widetilde{\mathbf{h}}\rangle\right), \tag{18}$$

where $\mathbf{P}_i\widetilde{\mathbf{h}}$ is the locally generated watermark, $\operatorname{sign}(\cdot)$ is the sign operator, $\operatorname{Re}(\cdot)$ is the real operator, and $\langle\cdot\rangle$ denotes inner product. The average signal-to-interference and noise ratio (SINR) in the above decision variable can be shown equal to

$$\text{SINR} = 10\log_{10}\left(\frac{N\alpha^2}{\sigma_x^2 + \sigma_n^2 + \alpha^2\Delta\widetilde{h}_{\text{MSE}}}\right), \tag{19}$$

where $\Delta\widetilde{h}_{\text{MSE}} = \sum_{l=0}^{L-1}|\widetilde{h}_l - h_l|^2$ is the channel estimation error. Here we assume $\sum_{l=0}^{L-1}|h_l|^2 = 1$. The SINR in (19) provides a rough idea on the performance of the new data pipe by modulating the watermarks. Specifically, for a given channel response $\mathbf{h}$, the bit error rate (BER) is related to SINR according to

$$P_b = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\text{SINR}}\right), \tag{20}$$

where $\operatorname{erfc}(x) = (2/\sqrt{\pi})\int_x^\infty e^{-t^2}dt$.

### 3.2. *Position location for mobile receivers*

Due to the mobility of the wireless transceivers, the ability for mobile station to determine their position through automatic means is recognized as an essential feature, since location information is particularly important for network optimization, including energy conservation and location-aware routing [15]. Mobile hosts are typically battery powered and have limited wireless communication bandwidth. Therefore, the transmission power should just be at the right level and this can be achieved if the mobile is aware of its location. By assigning different orthogonal Kasami sequences to different transmitters, the source of a received signal can be easily identified. Location awareness can also improve the routing efficiency by selectively forwarding data in the desired direction [16, 17].

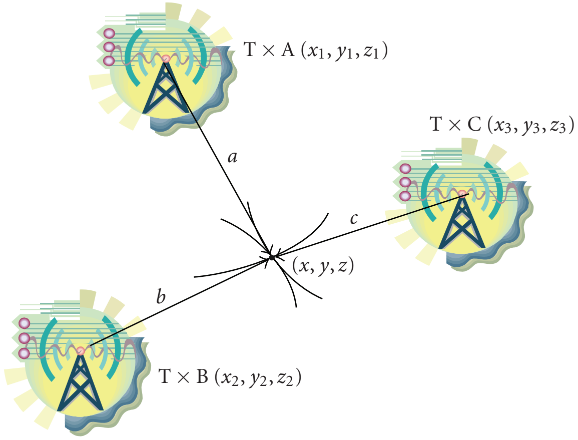


Figure 2: Position location using three transmitters

There are several different approaches to determine the location of receiving devices in a wireless network, ranging from direction-of-arrival detection to determination of received signal strength. The technique considered herein is based on triangulation. This method derives its name from the availability of at least three distance measurements between known points. When the total number of known transmitters is less than three, position location can be achieved by direction-based techniques, aided by the strength of the received signal. Since direction-based techniques require the availability of an antenna array, they involve more complicated signal processing and the accuracy of the position information is also lower.

If one can measure the precise time a signal is transmitted and the precise time the signal arrives at a receiver, the distance between the transmitter and receiver can then be determined. The extra signaling link obtained via modulating the embedded watermarks is an excellent candidate for the distribution of this network timing information. Consider the three base station (backbone node) transmitters and the positioning receiver shown in Figure 2. The coordinates of the three transmitters are $(x_1, y_1, z_1)$, $(x_2, y_2, z_2)$, and $(x_3, y_3, z_3)$, respectively. For base station transmitters, these coordinates are known a priori to the positioning receiver. Denoting the propagation time from the $i$th transmitter to the receiver as $t_i$, then in the absence of any measurement error, the co-ordinate of the receiver, $(x, y, z)$, is the solution to the following equations: [18–20]

$$\begin{aligned} t_1 c &= \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2},\\ t_2 c &= \sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2},\\ t_3 c &= \sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2}, \end{aligned} \tag{21}$$

where $c$ is the speed of light.

