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Agenda item: **6.4 Uplink Reference Signals**

Source: **Lucent Technologies**

Title: **Precoded FDM Reference Signals for SC-FDMA**

Document for: **Discussion and Decision**

1 Introduction

Reference signal design is an important issue to fully exploit the potential benefit of the SC-FDMA system considered in the uplink of the E-UTRA. The reference signal is needed for uplink CQI estimation and coherent data demodulation. There has been on-going discussion on the uplink reference signal structure in RAN1. Pros and cons of CDM and FDM reference signal structures are summarized in [1-6]. In RAN1#44bis, combinations of CDM and FDM were agreed upon for further consideration as the uplink reference structure [7]. In this contribution we focus on the reference signal for coherent data demodulation. It has been generally agreed that FDM will be used for the reference signal for coherent demodulation in the case of localized data transmissions, while for distributed data transmission the reference signal for coherent demodulation may be either FDM or CDM [7]. We propose an FDM reference signal, in which the reference signal sequence is constructed by repetition of a CAZAC sequence with length equal to the basic resource unit size.

The FDM reference signal is advocated because it offers in-cell user orthogonality in the presence of fading. So far, comb-shaped pilot tones and staggered pilot structure are agreed as reference patterns for the FDM pilot [7]. One of the major drawbacks of the FDM reference signal, however, is the possibility of collision in the presence of strong co-channel interference. In particular, when two users at the cell edge use the same set of sub-carriers for the uplink reference signal, it may not be possible to reliably estimate the channel unless the pilot sequence is chosen carefully to provide some level of immunity to co-channel interference.

The main requirements of the SC-FDMA reference signal design can be summarized as follows:

1. Equal power channel sounding in the frequency domain
2. Immunity to co-channel interference
3. Support of users that have been assigned multiple resource units
4. Support of both localized and distributed sub-carrier mapping with reliable channel estimation performance
5. Efficient transmitter and receiver structure
6. Large number of sequences with the desired characteristic to support multi-cell deployment

To meet these design requirements, we propose to use a CAZAC sequence with length equal to the basic resource unit size as the FDM reference signal for coherent demodulation. For users allocated multiple resource units, repetition of the same basic resource unit length CAZAC sequence is used to generate a longer pilot sequence. The family of Generalized Chirp Like (GCL) sequence is an example of a type of CAZAC sequence that can be used. In the proposed scheme, in-cell users are orthogonal in the frequency domain, thus the same GCL sequence is reused for all users in the same cell. For neighboring cell users, different GCL sequences are used to exploit the desirable cross-correlation properties of the sequence.

In the following sections, we describe the proposed uplink pilot structure and the pilot sequence assignment rules. We analyze the potential benefits of using the proposed pilot structure and provide simulation results. Finally, we provide a text proposal for the proposed pilot structure.

2 Proposed Pilot Structure

The sub-frame structure is shown in Figure 1. The pilot is transmitted in the two short blocks. We address pilot structure for coherent data demodulation. The proposed coherent demodulation pilot may be transmitted in one or both short blocks.

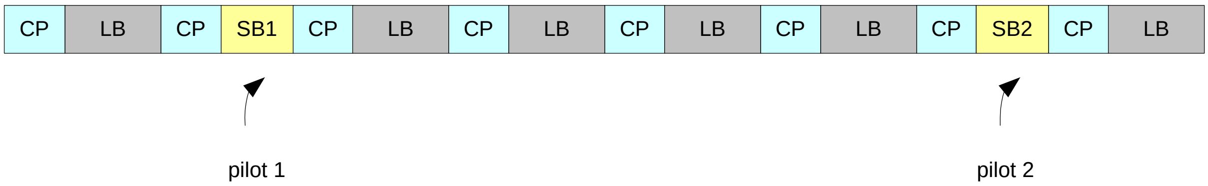


Figure 1: Sub-frame structure

The GCL sequence is a good candidate as a reference signal because of the following properties:

