Synchronization and Cell-Search Technique Using Preamble for OFDM Cellular Systems

Kwang Soon Kim, *Senior Member, IEEE*, Sung Woong Kim, *Student Member, IEEE*, Yong Soo Cho, *Senior Member, IEEE*, and Jae Young Ahn, *Member, IEEE*

***Abstract*—In this paper, a novel preamble structure, including a synchronization field (S-field) and a cell-search field (C-field), is proposed for orthogonal-frequency-division-multiplexing-based cellular systems. An efficient algorithm for downlink synchronization and cell search using the preamble is also proposed. The synchronization and cell-search process includes the initial symbol-timing estimation using continuously or, at least, periodically transmitted downlink signal, the frame detection, the fine symbol-timing estimation, the frequency-offset estimation using the preamble S-field, and the cell identification using the preamble C-field. Performance of each synchronization and cell-search step is analyzed and verified by computer simulation. The overall performance of the synchronization and cell search is then analyzed in terms of the mean acquisition time. It is shown that the proposed preamble with the corresponding synchronization and cell-search algorithm can provide a very robust synchronization and cell-search capability, even in bad cellular environments.**

***Index Terms*—Cell search, cellular, orthogonal-frequency-division multiplexing (OFDM), preamble, synchronization.**

I. Introduction

RECENTLY, orthogonal-frequency-division multiplexing (OFDM) has been widely accepted as the most promising radio transmission technology for the next-generation wireless systems due to its advantages such as robustness to multipath fading, granular resource allocation capability, and no intracell interference. Among the conventional OFDM-based wireless systems, digital audio broadcasting, IEEE 802.11a, and Hiperlan/2 are well known [1]–[5]. For cellular systems, it is one of the most important requirements to provide robust synchronization and cell-search capability. For example, the wideband code-division multiple-access (WCDMA) system provides a hierarchical three-step cell search using the primary synchronization code and the secondary synchronization code in the synchronization channel (SCH) and the common pilot channel (CPICH) [6]. However, the synchronization schemes used in such conventional OFDM schemes are not appropriate for a cellular system since they cannot discriminate signals from different cells unless their carrier frequencies are different. Thus, devising a new synchronization and cell-search technique for OFDM-based cellular systems is required.

Recently, synchronization and cell-search techniques have been proposed for asynchronous OFDM–code-division-multiplexing cellular systems having a channel structure similar to the WCDMA [7], [8]. The differentially encoded SCH uses equally spaced subcarriers in every OFDM symbol and is common for every cell, while CPICH is spread by a cell-specific code in both the time and the frequency domains. However, asynchronous cellular systems generally suffer from longer cell-search time, particularly for a neighbor-cell search. Thus, synchronous cellular systems using the global positioning system (GPS) are considered to be more attractive for the next-generation cellular systems. In this paper, a novel preamble-based synchronization and cell-search technique for synchronous OFDM-based cellular systems using a novel preamble structure, which is comprised of a synchronization field (S-field) and a cell-search field (C-field), is proposed. The initial result of this work has been presented in [9]. The proposed preamble-based synchronization and cell search is fully analyzed, and the performance of the proposed algorithm is then verified by computer simulations in this paper. In addition, the overall performance of the proposed cell search is analyzed in terms of the mean acquisition time (MAT).

II. Proposed Preamble Structure

A. Design Motivation

In conventional OFDM-based wireless systems, such as IEEE 802.11a or Hiperlan/2, the functionality required for an initial synchronization includes signal detection, frame-timing estimation, and frequency-offset estimation. In order to achieve the above functionality, the most commonly used preamble structure in conventional OFDM-based wireless systems is to repeat a pattern, which is a sequence with a good autocorrelation property (autocorrelation function is close to the Kronecker delta function), a few times in a preamble symbol. Such a structure can provide a good time and frequency synchronization capability and has been successfully used in many commercial systems (see [5] and [11] for more detailed discussion).

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K. S. Kim is with the Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea (e-mail: ks.kim@yonsei.ac.kr).