The first step in solving the above equations is to identify the operating transmitters. To identify the existence of the $l$th transmitter, a cross-correlation between the received signal from the $l$th transmitter, $y_l(n)$, and the locally generated watermark, $p_{r,l}(n)$, has to be performed. Mathematically, this correlation is

$$\begin{aligned} &R_{y_l p_{r,l}}(m)\\ &\quad= \sum_{n=0}^{N-1} y_l(n) p_{r,l}(n-m)\\ &\quad= \sum_{n=0}^{N-1} \left\{\left[x_l(n)+p_l(n)\right] \otimes h_l + n_l(n)\right\} \cdot p_{r,l}(n-m)\\ &\quad= \alpha R_{p_{r,l}p_{r,l}} \otimes h_l + \left\{\sum_{n=0}^{N-1}\left[x_l(n)+jp_{i,l}(n)\right]p_{r,l}(n-m)\right\}\\ &\qquad\quad \otimes h_l + \sum_{n=0}^{N-1} n_l(n)\, p_{r,l}(n-m), \end{aligned} \tag{22}$$

where $N$ is the length of the transmitter identification watermark. The first term on the last line of (22), that is, the autocorrelation function $R_{p_{r,l}p_{r,l}}$, exists only when the watermark signal $\alpha p_{r,l}(n)$ is found in the received signal. The existence of the $l$th transmitter can then be determined by the correlation peak in (22), because the watermark signal $\alpha p_{r,l}(n)$ is uniquely associated with the $l$th transmitter. Equation (22) also indicates that the correlation peak in the first term on the last line undergoes the same attenuation and channel distortion as the OFDM signal described by the second term. Due to the orthogonal property of the Kasami sequences, $R_{p_{r,l}p_{r,l}}$ can be approximated as a delta function. The second term in (22) is only a noise-like sequence resulting from the in-band data signal from the same transmitter. Therefore, the channel response $h_l$ from the $l$th transmitter can be approximated by $R_{y_l p_{r,l}}$, that is,

$$R_{y_l p_{r,l}} = Ah_l + \text{noise}, \tag{23}$$

where $A$ is a constant determined by $R_{p_{r,l}p_{r,l}}$ and the gain coefficient $\alpha$. The earliest correlation peak that exceeds a particular threshold is chosen to be the direct propagation path from the $l$th transmitter to the position location receiver. The threshold for each transmitting station is decided by the station's transmission power, the approximate distance between the station and the receiver (as determined by the propagation delay in the main path), as well as the maximum expected excess path loss due to building penetration [21, 22]. The arrival time of the earliest correlation peak can then be converted to a relative propagation time in terms of second. However, the strength of the first arrived signal sometimes is very weak and it is difficult to discriminate multipath echoes from interference. In such circumstances, the interference in (22) or (23) from the OFDM data signal can be cancelled to improve the precision of position location after the OFDM signal is demodulated. Another approach to reduce the interference is through time-domain averaging of the correlation functions from different OFDM symbols. In this case, the main path can always be used as a timing reference for averaging a number of adjacent transmitter identification results. Simple averaging of the transmitter identification results in the time domain would reduce the impact of the interference by $10\log_{10} V$, where $V$ is the number of averaging.

Regarding the implementation complexity, the proposed position location algorithm can be divided into two separate steps, that is, transmitter identification and position location. Computation complexity associated with the transmitter identification, which is the major part of the position location algorithm, is proportional to the total number of the transmitters used in this process. The total number of the multiplications for identification of each transmitter can be approximately estimated as $TN\Delta M$, where $T$ is the total number of the transmitters in the network and $\Delta M$ is the correlation range in (22) for transmitter identification. The position of the mobile receiver can then be determined by (21). When the number of the available transmitters is more than needed, a nonlinear optimization process can be invoked to finalize the location. The complexity associated position location and optimization process is minimal compared to the transmitter identification process. Therefore, the overall implementation complexity of the proposed algorithm is approximately proportional to the total number of the transmitter used for position location.

