rms Angular Spread Estimation using CDM based MIMO Channel Sounder with Loosely Synchrounous Codes and Kasami Codes

Ji Hwan Choi, Hyunseok Lee, Hyoungsuk Jeon, Jongsub Cha and Hyuckjae Lee
School of Engineering
Information and Communications University (ICU)
119 Munjiro, Yuseong-gu, Daejeon, 305-714, Korea
E-mail: {jihwanchoi, lhs144, hschun, s1009, hjlee}@icu.ac.kr

***Abstract*— This paper presents rms angular spread estimation using the code-division multiplexing (CDM) based MIMO channel sounder applied loosely synchronous (LS) codes and Kasami codes for real time measurement of MIMO radio channel. Since this scheme has drawback of reduced dynamic range depending on the number of transmit antennas, it is important that low correlation codes should be utilized to get reliable performance. In this paper, the proposed scheme adopts two efficient codes, LS codes and Kasami codes, of which performance is investigated through Monte-Carlo simulation in 2×8 and 4×8 MIMO channel environment, respectively. According to the simulation focused on rms angular spread estimation, LS codes can be used for 2×8 MIMO channel measurement and Kasami codes is suitable for measuring 4×8 MIMO channel. For measuring 4×8 MIMO channel with LS codes properly, some modification is taken to the LS codes. Unitary ESPRIT is chosen for DOA estimation and rms angular spread is taken for the performance comparison.**

***Index Terms*—DOA estimation, MIMO Channel measurements, loosely synchronous codes, Kasami codes**

I. INTRODUCTION

Lately, the demand for both higher data rates and more reliable wireless communications against multipath fading is rapidly increasing. For future wireless communication systems, MIMO techniques can be considered to provide high data throughput as well as significant enhancement in link reliability over existing systems. In real environments, however, accurate knowledge of the propagation channel is required to process MIMO receiving systems. Thus, the accuracy of MIMO channel measurement is an important issue in many aspects like simulation, system design, and performance analysis for future wireless communication systems [1,2].

Previously, Time-division multiplexing with synchronized switching (TDMS) based MIMO channel sounder is used for MIMO channel measurement as shown in Fig.1(a). Although this technique is cost effective, it has the major drawback that absolute time synchronization and excess time slots are needed, considering that each channel uses its own time slot [2,3,6,8]. As another approach, code-division multiplexing (CDM) based MIMO channel sounder with low correlation codes was introduced in [8]. However, it also has disadvantage that dynamic range is limited by the number of transmit antennas due to none-zero correlation values.

This paper proposes new efficient CDM-based MIMO channel sounder with loosely synchronous (LS) codes and Kasami codes. To enhance the system performance, some modification is applied to LS codes to deal with the problem that the interference free window (IFW) zone decreases as the number of codes increases. In the simulation, we consider rms angular spread as a main factor of MIMO channel characteristics and Unitary ESPRIT is chosen for DOA estimation [7].

Simulation results show that the proposed channel sounder using LS codes gives excellent performance for measuring rms angular spread of 2×8 MIMO channel environment. The scheme using Kasami codes achieves good performance in 4×8 MIMO channel environment as well. The modified LS codes get somewhat better performance than the others in 4×8 MIMO channel environment.

This paper is organized as follows. In section II, the CDM-based MIMO channel sounding technique is introduced. In section III, the simulation environments are shown, and the results are analyzed in section IV. The conclusion is discussed in section V.