S. W. Kim is with the Samsung Electronics Company, Ltd., Suwon 442-742, Korea.

Y. S. Cho is with the School of Electrical and Electronic Engineering, Chung-Ang University, Seoul 156-756, Korea.

J. Y. Ahn is with the Electronics and Telecommunications Research Institute, Daejeon 305-350, Korea.

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However, for a cellular system (in a single-frequency network as in commercial cellular systems), neighboring cells should use different preambles so that a mobile station can discriminate signals from different cells. Thus, the functionality required for the synchronization and cell search includes frame-timing estimation, frequency-offset estimation, and cell identification. Note that the signal detection is not required since a cellular system is not a burst transmission system. Once the cell number is obtained, a receiver can receive the broadcasting channel of the cell, and the whole cell information can be retrieved. A straightforward way to obtain the above functionality in an OFDM-based cellular system is to use different sequences, as many as the number of different cells, as the repetitive patterns of the preambles. Unfortunately, such a preamble design results in a formidable complexity of the synchronization and cell search (the number of candidates is the number of samples in a frame times the number of different cells). Thus, a preamble structure for a cellular system should not only provide robust capability of synchronization and cell search but also enable us to use a low-complexity hierarchical synchronization and cell-search algorithm. Thus, the motivation of the proposed preamble design is as follows.

1) It should provide an acceptable acquisition time even in a very bad cellular environment where the mobile speed is quite fast and the average signal-to-noise ratio (SNR) is very low.
2) It should allow a low-complexity hierarchical algorithm.

B. Preamble Design

The rough structure of the proposed preamble to obtain the functionality and to meet the design motivation described in Section II-A can be determined from the following observations.

1) In a synchronous system, base stations can transmit a common preamble for the timing-estimation stage, and the received signal is equivalent to the signal from a single transmitter through a multipath channel.
2) We can ignore the relative frequency offset between different base stations in a GPS-aided synchronous system.
3) In order to identify the cell number, the signals from different base stations should be as different as possible.

Based on the above observations, we determine to use two different components, which are denoted as the preamble S-field and the preamble C-field, for the proposed preamble structure. The preamble S-field is common for all base stations and is used for the frame-timing estimation and the frequency-offset estimation. The detailed requirements and the design approach of the preamble S-field are as follows.

1) To reduce the complexity of the cell identification, the integral part of the frequency offset should be estimated. This requirement can be fulfilled by using a repetitive pattern in the preamble S-field.
2) A reliable frame-timing estimation can be fulfilled by
3) A natural way to perform a low-complexity hierarchical estimation is as follows:
   a) estimating a rough symbol timing;
   b) determining the location of the S-field symbol;
   c) estimating the exact frame timing.
4) Step a) above can easily be done using the cyclic prefix (CP). In addition, Step c) can be done using the autocorrelation property of the S-field. Thus, the remaining task is to give the S-field a unique structure that differentiates the S-field from other ordinary OFDM symbols. This can be fulfilled by using the inverted postfix structure of the S-field.

The preamble C-field is used for the cell-number identification, and each cell with a different cell number uses a different preamble C-field. Then, the detailed requirements and the design approach of the preamble C-field are as follows.

1) The best way to make OFDM signals is to use different subcarriers. Thus, the C-fields of adjacent cells should use different sets of subcarriers.
2) To increase the number of different cells, the different cells (not adjacent) may use the same set of subcarriers with different sequences (with a good cross-correlation property) on these subcarriers.
3) Even to accommodate a higher number of different cells, the C-field can be comprised of more than one OFDM symbol.

The detailed preamble design from the above design strategy is as follows. The downlink frame structure considered in this paper and the proposed preamble structure (both in the time and the frequency domains) are shown in Fig. 1. A preamble, with length T_p, is located at the beginning of the frame and is followed by a number of data slots, where pilot symbols are well spread both in the time and the frequency domains. The length of the S-field is T_{ps}, which is equal to the OFDM symbol duration T_s. The S-field signal is composed of one S symbol and one IS' symbol. The IS' symbol is the first T_{CP}-length part of the π-phase-rotated version of the S symbol, and the S symbol is comprised of $N_{S\mathrm{sym}}$ repetitive S_a symbols. Here, T_{CP} is the length of the CP. As shown in Fig. 1, one good example of the preamble S-field signal $P_S(t)$ is

$$P_S(t) = \begin{cases} \sum_{k=0}^{N_F-1} g(k)\varphi_k(t), & 0 \le t < T_d \\ -\sum_{k=0}^{N_F-1} g(k)\varphi_k(t-T_d), & T_d \le t < T_{ps} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where N_F is the size of the fast Fourier transform (FFT), $\varphi_k(t) = \exp(-j2\pi(k - N_F/2)t/T_d))$, $T_d = T_s - T_{\mathrm{CP}}$, $g(k) = \mu(i)\delta_{\mathrm{K}}(k - iN_{S\mathrm{sym}})$, $\mu(i)$ is a pseudorandom sequence such as the m-sequence, and $\delta_{\mathrm{K}}(\cdot)$ is the Kronecker delta function. Since nonzero symbol values are assigned at every $N_{S\mathrm{sym}}$ subcarrier in (1), the S symbol has $N_{S\mathrm{sym}}$ repetitive patterns (each is denoted as the S_a symbol). Among the many possible S-field signals given by (1), the signal with a low peak-to-