### 3.3. *Position aware routing algorithms*

Mobile hosts in a wireless network are dynamically located and continuously changing their locations. The mobility in wireless networks makes it difficult to predetermine "optimal" routes between mobile hosts. It therefore becomes important to design efficient and reliable routing protocols to maintain, discover, and organize the routes based on the most recent locations of the mobile hosts. Assuming that each node can obtain its position through the proposed position location technique in Section 3.2 and update the location information using the new signaling link proposed in Section 3.1, then various efficient position-based routing algorithms can then be readily applied [23]. Position-based routing algorithms eliminate some of the limitations of topology-based routing by using additional location information. The routing decision by a node is primarily based on the position of a packet's destination and the position of the node's immediate one-hop neighbors.

Before a packet can be sent, it is essential to determine the position of the destination host. Typically, a location service is required for this task. Different techniques, for example, grid and quorum-based location service, are available.

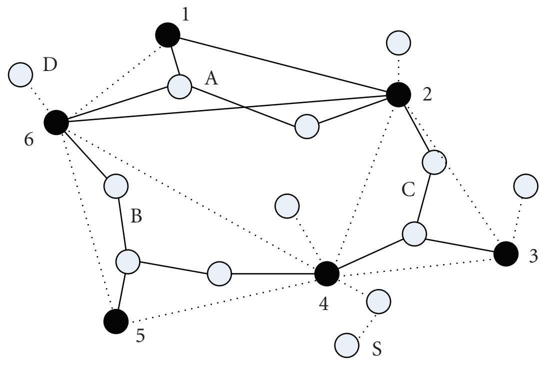


FIGURE 3: Example of position-based routing for wireless communication networks [23].

Example of a quorum-based location service is shown in Figure 3 [23]. After a mobile node determines its position using the technique in Section 3.2, it then sends position update messages to the nearest backbone node, which then chooses a quorum of backbone nodes to host the position information. Thus, node D sends its updates to node 6, which might then select quorum A with the nodes 1, 2, and 6 to host the information. When the node S wants to obtain the position information, it sends a query to its nearest backbone node, which in turn contacts the nodes of (a usually different) quorum.1. Since by definition, the intersection of two quorums is nonempty, the querying node is guaranteed to obtain at least one response with the desired position information. It is also important to time-stamp position updates, since some nodes in the queried quorum might have been in the quorum of previous updates and would then report outdated position information. If several responses are received, the one representing the most current position update is chosen. Once the position of the destination host is obtained, three forwarding strategies for position-based routing could be used: greedy forwarding, restricted directional flooding, and hierarchical approaches. The watermark signal in (17) can be used to indicate the selected forwarding route for the chosen forwarding strategy.

## 4. NUMERICAL RESULTS

Numerical simulations have been conducted to quantify the performance of the proposed overlay OFDM system and the corresponding cross-layer design. The demonstration system considered has the FFT size of 512 with cyclic prefix of length 1/8 of the symbol duration. Choice for the modulation format in the demonstration system is QPSK. Note that the transmission power of the overlay OFDM signal is normalized to that of a conventional OFDM signal. Unless otherwise stated, the parameter $\alpha$ is set to 0.5774 in all the figures. As for the channel model, we consider the channel

$$\begin{aligned}\mathbf{h} = [&0.0855, 0, 0.8334, 0, 0, -0.3419, 0, 0, 0,\\ &0.1282, 0, 0, 0, 0, 0, -0.4060]^T.\end{aligned} \tag{24}$$

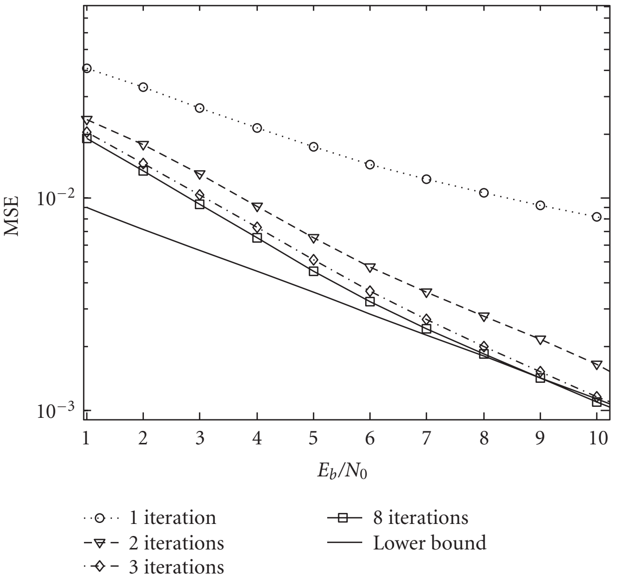


FIGURE 4: Mean square error of the iterative receiver for the overlay OFDM system with QPSK modulations.