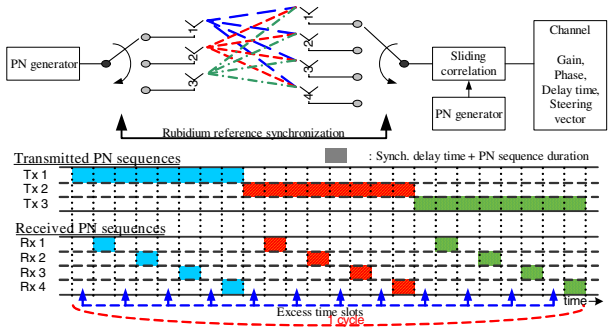
II. CODE DIVISION MULTIPLEXING BASED MIMO CHANNEL SOUNDING TECHNIQUE

A. The proposed channel sounding system

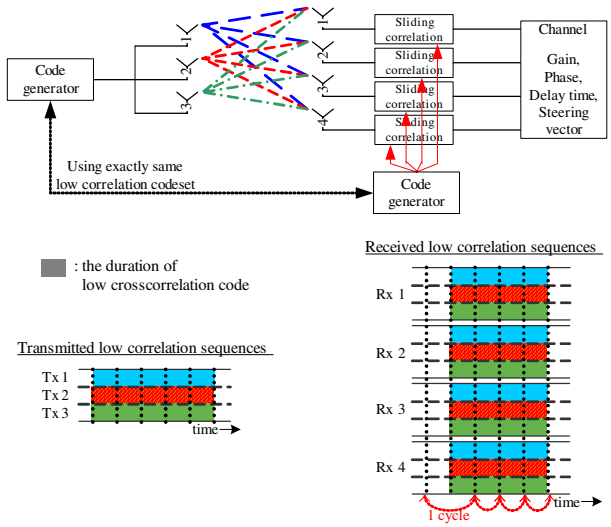
CDM-based MIMO channel sounding technique is depicted in Fig.1(b). A generated sounding signal adopting spread spectrum with low correlation codeset at the transmitter propagates to MIMO channel. At the receiver, the channel characteristic is observed after sliding correlation of the received signal simultaneously. This paper is focused on finding real rms-angular spread.

B. LS codes, Kasami codes, and modified LS codes

One of the efficient codes is loosely synchronous (LS) codes based on Golay complementary codes [9]. Additional zeros are inserted between a complementary pair as shown in Fig.2 [10,11,12]. These LS codes have the time delay region which

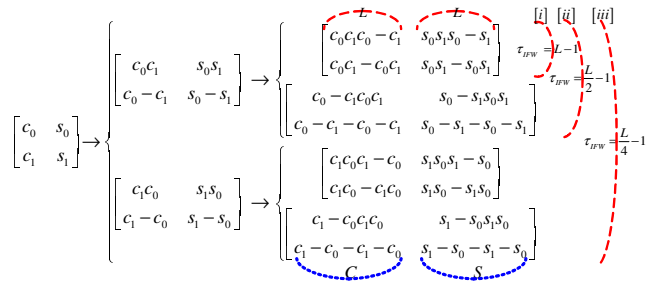


(a) Time-Division Multiplexing with synchronized switching based MIMO channel sounder

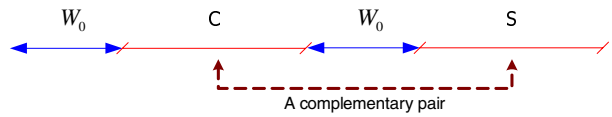


(b) Code-Division Multiplexing based MIMO channel sounder

Fig. 1. The basic principles of the sounding schemes

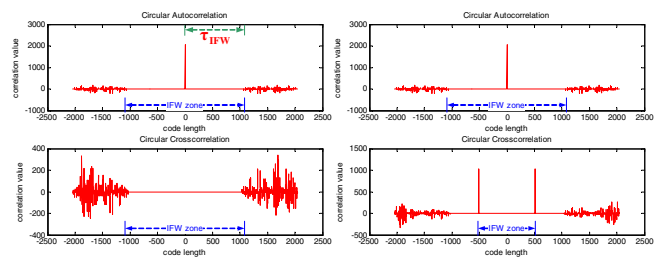


(a) Complementary pair generation



(b) LS code generation

Fig. 2. The generation method of LS codes



(a) the correlation characteristics between mate pairs (case [i])

(b) the correlation characteristics between other pairs (case [ii])

Fig. 3. Correlation property of LS codes

has no interference. This area calls interference free window (IFW) zone($= 2\tau_{IFW} + 1$). If either any delay signal or a signal using other LS code from the same codeset is within this region, we can perfectly know the delay time and channel gain. Inside IFW zone, the system is analyzed as several single-input single-output (SISO) components. The correlation property of LS codes is as follows.

$$R_{jk}(\tau) = \sum_{i=1}^{L-1} c_{j,i} c_{k,(l+\tau) \bmod L} = \begin{cases} L, & for\ \tau = 0,\ j = k \\ 0, & for\ \tau = 0,\ j \neq k \\ 0, & for\ 0 < |\tau| < \tau_{\mathrm{IFW}} \end{cases} \quad (1)$$

However, the width of IFW zone depends on the number of codes in used codeset. In case of using a mate pair of LS codes, the length of τ_{IFW} is L-1 where 2L is the length of a complementary pair and W_0 is L-1 to get optimum IFW zone (the total code length is 4L-2) [11]. For different pairs with the same parents codes, the achievable IFW zone is the half of the case using the mate pair. With the same grandparents codes, the quarter of the case using the mate pair is obtained through the different pairs with the different parents codes as IFW zone. In other words, if we use twice of the codes, we get half of IFW zone as shown in Fig.2 and Fig.3. In this reason, LS codes are not suitable to measure the channel which has many transmit antennas with longer delays.