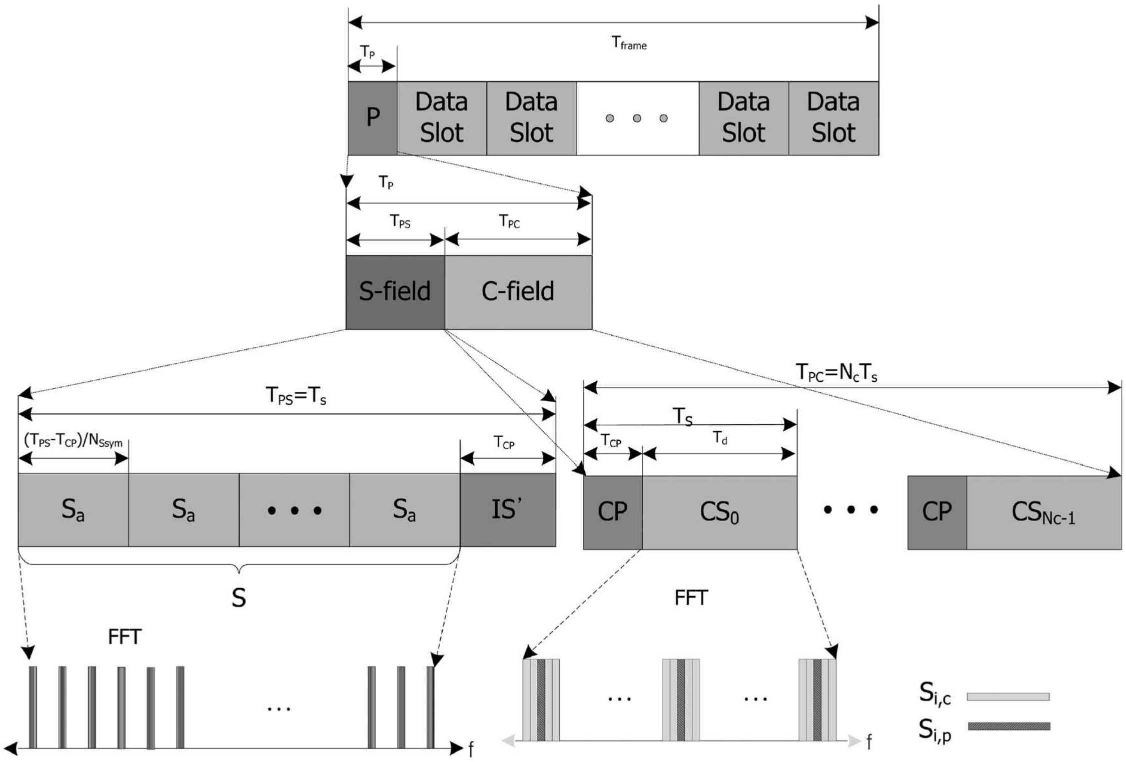

Fig. 1. Abstract downlink frame structure and the proposed preamble structure.

The length of the C-field is equal to N_cT_s. The C-field signal of the mth cell $P_C^m(t)$ is defined as

$$P_C^m(t) = \begin{cases} \sum_{k=0}^{N_F-1} c_n^m(k)\varphi_k(t+T_d-T_{\mathrm{CP}}), & 0 \le t-nT_s < T_{\mathrm{CP}} \\ \sum_{k=0}^{N_F-1} c_n^m(k)\varphi_k(t-T_{\mathrm{CP}}), & T_{\mathrm{CP}} \le t-nT_s < T_s \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where $c_n^m(k)$, $0 \le n \le N_c - 1$, is the frequency-domain signal at the kth subcarrier of the nth symbol of the C-field of the mth cell. The construction of $c_n^m(k)$ is as follows.