We would like to point out that the emphasis of the investigation is to demonstrate the workability of overlay OFDM and its functionalities in future communication systems. Consequently, the "exact" channel model and parameter selections are only of secondary concern.

The MSE of the proposed iterative ML channel estimator in Section 2 was simulated. The results are plotted in Figure 4, with different number of iterations as a parameter. Here $E_b/N_0$ is defined as the signal-to-noise ratio (SNR) per bit. The results in Figure 4 indicate that for QPSK modulation, only three iterations are needed to approach the lower bound. Similar observations can be found in the symbol error rate (SER) simulation results for the QPSK in Figure 5. The results in Figure 5 show that good SER performance can be achieved with only three iterations for QPSK. More iterations may be needed for higher-modulation schemes like 16 QAM. However, we would like to point out that the number of iterations in practical systems could be significantly reduced when error correction coding is used, since the desired bit error rate after decoding could be easily achieved when the SER before decoding is less than $10^{-2}$. In addition, the complexity of the iterative channel estimation can be further reduced when the channel estimate from the previous OFDM symbol is used as the initial input for the first round of the iteration.

The signal-to-interference and noise ratio (SINR) in the signaling link created from watermark modulation is also simulated and shown in Figure 6. We assume here the multipath channel is known to the receiver. It is found that at an OFDM data signal-to-noise ratio (SNR) of 10 dB and beyond, the SINR in the signaling link is insensitive to the SNR and attain fairly high values. At the SINR values plotted in Figure 6, very robust transmission of the cross-layer signaling can be achieved even without the assistance of error

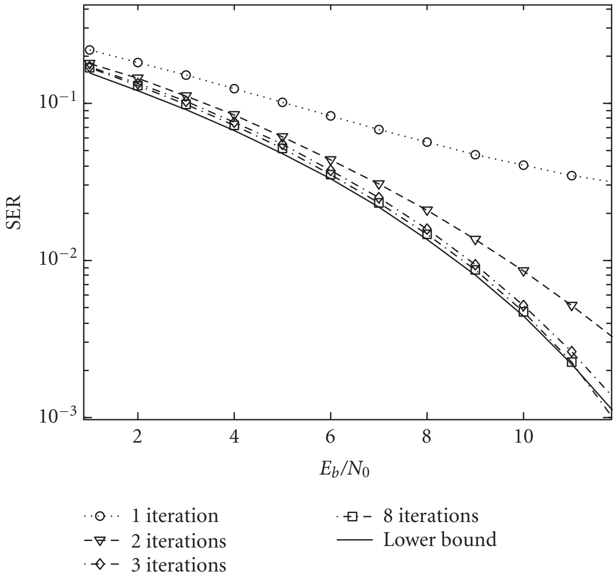


Figure 5: Symbol error rate of the overlay OFDM system with QPSK modulations.

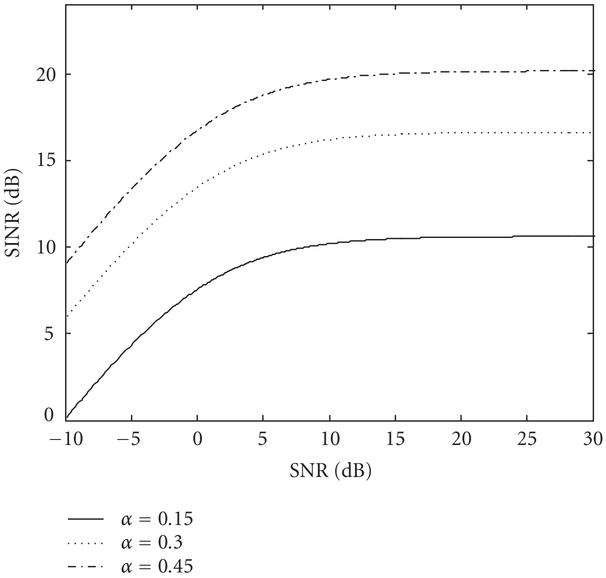


Figure 6: Signal-to-interference and noise ratio (SINR) for the cross-layer data link pipe based on watermark polarity modulation at difference signal-to-noise ratio (SNR).

