Code-Division Multiplexing based MIMO Channel Sounder with Loosely Synchronous Codes and Kasami Codes

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Abstract— **In this paper, the code-division multiplexing (CDM) based MIMO channel sounder with loosely synchronous (LS) codes and Kasami codes is presented 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. This paper adopts two efficient codes, LS codes and Kasami codes, of which performances are investigated through Monte-Carlo simulation in 2×8 and 4×8 MIMO channel environment, respectively. Basically, LS codes are noise-limited and Kasami codes are interference-limited in relation with cross-correlation characteristic. According to the simulation, LS codes are the best in 2×8 MIMO channel measurement and modified LS codes approach to this performance of LS codes in both 2×8 and 4×8 MIMO channel measurement. Kasami codes achieve somewhat less performance than the others, but are not nearly affected by the number of transmit antennas. Thus, Kasami codes are effective when transmit antennas are more than 4.**

Index Terms–**Channel measurements, loosely synchronous codes, multiple-input multiple-output channels, Kasami codes**

I. INTRODUCTION

Recently the demand for both higher data rates and more reliable wireless communications in severe 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 beyond the third generation wireless communication systems [1,4].

The previous schemes for MIMO channel measurement are to use time-division multiplexing with synchronized switching (TDMS) based MIMO channel sounder 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 [5,6,8]. In other words, the required time slots depend on the number of transmit antennas. 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.

In this paper, we propose new efficient CDM-based MIMO channel sounding technique with loosely synchronous (LS) codes and Kasami codes. To enhance the system performance, we apply some modifications to LS codes to deal with the problem that the interference free window (IFW) zone decreases as the number of codes increases.

Simulation results show that the channel sounding scheme using LS codes gives very good performance for measuring 2×8 MIMO channel, and the one using modified LS codes can achieve both 2×8 and 4×8 MIMO channel measurement to be very close to LS codes for measuring 2×8 MIMO channel. When the number of transmit antennas is more than 4, Kasami codes can be used to measure the MIMO channel with affordable degradation.

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.

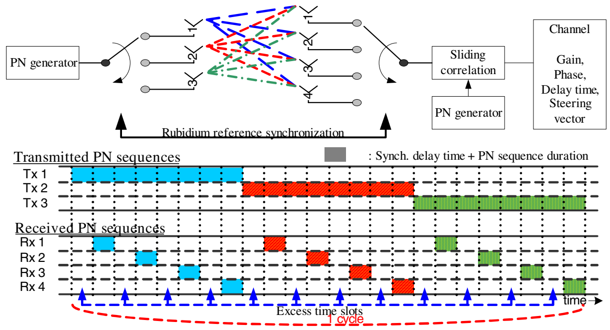
II. CODE DIVISION MULTIPLEXING BASED MIMO CHANNEL SOUNDING TECHNIQUE

A. The proposed channel sounding system

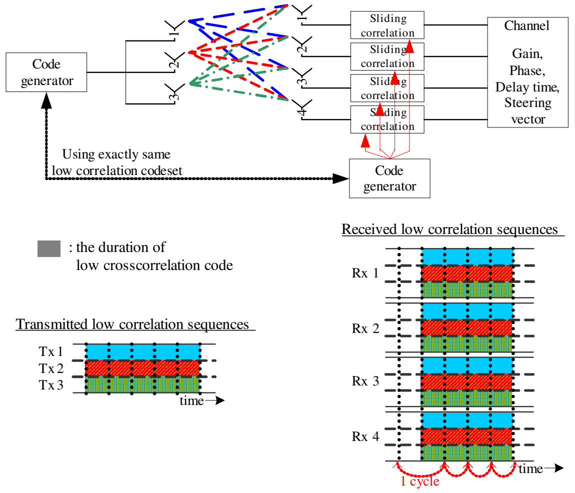
CDM-based MIMO channel sounding technique is depicted in Fig.1(b). A generated sounding signal adopting spread spectrum with low correlation codeset at the transmitter propagates to MIMO channel. At the receiver, the channel characteristic is observed after sliding correlation of the received signal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