Another codes are Kasami codes. The generation method of Kasami codes is shown in Fig.4. Kasami codes have three low correlation values, $\{-1, -s(n), s(n) - 2\}$ where $s(n) = 2^{n/2} + 1$ and n is the number of stages [13]. We can assume the system as several SISO components as well. With Kasami codes, we can measure longer delays and the system which has many transmit antennas. Yet, the system using Kasami codes is interference limited. Even though Kasami codes have low correlation values, these correlations are not ignorable. Hence, the sensitivity of the system using Kasami codes is limited by both the number of used codes and the maximum cross-correlation value over autocorrelation value ($R_{xx}(0)$).

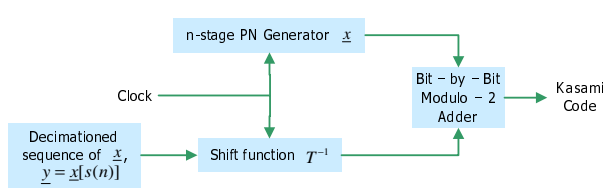


Fig. 4. Kasami code generation

LS codes have performance limit because of difficulty to extend IFW zone and to keep IFW zone when using more transmit antennas. Here, some modification is presented to extend IFW zone. The method is that using a mate pair of LS codes constructs a modified LS code as shown in Fig.5. In this scheme, we can generate 4 codes having equal τ_{IFW} depending on $L/2 + W_0$ where 2L is the length of a complementary pair and W_0 is the length of zero insertion between CS complementary pairs (the total code length is $4L + 4W_0$) as shown in Fig.6. Then, this codeset can be adopted to longer delay channel at 4×8 MIMO channel sounding.

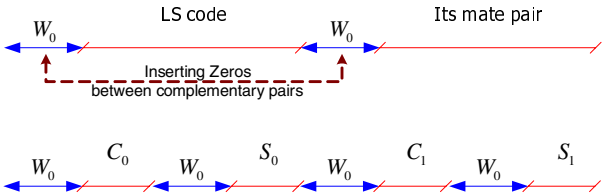
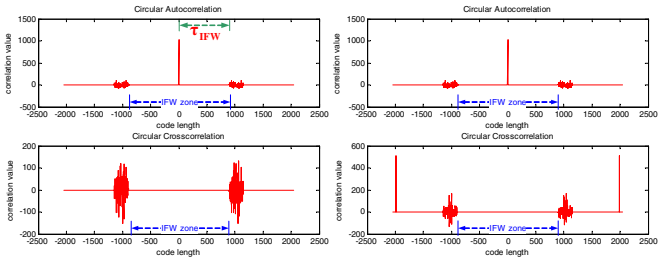


Fig. 5. Modified LS code generation using a mate pair of LS codes



(a) the correlation characteristics between mate pairs

(b) the correlation characteristics between other pairs

Fig. 6. Correlation property of MLS codes

C. Unitary ESPRIT algorithm

Unitary ESPRIT is one of well-known algorithms for DOA estimation [7]. ESPRIT is an abbreviation of Estimation of Signal Parameters via Rotational Invariance Technique.

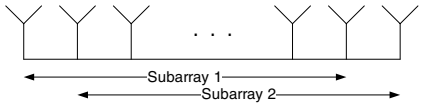


Fig. 7. Receive antenna subarrays at the receiver

First of all, we make the receive antenna subarrays as shown in Fig.7. After then, follow the procedure in next.

1) Signal modeling

$$\begin{aligned} x(t) &= \bar{A}s(t) + n(t) \\ \text{where } \bar{A} &= [A_1\, A_2]^T,\ n = [n_1(t)\, n_2(t)]^T \end{aligned} \tag{2}$$

2) Find unique non-singular T matrix

$$U_s = \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} AT \\ A\Phi T \end{bmatrix} \tag{3}$$

$$\begin{aligned} U_2 = U_1\Psi \ &, \text{where } \Psi = T^{-1}\Phi T \\ \Phi : diag.,\ e^{j\phi_m},\ m &= 1, 2, \cdots, M \end{aligned} \tag{4}$$

3) Eigen-decomposition (find the eigenvalues of Ψ)
Using least square or total least square
4) Find Direction of Arrivals

$$\begin{aligned} \hat{\phi}_i &= \arccos(angle(\lambda_i)/(\beta \times D_{sensors})) \\ \text{where } \lambda_i &: \text{i}_{\text{th}}\text{eigenvalue of } \Psi \\ \beta &: \text{wave number} \end{aligned} \tag{5}$$

