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1 Introduction

The random access channel (RACH) is used on the uplink of E-UTRA in order to notify the network that the UE has data to transmit, as well as to allow the Node B to estimate the timing of the UE. In WCDMA the RACH channel consists of a preamble and a message burst. There are multiple orthogonal preambles to allow simultaneous access of multiple UEs to the network. A message burst is transmitted after the Node B has acknowledged the successful reception of the RACH preamble.

In order to achieve low latency in accessing the network in E-UTRA it is desirable that the UE transmits at high power at the first transmission and avoids power ramping. It implies that the RACH preambles should allow for small power back-off in the UE's output power amplifier.

Another important factor to achieve low latency is the ability of the Node B to correctly detect several simultaneous random access preambles and to correctly estimate their timings. For that purpose, the RACH preambles should have the following properties: a) Good autocorrelation properties to allow for accurate timing estimation; b) Good cross-correlation properties to allow for accurate timing estimation of different simultaneous and asynchronous RACH preambles; and c) Zero cross-correlation for synchronous and simultaneous RACH preambles.

The RACH preambles in WCDMA satisfy to large extent all of the desired correlation properties. However, some of these properties, such as mutual cross-correlation, i.e. the detection probability of a single preamble in presence of a number of other simultaneous preambles still could be better at low SIR values.

The range of delays on which both out-of-phase autocorrelation and cross-correlation of RACH preambles should have low values is primarily determined by the maximum round-trip delay from the Node B to the UE, because the UE synchronizes its RACH transmissions to the timing of the broadcast pilot signals from the Node B. Depending on the length (duration) of RACH preambles, such low-correlation zone (of delays) of interest might be less than the length of the preambles. If that is the case, the sets of RACH preambles can be designed to have improved correlation properties for the delays of interest.

Thus in this contribution we deal with the design of the sets of RACH preambles for E-UTRA, with the major goal to reduce the latency of RACH procedure compared to the current UTRA system by improving preamble detection probability in presence of other simultaneous preambles. For certain applications it may be beneficial to transmit the RACH message immediately after the RACH preamble. This issue is investigated in [1].

In Section 2, the multiplexing of the random access channel is discussed. In Section 3 the RACH preambles based on zero correlation zone GCL sequences are proposed. In Section 4 the simulation results, both of the evaluation of the probability of preamble detection in presence of other received preambles, as well as of the evaluation of transmit power back-off, are presented. Finally, Section 5 concludes the paper.

2 Multiplexing of Random Access and Data Transmissions

According to the TR [2], the random access transmissions and data transmissions are multiplexed in time and/or frequency. Such orthogonal multiplexing allows for random access transmissions at high initial transmission power and thus low latency. The drawback of the orthogonal multiplexing is that resources are allocated to random access that may not be used. To reduce such waste of resources, the amount of resources allocated to RACH preambles can be semi-static and decided on the estimated need for random access transmissions.

Code division multiplexing (CDM) has also been proposed [3]. With CDM, specific resources that may not be used by the random access channel are not allocated. However, there is interference between the random access transmissions and the data transmissions. In [3] the interference analysis is based on the pre-condition that the RACH preambles are sent with the appropriate power for good detection probabilities. To achieve that, an accurate power control like power ramping in WCDMA is needed. Such ramping increases latency and is not desirable.

In order to minimize the latency we propose hybrid TDM/FDM for multiplexing of the RACH preamble and data in accordance with [2].

3 Zero Correlation Zone GCL Sequences

The starting point for the design of the new RACH preambles with improved correlation properties is the application of the sets of so-called Zero Correlation Zone (ZCZ) sequences. Namely, a set of ZCZ sequences consists of equal-length sequences whose periodic out-of-phase autocorrelation is zero over the range of delays $|p|\leq D$, while the periodic cross-correlation between any two sequences from the set is zero in the same range of delays $|p|\leq D$, which is referred to as a ZCZ. For given length of sequences, N, and given number of sequences in the set, M, the upper bound of the length D of the ZCZ is given by [4]

$$D\leq N/M-1. \quad (1)$$

Having in mind possible efficient implementation of the corresponding bank of matched filters for the new RACH preambles, as well as compatibility with the structure of RACH preambles in UTRA system, in the sequel we shall consider a new general ZCZ sequence sets that are defined as the orthogonal sets of Generalized Chirp-Like (GCL) sequences [5]. A GCL sequence $\{c(k)\}$ is defined as

$$c(k) = a(k)b(k \bmod m), \quad k = 0,1,\ldots,N-1. \quad (2)$$

where $N=sm^2$, s and m are positive integers, $\{b(k)\}$ is a “modulation” sequence of m arbitrary complex numbers of unit magnitude, while $\{a(k)\}$ is a special “carrier” sequence, which has to be a Zadoff-Chu sequence defined as

$$a(k) = W_N^{k(k+N \bmod 2)/2+qk}, \; k=0, 1, \ldots, N-1, \quad (3)$$

where $W_N=\exp(-j2\pi r/N)$, r is relatively prime to N, and q is any integer.