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

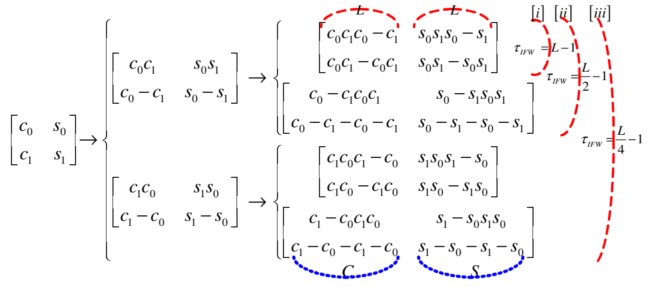


(a) Time-Division Multiplexing with synchronized switching based MIMO channel sounder

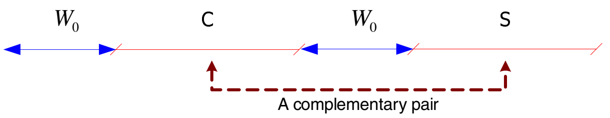


(b) Code-Division Multiplexing based MIMO channel sounder

Fig. 1. The basic principles of the sounding schemes

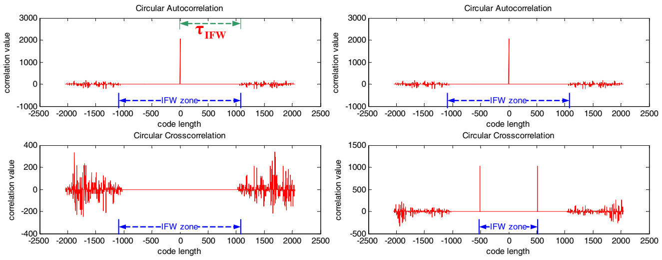


(a) Complementary pair generation



(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

are inserted between a complementary pair as shown in Fig.2 [10,11]. These LS codes have the time delay region which has no interference. This area calls interference free window (IFW) zone($= 2\tau_{IFW}+1$). If 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.

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

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) [10]. 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 [12]. 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 ($R_{xx}(0)$).

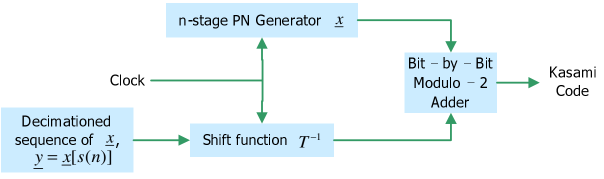


Fig. 4. The generation method of Kasami codes

LS codes have performance limit because of difficulty to extend IFW zone and to keep IFW zone when using larger 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 LS codes 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.

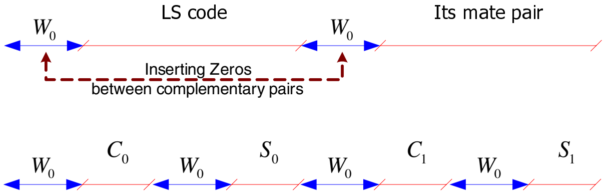
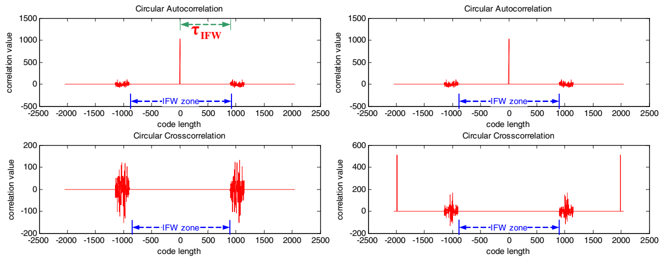