D. rms Angular Spread

To describe MIMO radio propagation channel, the rms angular spread θ_{rms} is the inevitably required statistical parameter [1]. To derive the rms angular spread from measured correlation matrix, all relevant paths should be taken without knowledge of noise peak [6]. There are two methods. One is using certain threshold and another is using the desired percentage of detected power over total power of all paths. The latter one might not be easily used in real situation as the total power of all paths is hard to know without any information from the radio channel. In our simulation, certain thresholds are taken in each system. The system using LS codes is noise limited, for that reason the threshold (T) depends on its processing gain (PG), E_C/N_0, and noise margin caused by enhancement of noise depending on the number of transmit antennas.

$$T_{LS} = 10\log_{10}(PG) + E_C/N_0 - 10\log_{10}(Tx)\ [dB] \tag{6}$$

Otherwise, The threshold of the system using Kasami codes depends on both the largest cross-correlation value $Rxx'_{\max}$ and the number of transmit antennas.

$$\begin{aligned} T_K = &-20\log_{10}\left(\frac{Rxx'_{\max}}{Rxx \times \mathrm{P}_{\max}}\right) \\ &+10\log_{10}\left(\frac{(Tx-1) + (1-P_{\max})}{P_{\max}}\right) \end{aligned} \quad [dB] \tag{7}$$

where $P_{\max}$ is the largest value normalized by total correlation value after sliding correlation and Rxx is the maximum autocorrelation value. For better performance, receiver diversity gain is used to determine the threshold. It reduces the variance of correlation values and makes the system operate stable.

The calculation of rms angular spread θ_{rms} is as follows.

$$\theta_{rms} = \sqrt{\frac{\int_{-\pi}^{\pi} (\theta - \theta_{mean})^2 P_g(\theta) d\theta}{\int_{-\pi}^{\pi} P_g(\theta) d\theta}} \tag{8}$$

where θ_{mean} is mean of angular spread

$$\theta_{mean} = \frac{\int_{-\pi}^{\pi} \theta P_g(\theta) d\theta}{\int_{-\pi}^{\pi} P_g(\theta) d\theta} \tag{9}$$

III. SIMULATION

The code length is fixed to 4094 (LS codes), 4095 (Kasami codes), and 4096 (modified LS codes), the channel bandwidth is 100 MHz (chip resolution is 10 ns), center frequency is 3.7 GHz, and mobile velocity is 16.67 m/s (60 km/h). At the first step, Tx=2 and Rx=8 is selected. The second step is to extend the MIMO channel as Tx=4 and Rx=8. E_C/N_0 is fixed to 8dB for the simulation. Here, the modified LS codes use 2L=512 and W=768 (the total code length is $4L + 4W_0 = 4096$ and IFW zone = $\{-896, 896\}$).

The simulated channel is generated by using 3GPP Spatial Channel Model Extended (SCME) released by Wireless World Initiative New Radio (WINNER) project for reliability [4,5]. This simulated channel generates 6 delay signals composed of 3 intra clusters individually. For testing the code properties, rms angular spreads are obtained in multipath nature with urban macro (typical metropolitan) and suburban macro (rural) scenario (respectively, mean of angular spread at receiver is 68 degrees in SCME). These scenarios are typical environment for mobile communications.

IV. RESULT

The results are analyzed separately in accordance with the scenarios. The purpose of analyzing these results is to find the performance of each codes in each scenario. The reference of the performance analysis is cumulative density function (CDF) of absolute rms angular spread error. The focus is how much the absolute rms angular spread error is occurred in each scenario and codes.

A. Suburban macro environment

We start with 2×8 MIMO channel measurement. In Fig.8, the system using LS codes has better performance than the others in terms of measuring absolute error of rms angular spread in 2×8 MIMO channel. Because IFW zone of LS codes can cover almost all of delay signals, the sounder using LS codes can estimate DOAs more accurate than that using Kasami codes. It is caused by natural property of those codes. LS codes are noise-limited (limited by the length of IFW zone) and Kasami codes are interference-limited (limited by the threshold). This characteristic is maintained if IFW zone of LS codes cover all significant delay signals. In suburban macro channel, almost all of multipaths are inside of IFW zone even 4×8 MIMO channel. Thus, the sounder using LS codes can be used for measuring rms angular spread in both 2×8 and 4×8 MIMO suburban macro channel.

The error is caused by the lost paths and DOA estimation error.