1) Let $S = \{s_0, s_1, \ldots, s_{P-1}\}$ be a set of partitions of all used subcarriers. Furthermore, the ith partition s_i is divided into $s_{i,p}$ and $s_{i,c}$.
2) Let $\psi_{i,j}$, $i = 0, \ldots, P-1$, $j = 0, \ldots, G-1$, be the sequences with good correlation properties and $\bar{\psi}$ be a sequence used for known pilot-symbol pattern.
3) For each symbol of the C-field, there are P different partitions and G different sequences. Thus, $M = PG$ different symbols are prepared.
4) Let p_n and q_n be the partition number and the sequence number for the nth symbol of the C-field, respectively. Then, the cell number m is determined by the combination of the N_c partition numbers $(p_0, \ldots, p_{N_c-1})$ and the N_c sequence numbers $(q_0, \ldots, q_{N_c-1})$ as
5) Finally, $c_n^m(k)$ is defined as

$$c_n^m(k) = \begin{cases} \psi_{p_n,q_n}(j), & k = s_{p_n,c}(j) \\ \bar{\psi}(j), & k = s_{p_n,p}(j) \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where $\psi_{p_n,q_n}(j)$, $\bar{\psi}(j)$, $s_{p_n,p}(j)$, and $s_{p_n,c}(j)$ denote the jth elements of ψ_{p_n,q_n}, $\bar{\psi}$, $s_{p_n,p}$, and $s_{p_n,c}$, respectively.

Here, we can see that, with the proposed C-field, M^{N_c} different cells can be discriminated. As an example, let $N_c = 2$, $P = 8$, and $G = 8$. Then, the number of cells that can be discriminated is $M^{N_c} = 64^2 = 4096$, which is large enough for a cellular system.

C. Comparison With the IEEE802.16e Preamble Structure

Among the recently developed OFDM-based wireless systems, IEEE802.16e [10] OFDMA physical layer adopted 114 different preamble patterns by using cell-specific sequences transmitted over one of the three frequency partitions called segments. In addition, an optional common synchronization preamble can be used at the end of the downlink frame structure for simpler timing estimation in which a pseudorandom code is transmitted on even-numbered subcarriers (two repetitive patterns in the time domain) with an ordinary CP. The advantage of the proposed preamble structure can be summarized as follows.

1) The inverted postfix structure of the proposed preamble (IS' symbols) is a very unique structure that enables us

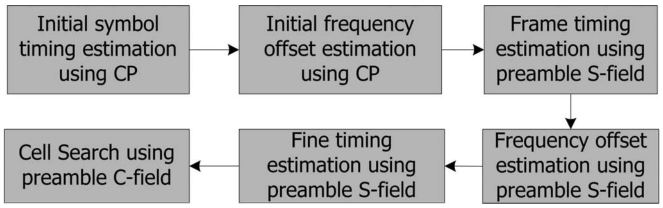

Fig. 2. Proposed synchronization process.

a low-complexity hierarchical synchronization algorithm similar to that in WCDMA [6] can be applied.

2) The main preamble structure of IEEE802.16e can be considered as a special case of the proposed C-field.
3) Additional advantages of the proposed C-field are as follows.
   a) Many more different cells can be implemented by allowing more than one OFDM symbol for the preamble C-field if necessary.
   b) The proposed C-field allows a flexible form of partitions.
   c) Performance can be improved by coherently combining whole symbols with the aid of the known pilot sequence in the proposed C-field, provided that channel estimation is reliable. In addition, when the proposed C-field uses a partition comprised of distributed clusters (adjacent subcarriers in a cluster), as shown in Fig. 1, the symbols within a cluster can be coherently combined without channel estimation.

Thus, it is apparent that we can easily reduce the complexity of the synchronization and cell search, which is critical for a mobile station. In addition, we can expect that the cell-identification performance of the proposed preamble is better when both preambles use the same number of subcarriers since the proposed preamble allows coherent combining.