Any GCL sequence has an ideal periodic autocorrelation function. If the two GCL sequences $c_x(k)$ and $c_y(k)$ are defined by using the *same* Zadoff-Chu sequence $\{a(k)\}$ but different, *arbitrary* modulation sequences $\{b_x(k)\}$ and $\{b_y(k)\}$, it can be shown (similar as in [6], see the Appendix) that the periodic cross-correlation θ_{xy}□(p), defined as

$$\theta_{xy}(p) = \theta_{yx}(-p) = \sum_{k=0}^{N-1} c_x(k)c_y^*(k+p),$$

is zero for all time shifts $p\neq lsm$, $l=0,1,\ldots,m-1$, i.e.

$$\theta_{xy}(p) = 0, \text{ for } 0<|p|<sm, \; sm<|p|<2sm, \ldots,(m-1)sm<|p|< sm^2. \quad (4)$$

Thus, if the above two modulation sequences are orthogonal, the resulting GCL sequences will be not just orthogonal, but also will have a Zero Correlation Zone (ZCZ) of length sm-1, i.e. the periodic cross-correlation between any two sequences from the set will be zero for all the delays between $-sm$ and $+sm$. Based on this property, the set of m preambles is defined by the following construction:

Construction: The set of orthogonal GCL sequences is obtained by modulating a common Zadoff-Chu sequence $\{a(k)\}$ of length $N=sm^2$ with m different orthogonal modulation sequences $\{b_i(k)\}$, $i=0,1,2,\ldots,m-1$, $k=0,1,2,\ldots,m-1$.

Although the matched filters for RACH preambles actually calculate the *aperiodic* auto/cross-correlations, it is expected that the ideal periodic cross-correlation properties will be to large extent preserved. The reason is that for delays between $-sm$ and $+sm$, typically much smaller than the length of the sequences, the summations in the formulas for the aperiodic and periodic cross-correlation values only differ in a small number of terms. This expectation is confirmed by numerical evaluations, as it will be shown later.

It can be seen that the above general construction produces the sets of ZCZ sequences with maximum length $D=sm-1$ of the ZCZ for given sequence length $N=sm^2$ and given number of sequences in the set $M=m$, i.e. D satisfies the upper bound (1).

3.1 Some Interesting Special Cases of Orthogonal GCL Sequence Sets

The most obvious choices for the selection of orthogonal modulation sequences would be either the sets of Hadamard sequences or Discrete Fourier Transform (DFT) sequences. The set of DFT sequences is defined as

$$b_i(k) = W_m^{ik}, \quad i,k = 0,1,\ldots,m-1. \tag{5}$$

The set of Hadamard sequences is defined as the rows in an mxm Hadamard matrix, which is defined as follows: A Hadamard matrix $\mathbf{H}_\mathrm{m}$ of order m consists of only 1s and -1s and has the property $\mathbf{H}_\mathrm{m}\mathbf{H}_\mathrm{m}{}^T=m\mathbf{I}$ where $\mathbf{I}$ is the identity matrix and ^{T} denotes transpose. For $m=2^n$, where n is a positive integer, Hadamard sequences can be defined as

$$b_i(k) = (-1)^{\sum_{l=0}^{m-1} i_l \cdot k_l}, \quad i,k = 0,1,\ldots,m-1, \tag{6}$$

where i_l, k_l are the bits of the m-bits long binary representations of integers i and k.

3.2 Design of Numerical Parameters of the Proposed RACH Preambles

The question is now how to select the actual numbers m and N to fit into the requirements of E-UTRA. The access slot, i.e. the time-frequency resource allocated for RACH, has a duration T_A and can be confined to a sub-band of the total available spectrum. In order to distinguish which cell a transmitted RACH preamble is intended for, the access slots in adjacent cells should as much as possible be separated in time and frequency.