B. Urban macro environment

The sounder using LS codes experiences degradation of system performance when IFW zone can not cover the maximum delay. In urban macro channel, the standard deviation of delay is 680ns. Then, IFW zone cannot cover all significant delay signals without enlarged code length. With fixed code length in our simulation, the error of measuring rms angular spread

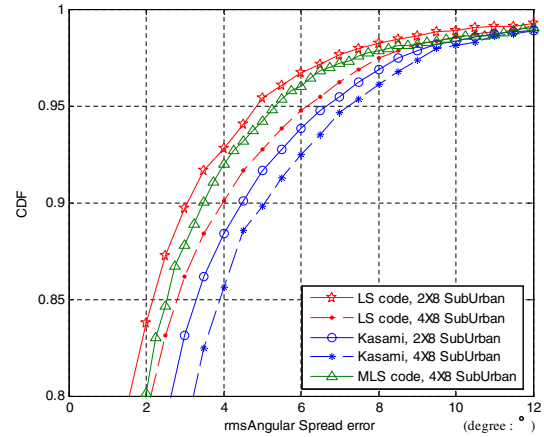


Fig. 8. Absolute error of rms angular spread in Suburban macro environment

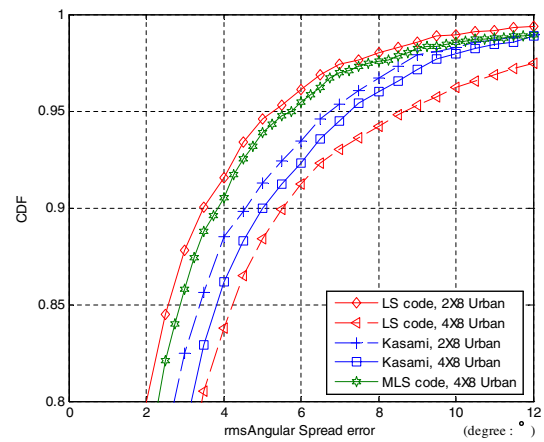


Fig. 9. Absolute error of rms angular spread in Urban macro environment

is fairly increasing in 4×8 MIMO channel as shown in Fig.9. The reason is that we get half of IFW zone when we use two times of the number of codes.

The sounder using Kasami codes gets performance degradation as well. However, the amount of increasing error is not as much as the case of LS codes. The effect from the enlarged number of transmit antennas to Kasami codes is only slight increase of the threshold. Although this situation makes the sounder lost several weak delay signals, the contribution of lost paths to measure rms angular spread is not as large as that of LS codes. In the case of LS codes, we lost significant paths if those are outside of IFW zone. Accordingly, Kasami codes can be used for measuring 4×8 MIMO urban macro channel. Also, we can assume the sounder using Kasami codes can be used for the increased number of transmit antennas than 4.

To overcome the degradation of system performance in 4×8 MIMO channel measurement, the sounder takes modified LS codes. The performance of using modified LS codes

approaches to the case of measuring 2×8 MIMO channel with the sounder using LS codes. The reason is that the widen IFW zone makes the systems found more signals than that of using LS codes. Hence, we would rather choose modified LS codes for measuring 4×8 MIMO channel. However, modified LS codes can not avoid the property of LS codes which is that the length of IFW zone is decreased with increasing the used codes. Thus, modified LS codes are dedicated to 4 transmit antennas.

V. CONCLUSIONS

In this paper, the code-division multiplexing based MIMO channel sounder with loosely synchronous codes and Kasami codes is introduced for rms angular spread estimation. The impact of imperfect system response on rms angular spread is analyzed in terms of the 3GPP Spatial Channel Model Extended. Both suburban macro environment and urban macro environment are taken for the reliable simulation. For DOA estimation, we use Unitary ESPRIT algorithm. According to the simulation, the sounder using LS codes can cover the most delay signals with IFW zone in both 2×8 and 4×8 MIMO suburban macro channel measurement. Although the performance of rms angular spread error is experienced slight degration, it still maintains good performance. Accordingly, LS codes can be chosen to the channel measurement. In urban macro channel, the performance depends on the number of transmit antennas. While the sounder using LS codes undergoes significant degradation of performance when the number of transmit antennas is increasing from 2 to 4, the scheme using Kasami codes achieves similar performance compared with 2×8 MIMO channel measurement. Then, the sounder using Kasami codes fulfills better performance than that using LS codes. With modified LS codes, the system obtains better performance than that using Kasami codes. In consequence, we choose LS codes for 2×8 MIMO urban macro channel measurement and modified LS codes for 4×8 MIMO urban macro channel measurement. However, LS codes can not surmount the decreasing IFW zone when increasing the used codes. Therefore, Kasami codes can be utilized to the channel measurement when the number of transmit antennas is more than 4 because the sounder using Kasami codes keeps the performance with slight degradation.

VI. ACKNOWLEDGEMENT

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