1. Unit magnitude in the transform domain
2. Optimal cyclic auto-correlation
3. Low, constant cyclic cross-correlation for odd-length sequence

Because of the low, constant cyclic cross-correlation property, the GCL sequence is an ideal candidate for the uplink reference signal. The Zadoff-Chu sequence is a special case of the GCL sequence. The co-channel interference power is suppressed by the cyclic cross-correlation value. Figure 2 shows the co-channel interference mitigation characteristic of the GCL sequence for sequence lengths ranging from 3 to 151. The full-length sequence has the capability to suppress the interference by up to 21.8 dB. Although the shorter sequence does not have these very low cross correlation values, we observe that most of the gain is obtained with shorter sequences. For the sequence lengths of 13 and 25, that correspond to the resource block sizes of 1 and 2, the interference can be suppressed by –11.1 dB and –14.0 dB, respectively. We use a short sequence that corresponds to the smallest resource block as the constituent sequence, and construct longer pilot sequences for the larger resource block.

2.1 Pilot Sequence Generation

A GCL sequence of length P is generated in the time domain. For example, the Zadoff-Chu sequence $c_p(n)$ of length P is generated as

$$c_p(n) = \begin{cases} \exp\left[\dfrac{j2\pi p}{P}\left(n + \dfrac{n(n+1)}{2}\right)\right] & \text{for P odd} \\ \exp\left[\dfrac{j2\pi p}{P}\left(n + \dfrac{n^2}{2}\right)\right] & \text{for P even} \end{cases}$$

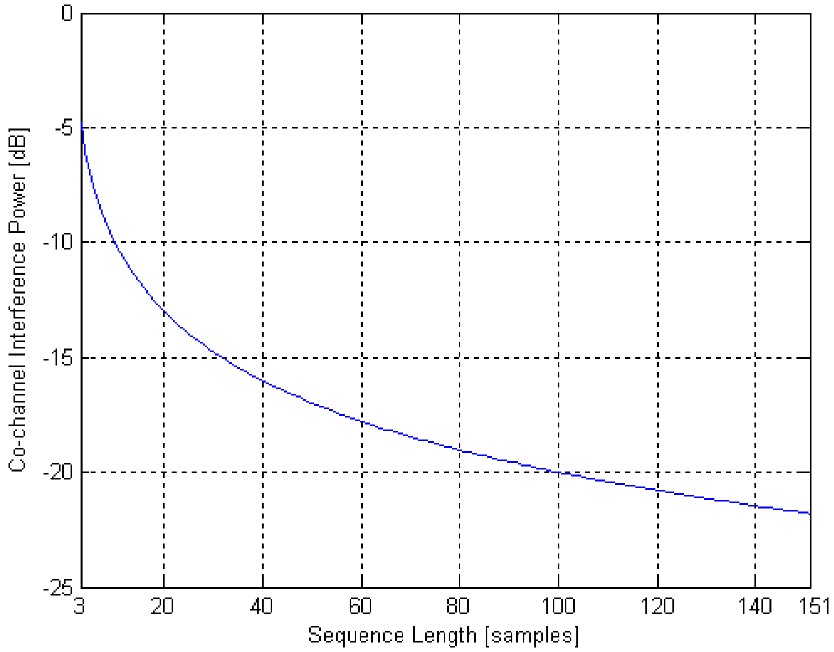


Figure 2: Co-channel interference mitigation characteristic of the GCL sequence.

The transmitter structure is shown in Figure 3. A GCL sequence of length P is used as the constituent sequence to generate the reference signal for users assigned multiple resource units. P is equal to the basic resource unit size. In the current numerology, the resource unit size for data transmission is 25 15-KHz subcarriers, which would make P equal to 12 or 13 30-kHz subcarriers For a user assigned S resource blocks, repetition by S results in a length (S x P) sequence (in Figure 3 we show the case of S = 2). The sub-carrier mapping generates localized or distributed FDM reference signals that correspond to the assigned resource blocks of each user's data transmission, be it localized or distributed. The resulting sequence is converted to time-domain by an N-point IFFT. After parallel-to-serial conversion, cyclic prefix (CP) is added before transmission.

