LOW-COMPLEXITY AND HIGH-PERFORMANCE NON-COHERENT CELL IDENTIFICATION DETECTION SCHEMES FOR OFDM-BASED SYSTEMS

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ABSTRACT

This work proposes two low-complexity and high-performance cell ID detection schemes for cellular communication systems. The first one, called real-correlation multiple differential detection (RMDD), derived from our previous work on cell ID detection called CERCD method, has much less complex multiplication operations while maintains the same performance. Although CERCD algorithm is more robust than existing cell detection methods in AWGN and multipath channel conditions, its performance still can be further improved. As such, the second scheme, called multiple differential detection (MDD), is proposed to improve CERCD method. Simulation results show that MDD has much better performance in frequency-selective channels. Performances and computational complexities of proposed schemes are also evaluated and analyzed under different channel environments to demonstrate their effectiveness. [1]

Index Terms— Cell search, PSS, Wimax, LTE, 4G

1. INTRODUCTION

Cell search is an essential procedure for network entry in cellular-based communication systems. When a mobile user attempts to access a network, synchronization parameters and cell ID information must be obtained. Specifically, each base station transmits its specific cell and sector preambles so that mobile users can detect the particular preamble number from a set of reference preambles. The associated issues of computational complexity and performance are major concerns in designing a high-quality mobile device with long battery life.

For cellular-based OFDM systems, such as Wimax [1] and LTE [2][3], initial synchronization processes, including the cell identification, are conducted first. As such, various non-coherent cell ID detection algorithms [4]-[10] are proposed in the literature. The concept of matching techniques in [4][5] is to determine the cell ID by detecting the maximum value of all correlation values between the received frequency-domain signal and all the reference preamble signals. However, the frequency-domain matching operations are easily influenced by frequency-selective fading effects. As such, most of existing noncoherent detectors [6]-[9] are developed based on the differential autocorrelation (DA) algorithm which can mitigate such fading effects, assuming that adjacent subcarrier responses are the same. However, in practical situations, the assumption is often not true. For alleviating the problem, our recently proposed channel-effect-resilient cell ID detection (CERCD) algorithm [10] achieves much better performance than DA-based detectors in both AWGN and frequency-selective channels, with lower complexity. Nonetheless, both CERCD and DA-based detectors are computation intensive. Thus, the design of hardware-efficient and high-performance non-coherent cell ID detection algorithms is a crucial and challenging issue.

In order to overcome the mentioned disadvantages of existing works, two non-coherent cell search techniques are presented. The proposed schemes are shown to noticeably have better performance than CERCD and widely used DA schemes in all the following measures: detection accuracy, computational complexity, and robustness against channel selectivity. In addition, the proposed schemes are not limited to particular preamble formats and can be applied to both WiMAX and LTE systems.

The rest of this paper is organized as follows. The system model is described in Section 2. In Section 3, existing cell ID detection schemes are briefly reviewed. Then, proposed schemes are introduced and investigated in section 4. In Section 5, simulations are conducted and evaluated. Finally, Section 6 is the conclusion.

2. SYSTEM MODEL

Consider OFDM system with N_l synchronization preamble sequences and N subcarriers. Assume that the system is transmitting a specific preamble signal $P_i(k)$, $0 \le k \le N-1$, where i and k are the preamble index and subcarrier index, respectively. After passing through IDFT and adding cyclic prefix of length N_g, the n-th time-domain sample $p_i[n]$ within a complete OFDM symbol duration is

$$p_i[n] = \frac{1}{N}\sum_{k=0}^{N-1} P_i(k) e^{j\frac{2\pi kn}{N}}, \quad -N_g \le n \le N-1 \cdot \tag{1}$$

Assuming that the signal is then experiencing a stationary fading channel whose delay spread is shorter than the cyclic prefix. If neglecting symbol timing offset (STO) and carrier