III. Synchronization

In Fig. 2, the synchronization process proposed in this paper is shown. In the conventional OFDM-based systems such as wireless LAN, all of the initial synchronization processes, including signal detection, are performed using the preamble [11]. However, in an OFDM-based cellular system employing frequency-division multiplexing (FDD), signals are transmitted continuously or, at least, periodically due to the common pilot symbols and common channels used for broadcasting. By taking these into account, we can devise a more efficient hierarchical synchronization and cell-search algorithm. First, the signal-detection step is not required in the synchronization of OFDM-based cellular systems using FDD. In addition, a symbol-timing acquisition within a certain range (roughly speaking, 10%–20% of the length of the CP, which corresponds to 1 dB–2 dB SNR loss) is enough for the cell search. Thus, as the first step of the synchronization and cell search, an initial symbol timing and an initial frequency offset are obtained using a simple CP-based methods such as in [12] and [13]. Note that the required length of the searching window in the initial mate the frame timing using the novel structure of the preamble S-field. As will be seen later, we evaluate a metric for the frame-timing estimation at the sample point obtained from the initial symbol-timing estimation for each OFDM symbol. Thus, the number of candidates in the frame-timing estimation is at most the number of OFDM symbols in a frame. Thus, the proposed hierarchical synchronization scheme has much lower complexity than the conventional synchronization schemes [11], [14]–[16]. Although the fine timing estimation is not an essential task required for a cell search, it is eventually required for successful data reception. Thus, a fine timing estimation is performed using the preamble S-field after the frame timing is obtained. In this paper, a cross-correlation-based method [11], [17] is adopted with a timing back-off for better performance [18]. Finally, frequency-offset estimation is performed by applying an autocorrelation-based method, such as in [11] and [19], to the repetitive structure of the preamble S-field.

A. Initial Symbol Timing and Frequency-Offset Estimation

Let the sampled received signal be $y(n)$ and $z(k)$ be

$$z(k) = \frac{1}{N_{\text{CP}}} \sum_{r=0}^{N_{\text{CP}}-1} y^*(k+r)y(k+r+N_F) \tag{5}$$

where N_{CP} is the number of samples in the CP. Then, the initial symbol timing τ_{init} is obtained using the CP correlation as [12]

$$\tau_{\text{init}} = \arg\max_n \left| \sum_{j=0}^{N_{\text{init}}-1} z(n+jN_s) \right| \tag{6}$$

where N_s and N_{init} are the number of samples in an OFDM symbol and the number of OFDM symbols used in the initial symbol-timing estimation, respectively. In addition, we can estimate the initial frequency offset ϵ_{init} as [12]

$$\epsilon_{\text{init}} = \frac{1}{2\pi} \arg\left\{ \sum_{j=0}^{N_{\text{init}}-1} z(\tau_{\text{init}}+jN_s) \right\}. \tag{7}$$

Note that (7) can estimate only the fractional part of the frequency offset (normalized by the subcarrier spacing). The estimation of the integral part of the frequency offset will be taken care of using the preamble S-field.

B. Frame-Timing Estimation

After obtaining the initial synchronization, we have $N_f(= T_{\text{frame}}/T_s)$ candidates for the frame timing. Here, we utilize the property of the preamble S-field where every OFDM symbol, except the preamble S-field, has a positive value of autocorrelation due to the CP, while the preamble S-field has a negative value of autocorrelation due to the inverted postfix structure. By exploiting the unique structure of the preamble S-field, the frame timing is estimated as where $\Re\{x\}$ is the real part of x, and $z_c(\cdot)$ in (8) is the same as (5), except that the received samples after frequency-offset compensation with the initial frequency-offset estimate obtained in (7) $y_c(\cdot)$ is used instead of $y(\cdot)$. For better frame-timing estimation performance, one may use $\tau_{\text{frame}} = \min_\iota \Re\{z_c(\tau_f(\iota))\}$ instead of using (8), particularly when SNR is low. However, this will cause additional delay since the observation window should be at least one frame, which may degrade the performance of the whole cell-search process in terms of the MAT.

C. Fine Symbol-Timing Estimation

In the case where the frequency offset have both the integral and the fractional parts, the frequency offset ϵ_f can be estimated using the repetitive property of the preamble S-field as [11], [19]

$$\epsilon_f = \frac{N_{S\text{sym}}}{2\pi} \arg\left\{ \sum_{r=0}^{N_{\text{CP}}-1} y^*(\tau_s + r) y(\tau_s + r + N_F/N_{S\text{sym}}) \right\}. \tag{9}$$

Note that (9) can estimate the normalized frequency offset in the range of $[-N_{S\text{sym}}/2, N_{S\text{sym}}/2]$.

After obtaining the frame timing, we can assume that the starting point of the preamble S-field is around the estimated frame timing τ_{frame}. Then, we can estimate the fine symbol timing τ_s with the timing backoff by taking the cross correlation between the frequency-offset compensated signal $y_c(\cdot)$ with the result obtained in (9) and the preamble S-field signal as [11], [17]

$$\tau_s = \arg\max_n \left| \sum_{r=0}^{R-1} P_S^*(r + R_s) y_c(n + r + R_s) \right| - N_B \tag{10}$$

where $P_S(r)$ is the sampled signal of the preamble S-field, R is the number of samples used for the fine symbol-timing estimation, R_s is the starting point for accumulation, and N_B is the number of samples for the timing back-off. In OFDM systems, a negative timing error (estimated timing is greater than true timing) causes intersymbol-interference (ISI) and interchannel-interference (ICI) effects, while a small positive timing error (less than the CP length minus the channel delay) does not. Thus, we can reduce the ISI and the ICI effects by introducing an appropriate timing backoff.