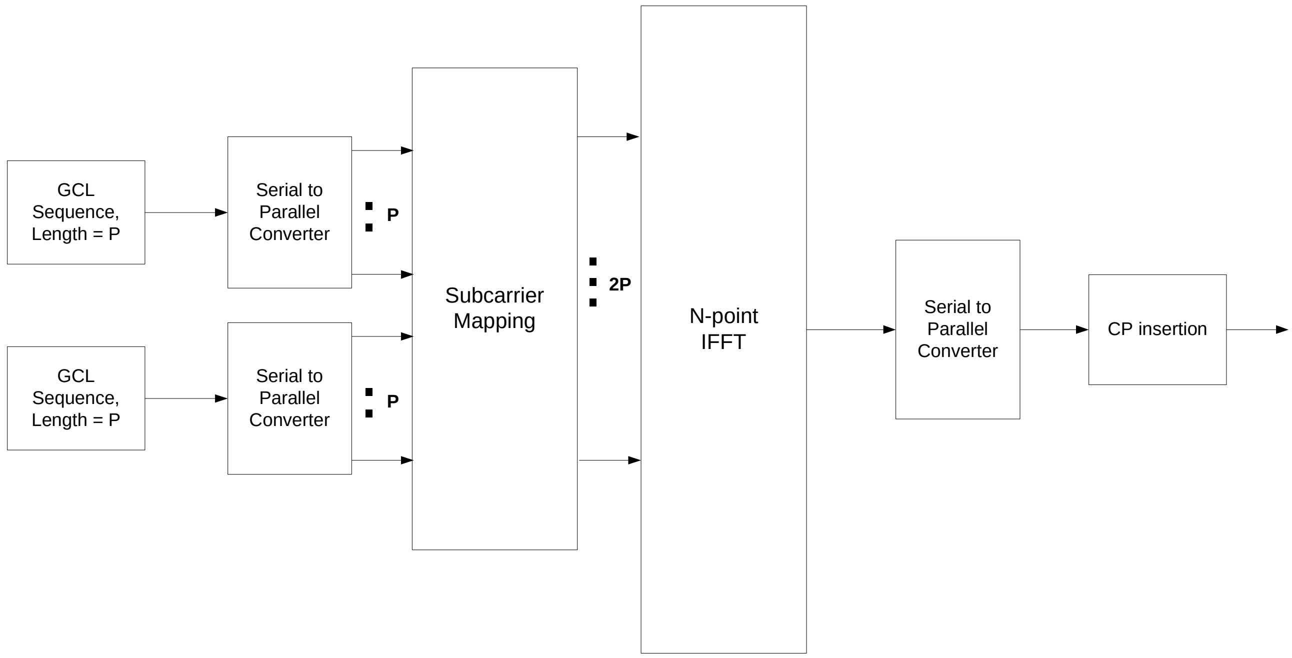


Figure 3: Transmitter structure of the proposed pilot. in the case of two resource units assigned for data transmission. P=length of the constituent sequence corresponding to the basic resource unit size for example in the current numerology this would be 12 or 13, corresponding to a resource unit size for the data transmission of 25 subcarriers.

Figure 4 illustrated the pilot structure in the frequency domain. Figure 4 (a) shows a localized pilot structure and Figure 4 (b) shows a distributed pilot structure. Suppose UEs 1 and 3 are assigned 2 basic resource units (S=2) and UEs 2 and 4 are assigned 1 basic resource unit (S=1). For UEs 1 and 3, repetition is used to generate a length-SxP reference sequence. For localized data mapping, pilot sub-carrier mapping generates the localized FDM pilot structure shown in (a). For distributed data mapping, the distributed FDM pilot structure shown in (b) may be used.