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frequency offset (CFO), the received frequency-domain signal can be expressed as

$$Y(k)=P_i(k)H(k)+W(k), \tag{2}$$

where $H(k)$ and $W(k)$ denote the channel frequency response at the k-th subcarrier and the DFT of the additive white complex Gaussian noise (AWGN), respectively

3. EXISTING WORKS ON CELL ID DETECTION ALGORITHMS

Two existing cell ID detection algorithms, DA and CERCD, are briefly introduced in this section. First, cell ID detection based on DA is given by

$$\hat{i}=\arg\max_l \left|\sum_{k=0}^{N-2} P_l^*(k)P_l(k+1)Y(k)Y^*(k+1)\right|^2 . \tag{3}$$

When the tested preamble P_l matches the transmitted preamble P_i, the detection metric (3) by neglecting the noise term would exhibit a peak value with assumption of $H(k)\approx H(k+1)$.

Secondly, the mathematical expression of the CERCD method is expressed as

$$\hat{i}=\arg\max_l \sum_{j=0}^{N-M}\left|\sum_{k=j}^{M+j-1} P_l^*(k)Y(k)\right|^2 \tag{4}$$

where M is a positive integer larger than or equal to 2. In addition, preamble subcarriers are assumed to satisfy the condition $P_l(k)P_l^*(k)=1$, for the ease of discussion. Then, when the tested preamble matches the transmitted preamble, the detection metric (4), excluding the noise term, becomes

$$\hat{i}=\arg\max_l \sum_{j=0}^{N-M}\left|\sum_{k=j}^{M+j-1} H(k)\right|^2 . \tag{5}$$

As channel frequency response is generally highly correlated, the transmitted preamble can be detected via searching a preamble sequence which maximizes (5). Also, in order to maximize cell search detection performance, M is suggested to be equal to the coherent bandwidth of targeting channel frequency responses. Via inner averaging operations in (4), the channel noise effect can be greatly reduced, and, hence, CERCD is more robust to the noisy channels against DA-based detectors.

4. THE PROPOSED CELL SEARCH SCHEME

In this section, the proposed cell search detection schemes are firstly derived. Subsequently, effects of imperfect channel factors, such as channel selectivity and timing offsets, are analyzed. Finally, computational complexities of proposed works and existing CERCD are discussed and compared as well.

First, the proposed scheme, called RMDD, starts from CERCD method given below

$$\begin{aligned}\hat{i}&=\arg\max_l \sum_{j=0}^{N-M}\left|\sum_{k=j}^{M+j-1} P_l^*(k)Y(k)\right|^2\\&=\arg\max_l \sum_{j=0}^{N-M}\sum_{g=0}^{M-1}\left|Y(j+g)\right|^2\\&\quad+\sum_{g=0}^{M-2}\left\{\begin{array}{l}(M-1-g)\\ \times\sum_{k=0}^{N-2-g}\Re\left[P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1)\right]\end{array}\right\}\\&=\arg\max_l \sum_{g=0}^{M-2}\left\{\begin{array}{l}(M-1-g)\\ \times\sum_{k=0}^{N-2-g}\Re\left\{\begin{array}{l}P_l^*(k)P_l(k+g+1)\\ \times Y(k)Y^*(k+g+1)\end{array}\right\}\end{array}\right\},\end{aligned} \tag{6}$$

where operator $\Re\{\bullet\}$ returns the real value of its argument. In (6), it is shown that CERCD method can achieve its optimal performance for frequency-flat channels, whose complex products for (j, j+1) and (j+1, j+2) subcarrier pairs are roughly equal. As such, one can further simplify the computational complexity and intuitively consider that all the real correlation terms in (6) should have the same contribution to the detection metric. Therefore, if further approximating the weighted factor $(M-1-g)$ to one for small M, the first proposed cell ID detection scheme, RMDD, is defined as follows

$$\hat{i}=\arg\max_l D_l, \tag{7}$$

where

$$D_l=\sum_{g=0}^{M-2}\sum_{k=0}^{N-2-g}\Re\left\{P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1)\right\}. \tag{8}$$