Fig. 5. Modified LS code generation using a mate pair of LS codes



(a) the correlation characteristics between mate pairs

(b) the correlation characteristics between other pairs

Fig. 6. Correlation property of MLS codes

C. rms Delay Spread

To describe multipath behavior of a radio propagation channel, the rms delay spread τ_{rms} is the most widely used statistical parameter [1]. To derive the rms delay spread from measured power delay profiles (PDPs), all relevant paths should be taken without knowledge of the channel effect [7]. 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, a certain threshold is 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.

$$T_{LS} = 10\log_{10}(PG) + E_C/N_0 - 10\log_{10}(Tx) \; [dB] \quad (2)$$

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.

$$\begin{aligned} T_K = & -20\log_{10}\left(\frac{Rxx'_{\max}}{Rxx \times \mathrm{P}_{\max}}\right) \\ & + 10\log_{10}\left(\frac{(Tx-1)+(1-P_{\max})}{P_{\max}}\right) \end{aligned} \quad [dB] \quad (3)$$

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 delay spread τ_{rms} is as follows.

$$\tau_{rms} = \sqrt{\frac{\int_{-\infty}^{\infty} (\tau - \tau_{mean})^2 P_g(\tau) d\tau}{\int_{-\infty}^{\infty} P_g(\tau) d\tau}} \quad (4)$$

where τ_{mean} is mean excess delay

$$\tau_{mean} = \frac{\int_{-\infty}^{\infty} \tau P_g(\tau) d\tau}{\int_{-\infty}^{\infty} P_g(\tau) d\tau} \quad (5)$$

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. Then, the system using LS codes is expected to degrade the performance in the situation where there are longer excess delays. In other words, the system cannot cover the delay signals which have larger than 511 chip delay (5.11 μs in this simulation). Accordingly, Kasami codes and modified LS codes are applied to 4×8 MIMO radio channel. 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 [2]. This simulated channel generates 6 delay signals composed of 3 intra clusters individually. For testing the code properties, rms delay spread is obtained in multipath nature with urban macro (typical metropolitan) and suburban macro (rural) scenario. Those scenarios show the largest and the smallest rms delay spread respectively (urban macro = 680 ns, suburban macro = 170 ns [3]) in the model.

IV. RESULT

The results are analyzed separately in accordance with the scenarios. The purpose of analyzing these results is to find which codes have better performance in each scenario. The reference of the performance analysis is cumulative density function (CDF) of absolute rms delay spread error. The focus is how much the absolute rms delay spread error is when CDF has the value 95%.

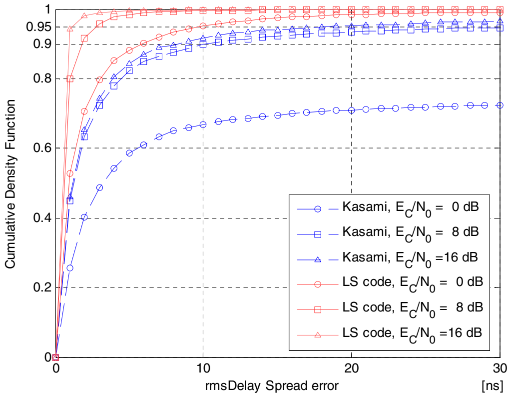


Fig. 7. Absolute error of rms delay spread in 2 × 8 suburban macro channel (LS codes, Kasami codes)

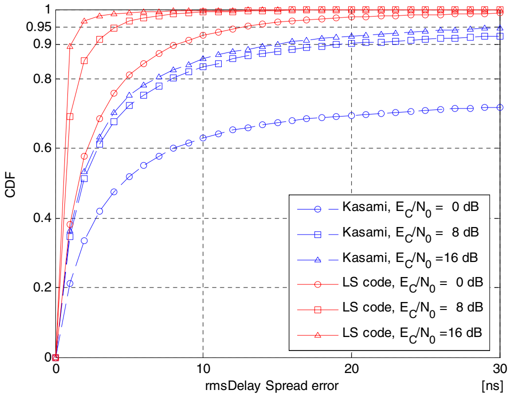


Fig. 8. Absolute error of rms delay spread in 4 × 8 suburban macro channel (LS codes, Kasami codes)