The main advantage constructing the reference signal from constituent sequences equal to the basic resource unit size is that such a choice will result in low cross-correlation between the reference signals of two cell edge users in adjacent cells, regardless of the number of resource units assigned to each user. This is illustrated with a simple example in Figure 5. In the example, if UE 1B had used a direct length 2P CAZAC sequence instead of using two length-P constituent CAZAC sequences, it would not retain low cross correlation with UE 1A and UE 2A.

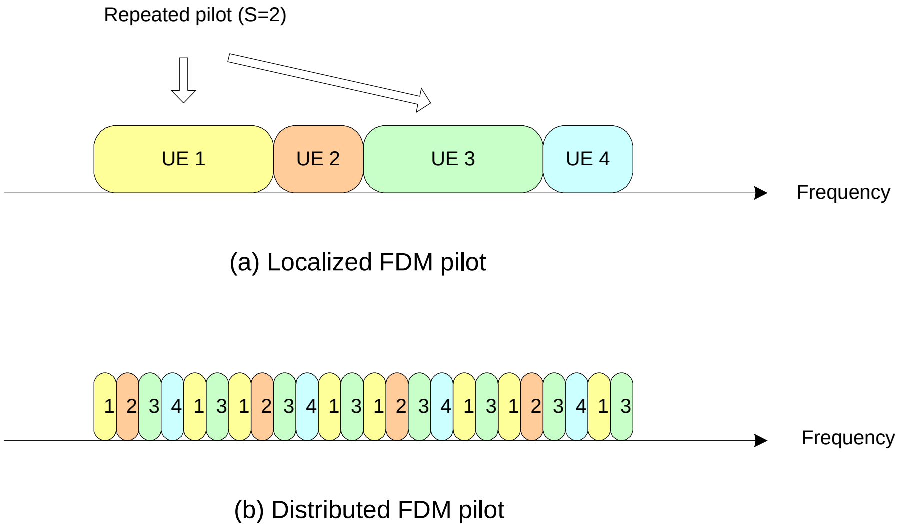


Figure 4: Illustration of the proposed pilot in the frequency domain. (Number of users = 4, S=2 for UEs 1 and 3 and S=1 for UEs 2 and 4)

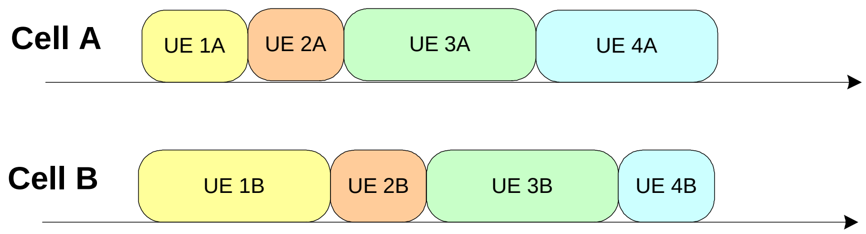


Figure 5: Using constinuent length CAZAC sequences equal to the resource unit size ensures low reference signal cross correlation between users in adjacent cells regardless of resource unit allocation. In this example, UE 1A and UE 2A in Cell A are assigned one resource unit while UE 1B in Cell B is assigned 2 resource units in the same frequency band as UE 1A and UE 2A. Because UE 1B uses two constinuent length CAZAC sequences for its reference signal, it retains low cross-correlation with both UE 1A and UE 2A.

The fact that a sequence that is CAZAC in the time domain is also CAZAC in the frequency domain allows us to apply the CAZAC sequence directly in the frequency domain for the transmitter. Note that in the receiver however we will exploit the cyclic autocorrelation property in the time domain to obtain channel estimates, as illustrated in Figure 6. Note that channel estimation is done per resource unit, hence will have reduced time resolution as the bandwidth of the constituent reference signal is only equal to the resource unit bandwidth (~375 kHz in the current numerology); however, we obtain multiple channel estimates, one for each resource unit.