However, in order to further enhance performance in frequency-selective channels, the second proposed cell ID detection scheme, named MDD, considers both real and imaginary parts of the correlations, are also given:

$$\hat{i}=\arg\max_l D_l', \tag{9}$$

where

$$D_l'=\sum_{g=0}^{M-2}\left|\sum_{k=0}^{N-2-g}P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1)\right|^2 . \tag{10}$$

The major enhancement of MDD over CERCD and RMDD is its consideration on the imaginary part of complex product in the inner accumulation. Therefore, the assumption of high similarity between adjacent channel frequency responses isn't necessary for MDD, and hence MDD can theoretically have better performance in frequency-selective channels. Note that when M=2, MDD and RMDD reduce to conventional DA scheme. However, by increasing M, the performance gain is also increased because of lower white noise effect. In addition, advantages of the proposed RMDD and MDD over the CERCD scheme can be analyzed in the presence of channel selectivity and timing offset effects.

4.1 Performance analysis for channel selectivity

Without loss of generality, if ignoring the noise term and considering the case of matched cell preamble, that is, $P_l(k) = P_i(k)$, then MDD scheme can be represented as

$$D_l^{'} = \sum_{g=0}^{M-2} \left| \sum_{k=0}^{N-2-g} \Re\left\{ H(k)H^*(k+g+1) \right\} \right|^2 + \sum_{g=0}^{M-2} \left| \sum_{k=0}^{N-2-g} \Im\left\{ H(k)H^*(k+g+1) \right\} \right|^2, \tag{11}$$

where operator $\Im\{\bullet\}$ returns the imaginary value of its argument. For less severe frequency-selective channels, the following condition

$$\Im\{H(k)H^*(k+g+1)\} \ll \Re\{H(k)H^*(k+g+1)\} \tag{12}$$

holds for small g. As such, (11) can be further simplified as

$$D_l^{'} \approx \sum_{g=0}^{M-2} \left| \sum_{k=0}^{N-2-g} \Re\left\{ P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1) \right\} \right|^2, \tag{13}$$

where only real parts are remained in (13). As such, square absolute operations can be neglected and further approximated as

$$D_l \approx \sum_{g=0}^{M-2} \sum_{k=0}^{N-2-g} \Re\left\{ P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1) \right\}. \tag{14}$$

Note that (14) has exactly the same form as the proposed RMDD scheme. On the other hand, for frequency-selective channels, the imaginary part of complex conjugate products terms can't be ignored due to its less similarity of channel frequency responses between successive subcarriers. In this condition, CERCD scheme would suffer performance degradation because only the real part of complex conjugate products is taken into considerations as shown in (6). In contrast, since MDD scheme contains both real and imaginary parts of $H(k)H^*(k+g+1)$, it is more robust to channel selectivity than the CERCD scheme.

4.2 Performance analysis for symbol timing offset

In the presence of STO $\Delta\tau$, the received signal at the k-th subcarrier can be expressed as

$$Y(k) = P_i(k)H(k)e^{-j\frac{2\pi k}{N}\Delta\tau} + W(k) \tag{15}$$

Table 1: Comparison of computational complexity

	RMDD	MDD	CERCD
Multiplication	N-1, real	(N-2)N_l, complex	(N-2)N_l, complex
$\lvert\bullet\rvert^2$		(N-2)	(N-2)N_l
Addition	(N-2)N_l, real	(N-2)N_l, complex	(N-2)N_l, complex

Table 2: Simulation Parameters

Parameters	Value
Operating Frequency	2.5 GHz
Signal Bandwidth	5 MHz
FFT Length	512
Cyclic Prefix Ratio	1/4