D. Performance Analysis

Let $h(t) = \sum_{l=0}^{L-1} h_l \delta(t - \tau_l^c)$ be the channel impulse response and $x(k)$ be the sampled transmitted signal with average power P_x/N_F. Assuming that the frequency-offset estimation is perfect, the received signal after sampling with sampling period T and frequency-offset compensation is given by

$$y(k) = \sum_{l=0}^{L-1} h_l x(k - \tau_l) + n(k) \tag{11}$$

$\tau_0 = 0$ and $k = 0$ represent the frame boundary without loss of generality. The complex channel gain of the lth path h_l is assumed to be a complex Gaussian process with mean zero and variance β_l (i.e., Rayleigh fading channel). Moreover, $n(k)$ is assumed to be a complex Gaussian process with mean zero and variance $2\sigma_n^2$. Define

$$\zeta(k) = \frac{1}{R} \sum_{r=0}^{R-1} x^*(r) y(k + r). \tag{12}$$

In the case where N_{CP} is sufficiently large, which is true for most OFDM cellular systems due to the large delay spread of outdoor environments, we can assume that $z(k)$ and $\zeta(k)$ are Gaussian random processes with means $m_z(k)$ and $m_\zeta(k)$ and variances $2\sigma_z^2(k)$ and $2\sigma_\zeta^2(k)$, respectively, using the central limit theorem (CLT). The statistics can be summarized as

$$\begin{aligned}
m_z(k) &\cong (-1)^{\delta_{\text{K}}(\lfloor k/N_s \rfloor)} \frac{P_x q(k) \kappa}{N_F} \\
\sigma_z^2(k) &\cong \frac{2\sigma_n^2 P_x \kappa}{N_{\text{CP}} N_F} + \frac{2\sigma_n^4}{N_{\text{CP}}} \\
m_\zeta(k) &= \frac{P_x}{N_F} \sum_{l=0}^{L-1} h_l \delta_{\text{K}}(k - \tau_l) \\
\sigma_\zeta^2(k) &\cong \frac{P_x^2 \kappa}{2RN_F^2} + \frac{\sigma_n^2 P_x}{RN_F}
\end{aligned} \tag{13}$$

where $\kappa = \sum_{l=0}^{L-1} |h_l|^2$, and $\lfloor x \rfloor$ is the greatest integer not exceeding x. Here, $q(k) = \max(0, 1 - (u(k)/N_{\text{CP}}))$ denotes the loss due to the initial timing-estimation error, where $u(k) = |k - N_s \cdot \lfloor k/N_s + 1/2 \rfloor|$ represents the distance to the nearest OFDM-symbol starting point from k. Derivations are given in Appendix A.

1) Initial Synchronization: The outage probability of the initial symbol timing $\Pr\{|\tau_{\text{init}}| > \tau_{\text{th}}\}$ can be calculated from the statistic of $z(k)$ by using a numerical method for a given threshold τ_{th}. In addition, the outage probability of the initial symbol-timing estimation can be reduced by increasing N_{init}. In the sequel, we assume that the initial timing estimation is successful with the initial timing error equals to τ_{init}. Furthermore, we assume that the frequency offset is well estimated so that the effect of the remaining frequency offset in the following synchronization and cell-search procedure can be ignored.

2) Frame-Timing Estimation: If the transmitted symbol is not the preamble S-field, i.e., $\iota \neq 0$, it can be easily seen from (8) and the statistic of $z(k)$ that the false-alarm probability of frame detection conditioned on the combined fading channel gain (κ) $P_{\text{fa,frame}}(\kappa)$ is given by

$$\begin{aligned}
P_{\text{fa,frame}}(\kappa) &= \Pr\left\{\Re\left\{z(\iota N_s + \tau_{\text{init}}) < 0\right\}\right. \\
&\cong Q\left(\sqrt{\frac{2g\gamma^2\kappa^2}{2\gamma\kappa + 1}}\right)
\end{aligned} \tag{14}$$

where $\gamma = P_x/(2\sigma_n^2 N_F)$, $g = q^2(\tau_{\text{init}})N_{\text{CP}}$, and $Q(x) =$

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