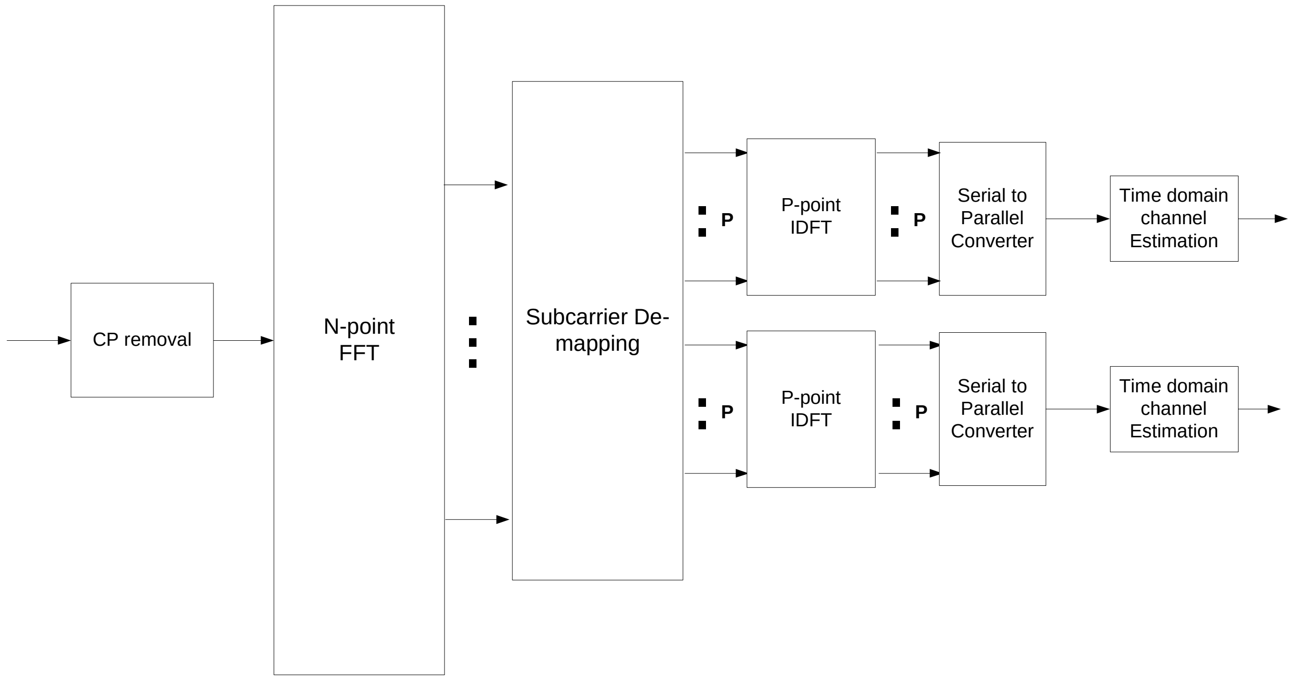


Figure 6: Receiver structure of the proposed pilot. Time domain channel estimation is performed over each resource unit separately.

2.2 Pilot Sequence Allocation

Figure 7 illustrates a pilot sequence allocation rule for a 3 sector system with clover-leaf shape. Length-13 GCL sequences are considered. There are 12 GCL sequences of length 13. As an example, an allocation scheme with 1/12 reuse of GCL sequence is shown in the figure. Pilot sequence can be allocated initially when a user is admitted to a cell, and does not need to be scheduled, which simplifies user configuration.