Neglecting the noise term, the effect of timing error on the CERCD detection metric (6) is:

$$\begin{aligned} &\sum_{g=0}^{M-2} \{(M-1-g) \sum_{k=0}^{N-2-g} \Re\{P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1)\}\} \\ &= \sum_{g=0}^{M-2} \{(M-1-g) \sum_{k=0}^{N-2-g} \Re\{P_l^*(k)P_l(k+g+1)P_i(k)P_i^*(k+g+1) \\ &\qquad \times H(k)H^*(k+g+1)e^{j\frac{2\pi(g+1)}{N}\Delta\tau}\}\}. \end{aligned} \tag{16}$$

(16) shows that, if M and $\Delta\tau$ are large, performance of CERCD algorithm is degraded. As for the MDD scheme, the STO effect can be completely removed from the detection metric in which the derivation is shown as follows:

$$\begin{aligned} &\sum_{g=0}^{M-2} \left| \sum_{k=0}^{N-2-g} P_l^*(k)P_l(k+g+1)Y(k)Y^*(k+g+1) \right|^2 \\ &= \sum_{g=0}^{M-2} \left| e^{j\frac{2\pi(g+1)}{N}\Delta\tau} \sum_{k=0}^{N-2-g} P_l^*(k)P_l(k+g+1)P_i(k)P_i^*(k+g+1) \right. \\ &\qquad \left. \times H(k)H^*(k+g+1) \right|^2 \\ &= \sum_{g=0}^{M-2} \left| \sum_{k=0}^{N-2-g} P_l^*(k)P_l(k+g+1)P_i(k)P_i^*(k+g+1) \right. \\ &\qquad \left. \times H(k)H^*(k+g+1) \right|^2. \end{aligned} \tag{17}$$

4.3 Computational Complexity

In order to compare the computational complexity between proposed algorithms and CERCD, the case of M=2 is taken as an example and listed in Table 1. Note that, the preamble sequence is assumed to be BPSK-modulated.

CERCD involves $|\bullet|^2$ operations and conjugate product at each subcarrier for all preamble sequences. As such, CERCD demands higher computational complexity than the proposed RMDD and MDD.

In contrast, in RMDD and MDD, since $\Re\{Y(k)Y^*(k+1)\}$ and $Y(k)Y^*(k+1)$ terms are common in correlating different preamble sequences and, they can be pre-computed before cell ID detection process. As such, computational complexity can be further reduced without repeating them during correlations with different preamble sequences. Moreover, the signal at each preamble subcarrier is simply ±1 due to BPSK modulation, and thus part of complex computations can be replaced by simple logic operations. In total, RMDD only requires N-1 real multiplication and doesn't need absolute squaring operations. Comparing to CERCD, RMDD not only reduces the complex operations to low-complexity real ones but also reduce the number of multiplication operations by an order of N_l. As for MDD, although it requires the same number of complex multiplications as CERCD, MDD only requires N-1 absolute squaring operations which are significantly reduced by N_l times than CERCD.

5. SIMULATION RESULTS

Detailed simulation profile, which adopts parameters of Wimax systems, is listed in Table 2. In addition, two different channel environments, ITU-R Vehicular A channel and ITU-R Vehicular B channel [10], where Vehicular B channel is a much more frequency-selective fading channel than Vehicular A channel, are also compared. Note that, only CERCD is compared due to its better performance than DA-based ones.

Fig. 1 depicts detection error rate of the proposed RMDD comparing with the CERCD scheme in Vehicular A channel. When M=2, these two schemes yield the same performance, as proved in (6). However, for M=3 and 4, RMDD scheme performs slightly better than the CERCD. In addition, by increasing the M value, performance gains for both RMDD and the CERCD are obtained. Fig. 2 depicts simulated results for MDD and CERCD in Vehicular B channel. Note that, MDD is shown to significantly outperform CERCD in highly frequency-selective Vehicular B channel because MDD isn't developed based on the high similarity of adjacent channel responses and can provide better correlation results for such channel conditions.