correction doing. Note that a 0 dB of SNR for the OFDM data link is an extremely low SNR in typical wireless communication systems. The curves in Figure 6 also show that the SINRs are mainly decided by the amplitude of the overlay watermark and the length of the OFDM symbol. When a large $\alpha$ is used, higher-order amplitude modulation schemes could be used to increase the capacity of the signalling link. The capacity of the proposed watermark transmission technique can easily reach a few thousand bits per second for any broadband OFDM system. It is therefore more than sufficient to provide media access control information and adaptive rate control purposes. In order to design an overlay OFDM signaling link with the desired system performance, the target bit error rate $P_b$ in (20) has to be selected first. For instance, $10^{-6}$ could be used for an uncoded system. With the desired bit error rate performance, the required SINR can be determined through table lookup approach based on (20). The watermark injection level is then determined with the OFDM symbol size given in (19).

Two base stations with known locations in a 2D Cartesian coordinate are used to test the proposed position location algorithm. The coordinates for the two stations, and the mobile receiver are (0, 0), (2000, 0), and (1000, 1000) meters. The channel model in the previous MSE and SER simulations is used as the propagation models for the signals from the two stations. The location results from the simulation were shown in Figure 7, where each star represents one round of location processing. The accuracy of the position location process can be evaluated by the distance between the location results and the true location of the receiver (origin of the coordinates). As independent random noise is added for each transmitter in position location simulation, ambiguity will be inevitably introduced to the positions obtained through the proposed position location algorithm in (22). Each star in Figure 7, which represents one simulation, will be driven away randomly from its true position at the original of the coordinate. The simulation results indicate that the accuracy of the proposed location system is within a few meters. Position-based routing algorithms and transmission power control can be effectively implemented at this precision level.

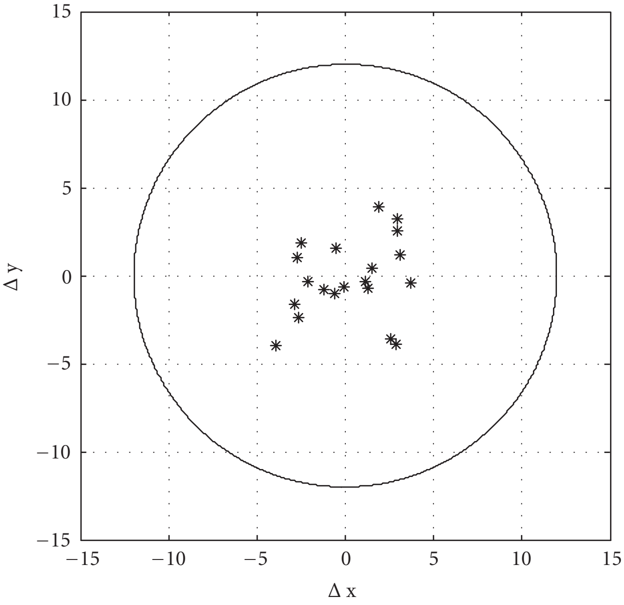


Figure 7: Numerical results for the proposed location position system based on watermark signal.

## 5. CONCLUSIONS

An OFDM system with overlay watermark for cross-layer design is proposed in this paper. The multiple roles played by the overlay watermark are investigated. It is demonstrated that an extra cross-layer signaling pipe can be created by modulating the overlay watermarks. New interfaces for cross-layer design can be established on top of this new supplementary data link. The major benefit of the proposed system is the improved network and bandwidth efficiency when compared to the conventional in-band pilot approach. Interruption to the physical link due to the cross-layer interaction can be significantly reduced with the introduction of the supplementary data link. When unique orthogonal Kasami sequences are assigned to individual transceivers as identifications, the location of the transmitter can be easily identified for position-based routing algorithms. An iterative channel estimation and data detection algorithm is investigated for the overlay system. Our analysis and simulations show that the impact from the overlay watermark to OFDM data detection is minimal.

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