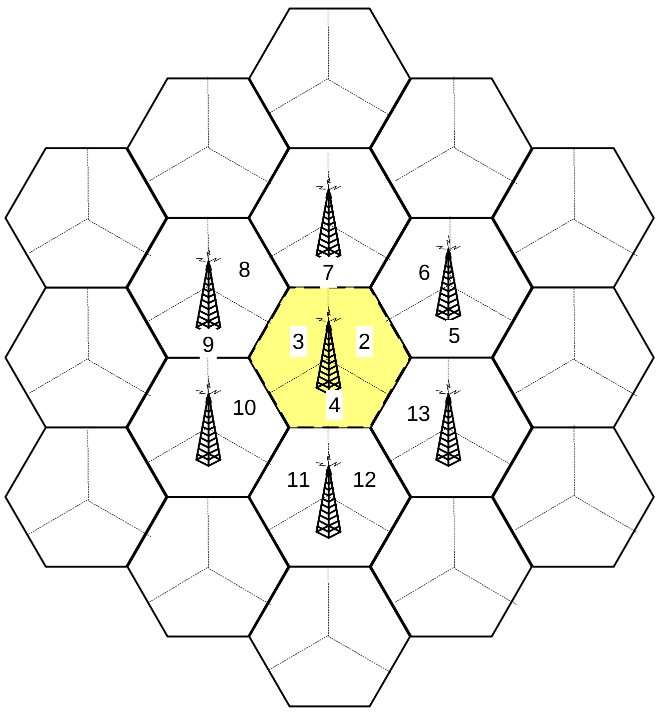


Figure 7: Illustration of pilot sequence allocation for neighboring cells. (Length-13 GCL sequence)

2.3 Sequence Length

The number of data sub-carriers in a basic resource unit is 25. On the average, 12.5 pilot sub-carriers may be allocated for each resource block. For 5 MHz bandwidth signal, the maximum number of users that can transmit simultaneously in a sub-frame is 12. There are a few options to generate the reference of desired length:

1. Option 1: Change in numerology

   When Short Blocks are used for pilot, the number of pilot sub-carriers available per resource unit may be 12 or 13. By using Long Blocks for pilot, each resource unit can have equal number of pilot sub-carriers.

2. Option 2: Change in numerology

   If the number of available sub-carriers for short block is increased from the current value 150 to 156, length-13 sequence may be used to construct the reference signal for all resource block sizes. This is the most desirable option from sequence design point of view.

3. Option 3: Usage of length 12 sequences

   Use 12 pilot sub-carriers for all resource blocks. Overall, 12 x 12 = 144 pilot sub-carriers are used from the 150 available sub-carriers. There are drawbacks of the length-12 GCL sequence though. There are only a small number of length-12 GCL sequences, and constant low cyclic cross-correlation property does not hold for an even-length sequence. Therefore, truncated length-13 GCL sequence could also be used instead, but the truncated sequences do not preserve the ideal cross-correlation properties.

4. Option 4: Alternating length 12 and length 13 sequences

   The number of pilot sub-carriers may be 12 for 6 resource blocks, and 13 for the other resource blocks to fit into 150 pilot sub-carriers. GCL sequence of length P=13 may be used for the block with 13 sub-carriers. Length-12 GCL sequence may be generated by truncating the length-13 GCL sequence.

3 Performance Aspects

3.1 Processing Gain

Using constituent CAZAC sequences with length equal to the basic resource unit size, we will suffer reduced processing gain (PG) compared to a larger length CAZAC sequence. However, even for P=13, processing gain of $\mathrm{PG} = 10 \times \log_{10}(13) = 11.1\ \mathrm{dB}$ is possible.