6. CONCLUSION

Low-complexity and high-performance cell ID detection schemes, RMDD and MDD, are proposed. The proposed RMDD is derived from CERCD but have much lower computational complexity while maintaining similar performance. On the other hand, in highly frequency-selective channels, the proposed MDD scheme can mitigate the effect of channel selectivity in its detection operation as well as the symbol timing error. Simulation results also show that MDD can significantly enhance the detection performance while requiring much less computational complexity of the existing CERCD one. The effectiveness of RMDD and MDD schemes are fully demonstrated.

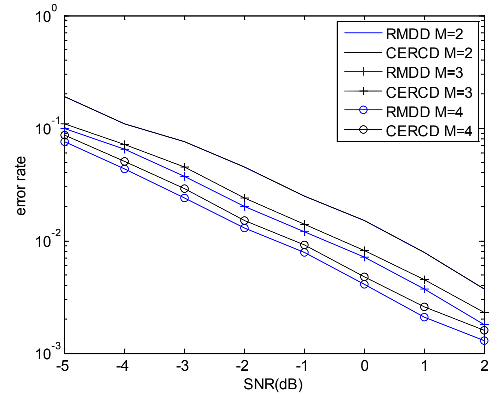

Figure 1. Performance comparison in Vehicular A channel.

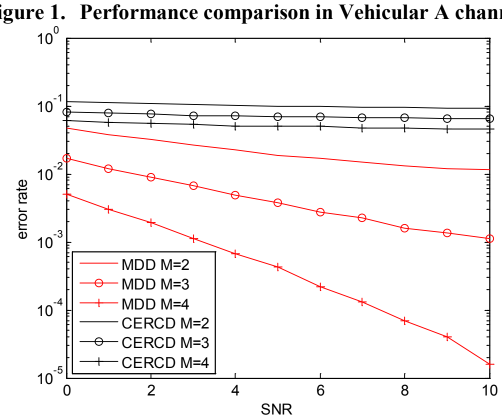

Figure 2. Performance comparison in Vehicular B channel.

7. REFERENCES

[1] IEEE std 802.16-2004. IEEE Standard for Local and Metropolitan Area Networks-Part 16: Air Interface for Fixed Broadband Wireless Access Systems, Oct. 2004.

[2] Draft IEEE std 802.l6e/D9. IEEE Standard for Local and Metropolitan Area Networks-Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems, Jun. 2005.

[3] 3GPP TS36.211 v8.5.0, Physical Channels and Modulation (Release 8), Dec. 2008.

[4] P. Cheng, Z. Zhang, X. Zhou, J. Li and P. Qiu, "A Study on Cell Search Algorithms for IEEE 802.16e OFDMA Systems," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC) 2007*, Mar., 2007, pp. 1848-1853.

[5] P. Cheng, Z. Zhang, X. Zhou, J. Li and P. Qiu, "A Study on Cell Search Algorithms for IEEE 802.16e OFDMA Systems," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC) 2007*, Mar., 2007, pp. 1848-1853.

[6] F. Berggren and B. M. Popovic, "A Non-hierarchical Cell Search Scheme," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC) 2007*, Mar., 2007, pp. 2300-2304.

[7] P. A. Murugesa Pandian and S. Srikanth, "Low Complexity Cell Search For Mobile OFDMA System," in *Proc. IEEE International Conference on Signal Processing, Communications and Networking (ICSCN) 2008*, Jan., 2008, pp. 189-193.

[8] J. W. Lee, J. W. Choi, and H. L. Lo, "Joint maximum likelihood estimation of channel and preamble sequence for WiMAX systems," *IEEE Trans. on Wireless Communications,* vol. 7, no. 11, Nov. 2008.

[9] K. S. Kim, S. W. Kim, Y. S. Cho and J. Y. Ahn, "Synchronization and cell-search technique using preamble for OFDM cellular systems," *IEEE Trans. on Vehicular Technology*, vol. 56, no. 6, Nov. 2007.

[10] C. L. Chen and S. G. Chen, "Non-coherent cell identification detection methods and statistical analysis for OFDM systems," *IEEE Trans. on Communications*, vol. 58, issue 11, pp. 3321-3243, Sep. 2010.