A. *Suburban macro environment*

We start with 2 × 8 MIMO channel measurement. In Fig.7, the system using LS codes has better performance than that of the system using Kasami codes with any E_C/N_0. The remarkable point is that the absolute rms delay spread error when CDF has the value 95% is significantly less than system resolution, 10 ns. It means that the sounder with LS codes approaches the almost perfect channel measurement in 2 × 8 suburban macro environment.

Fig.8 and Fig.9 show that the performance is maintained in 4×8 suburban macro environment with slight degradation and the performance of the system using modified LS codes has somewhat better performance than that of the system using LS codes because of the extended length of IFW zone.

The system using Kasami codes also has good performance but its performance is less than that of LS codes and modified LS codes. The reason is that the system using Kasami codes has higher threshold than the others. Repeatedly, Kasami codes do not fairly detect the small power signals than the others.

Actually, the IFW zone of LS codes sufficiently covers the delay signals in 4 × 8 suburban macro environment as the rms delay spread of suburban macro channel is only 170 ns. Almost all paths are inside IFW zone.

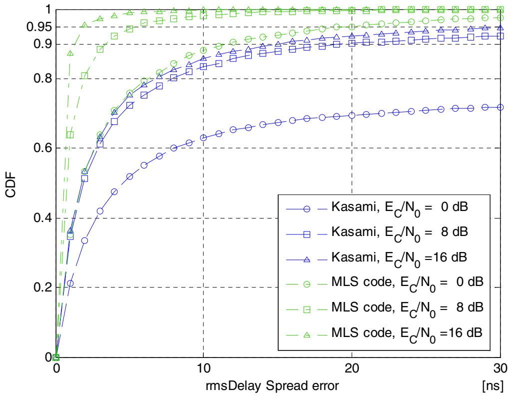


Fig. 9. Absolute error of rms delay spread in 4 × 8 suburban macro channel (modified-LS codes, Kasami codes)

In urban macro environment, however, the rms delay spread is large enough to make some paths exist outside of IFW zone. In consequence, the performance degradation is occurred.

B. *Urban macro environment*

With 2 × 8 MIMO channel measurement, the performance in urban macro channel does not show significant difference from suburban macro channel as shown in Fig.10. Even though one of the environments has the largest rms delay spread and another has the smallest rms delay spread in possible channel models of 3GPP SCME, both LS codes and Kasami codes cover the delay signals suitably.

With 4 × 8 MIMO channel measurement, the performance degradation is occurred to both. The system using LS codes cannot achieve the observation requirement which is that the CDF has the value 95% within 150 ns rms delay error. Kasami codes can fulfill the requirement, but the error is 70 ns as shown in Fig.11. It assumes that the channel sounder has significant error because it differs 22% from real rms delay

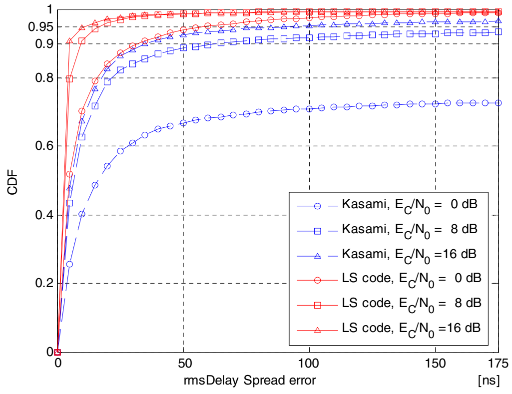


Fig. 10. Absolute error of rms delay spread in 2 × 8 urban macro channel (LS codes, Kasami codes)