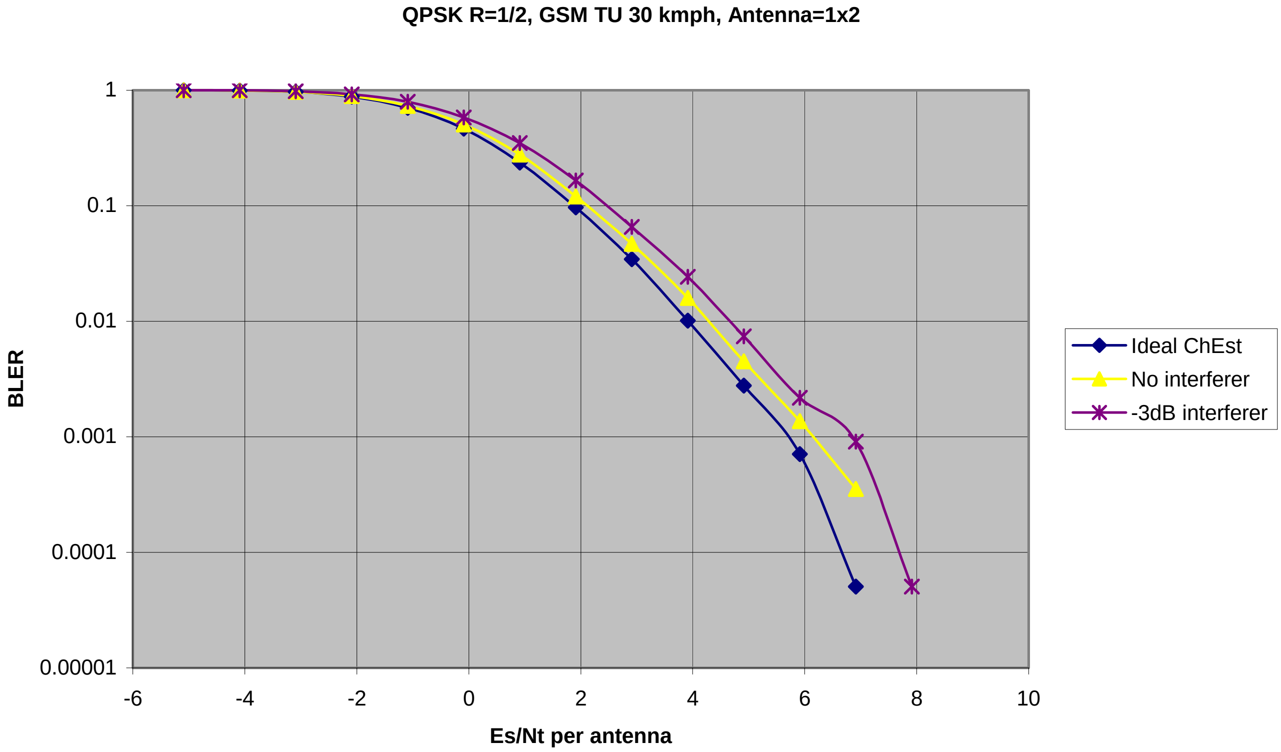
3.2 Other-cell Interference Mitigation

Using constituent CAZAC sequences with length equal to the basic resource unit size, we will reduced co-channel interference suppression compared to a larger length CAZAC sequence; however, as illustrated in Figure 2, even a length P = 13 we can obtain a significant –11.1 dB suppression.