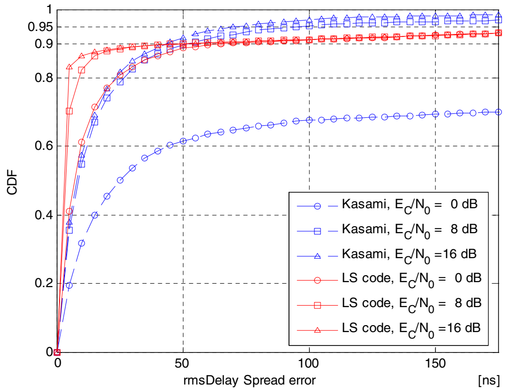


Fig. 11. Absolute error of rms delay spread in 4 × 8 urban macro channel (LS codes, Kasami codes)

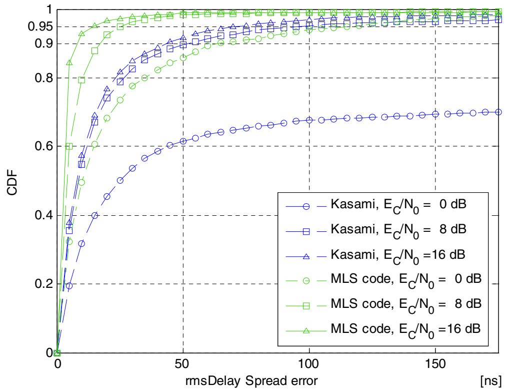


Fig. 12. Absolute error of rms delay spread in 4 × 8 urban macro channel (modified-LS codes, Kasami codes)

spread. Let we see the Fig.12. The performance of the system using modified LS codes is remarkable. The obtained rms delay spread error is 25 ns with $E_C/N_0 = 8$dB and 10 ns with $E_C/N_0 = 16$dB. This system achieves the error less than system resolution at high E_C/N_0. Consequently, the modified LS codes are useful to measure 4×8 MIMO radio channel.

The system using Kasami codes has the practically same performance for any channel scenarios, any number of transmit antennas, and any E_C/N_0 except 0dB. Of course, the slight degradation is occurred because of increasing the threshold level depending on the number of transmit antennas. As we already mentioned, the system using LS codes cannot be expected to measure the channel having many transmit antennas because of narrowed IFW zone. Also, the system using modified LS codes cannot be adopted to the channel having more than 4 transmit antennas. Accordingly, we would take Kasami codes when we do channel sounding with more than 4 transmit antennas. Then, we achieve similar performance with our results of Kasami codes. It is effective scheme in this case. Nevertheless, it requires some compensation against increasing threshold level. The one compensation method is extending the length of Kasami codes. The longer code length is used, the less correlation values are occurred.

V. CONCLUSIONS

In this paper, the code-division multiplexing based MIMO channel sounding technique with loosely synchronous codes and Kasami codes is introduced. The impact of imperfect system response on rms delay spread is analyzed in terms of the 3GPP Spatial Channel Model Extended. In suburban macro environment, the performance of rms delay spread error is similar to whenever the number of transmit antennas is 2 or 4. Accordingly, either LS codes or modified LS codes can be chosen to the channel measurement. In urban macro environment, the performance depends on the number of transmit antennas. For that reason, modified LS codes are chosen for any environment with either Tx=2 or Tx=4. Nevertheless, when the transmit antennas are increasing more than 4, modified LS codes cannot used because it is dedicated when Tx=4. LS codes cannot surmount the decreasing IFW zone when increasing the used codes. Consequently, Kasami codes would be taken for the channel measurement when the number of transmit antennas is more than 4. Then, the threshold would be slightly increasing, but this problem is solved with extending the code length.

VI. ACKNOWLEDGEMENT

This research was supported jointly by Samsung-ICU 4G Research Center and by the MIC, Korea, under the ITRC support program supervised by the IITA.

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