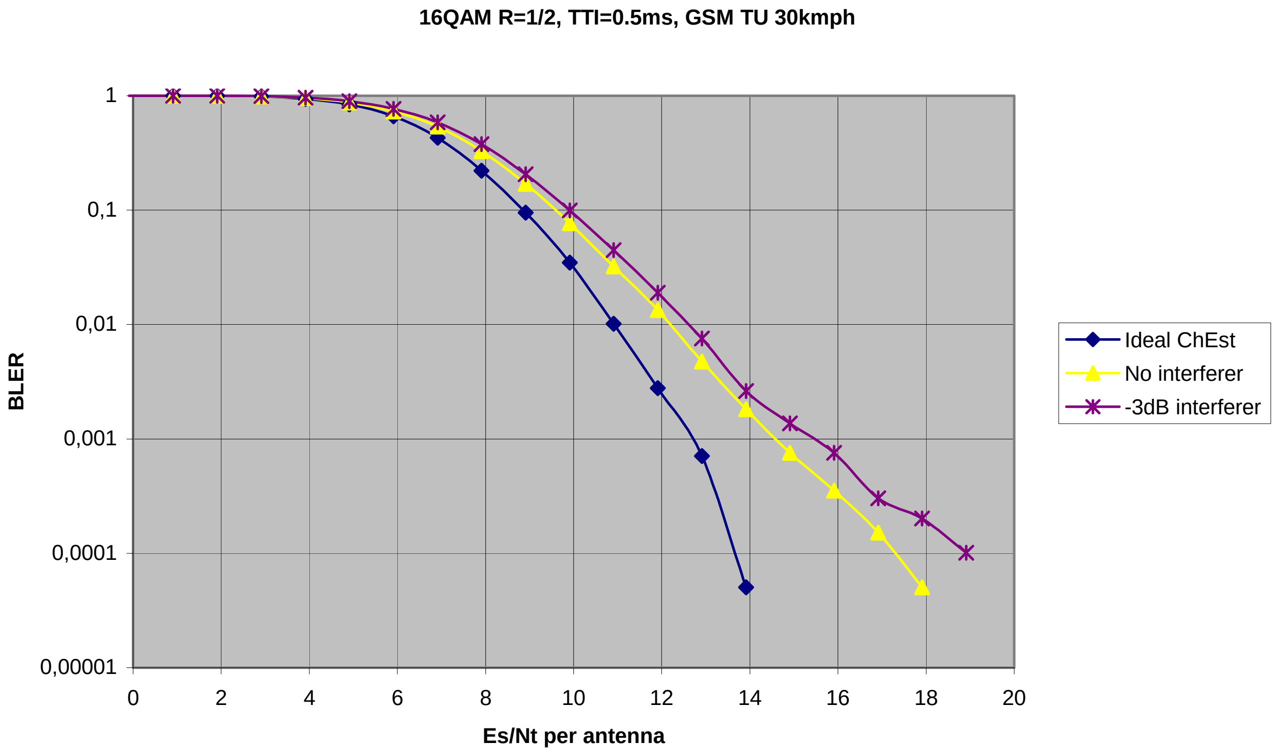
4 Simulation Results

Table 1: Simulation parameters

Transmission scheme	Localized SC-FDMA
Transmission Bandwidth	5 MHz
Sampling Rate	7.68 Msps
Sub-frame format	0.5 ms (6 LBs, 2 SBs)
TTI length	1 sub-frame
Number of pilot blocks	2 SBs
Data block size	512 samples per block
Pilot block size	256 samples per block
Cyclic prefix length	31 samples
Data modulation	QPSK, 16-QAM
Pilot sequence	FDM GCL
Pilot power offset from data	0 dB
Channel coding	Turbo, R=1/2
Antenna configuration	1 Tx, 2 Rx (uncorrelated)
Channel profile	GSM TU 6 Ray model
Fading model	Jakes fading (velocity = 30 kmph)
Channel estimation	LMMSE time-domain interpolation
Equalization	Frequency-domain MMSE equalizer
Time interpolation window size	5 sub-frames
LLR scaling	Ideal



(a)



(b)

Figure 8: Average BLER performance (a) QPSK (b) 16-QAM. Even in the presence of a –3dB interferer for the reference signal, a reference signal created using the reduced length GCL sequences provides good interference suppression.

5 Summary

We proposed an FDM pilot structure for detection and coherent demodulation of the SC-FDMA signal. In particular, we propose to use the CAZAC sequence with optimal cross-correlation property for use as the FDM reference sequence. Furthermore, we propose to use a constituent CAZAC sequence with the length corresponding to the basic resource unit and to use repetition to construct a longer reference sequences.

6 References

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