The duration of the preamble is denoted by T_S and is given as the quotient of the sequence length N and the bandwidth B of the RACH preamble: $T_S=N/B$. The maximum round-trip time, $\tau_d=2R/c$, where R is the cell range (radius) and c is the speed of light. The performance targets for E-UTRA are required to be met for cell ranges up to 5 km and to be met with slight degradation for cells ranges up to 30 km. The specifications should not preclude cell ranges up to 100 km [7].

The maximum delay spread, τ_s, depends on the environment. T_S should be shorter than T_A to avoid that the received signal extends after the access slot. Let τ_m be the sum of the maximum round-trip time and the maximum delay spread: $\tau_m=\tau_d+\tau_s$. Then $T_S< T_A - \tau_m$, so it follows

$$N < (T_A - \tau_m)B. \tag{7}$$

The duration of the ZCZ is equal to D/B, and should be greater than the total maximum delay τ_m.

Since $D=sm-1$ and $N=sm^2$, D can be expressed as $D=N/m-1$. Hence,

$$N/m-1 > \tau_m B. \tag{8}$$

Replacing N with the right-hand side of (7), it follows that

$$m < (T_A - \tau_m)/(\tau_m+1/B). \tag{9}$$

The bandwidth B has to be larger than the inverse of the required accuracy of the time-of-arrival estimation, which is much smaller than the shortest duration of the cyclic prefix, 3.65 μs [2]. τ_m is typically of the order of several microseconds and hence is much greater than $1/B$. It can be seen from (9) that the number of sequences in the set is then almost independent of B. Therefore, in order to use the spectrum efficiently, B should be as small as possible. The total number of preambles in a cell can then be increased by allocating several sub-bands for RACH. The number of preambles can also be increased by using several sets of GCL-sequences with different values of r. We select B to be 1.024 MHz, which gives a time-of-arrival estimation resolution of close to 1 μs. It also gives a margin to the minimum uplink nominal bandwidth, which is 1.25 MHz.

In the numerical design, T_A is first selected to give a large enough number of signatures as given by (9). Then, m and s should be selected such that (7) and (8) are satisfied. In order to fulfill the different requirements for various cell ranges we propose four different parameter sets, as shown in Table 1.

Table 1 Numerical parameters of RACH preambles

R (km)	T_A(ms)	$\tau_d(\mu s)$	τ_s (μs)	m	N
5	0.5	33	5	10	400
13	0.5	87	5	4	400
30	1.0	200	20	3	792
100	3.0	667	20	3	2367

As an example of extending the set of preambles consider the case of R=13 km. From Table 1, N=400 and there are 160 valid choices of r for which r and N are relatively prime. As a bandwidth of 5 MHz accommodates four 1.25 MHz wide subbands, there are then 4·4·160=2560 possible preambles.

4 Simulation results

Three kinds of evaluations are performed. First, the aperiodic cross-correlation functions of the GCL sequences are investigated, to confirm that the properties are similar to the ideal periodic cross-correlation functions. Then, the detection performance, in particular in the presence of interfering preambles, of the GCL sequences is compared to the performance of truncated WCDMA RACH preambles. Finally, the impact of the proposed sequences on the transmit power back-off is evaluated. The parameters of the GCL sequences are N=400 (s=25 and m=4), q=0, and r=1 throughout the section.

4.1 Aperiodic cross-correlation properties

The amplitude of the aperiodic cross-correlation function $\theta_{xy}(p) = \theta_{yx}^*(-p) = \sum_{k=0}^{N-1-p} c_x(k) c_y^*(k+p)$, $p \geq 0$, where p is the delay and "*" denotes complex conjugate, is shown in Figure 1, for the GCL-DFT sequence. The set of GCL-Hadamard sequences has similar autocorrelation and cross-correlation functions.

The peaks of the cross-correlation functions are located near multiples of sm=100. However, for the given parameters, the cross-correlation functions do not exceed 20 for delays less than 96.

4.2 Detection probability

The detection performances of the proposed preambles have been evaluated by link-level simulations. The truncated WCDMA RACH preamble has been used as a reference with modulating Hadamard sequences that are 4 bits long, instead of 16 bit long sequences, to keep the same number of signature sequences as for the proposed sequences.

The number of receive antennas is two and correlations from the two antennas at the same delay are combined non-coherently, i.e. the absolute values of the squared matched filter outputs from the two antennas at the same delay are added. The propagation channels simulated are AWGN and Typical Urban (TU) at 3 km/h.

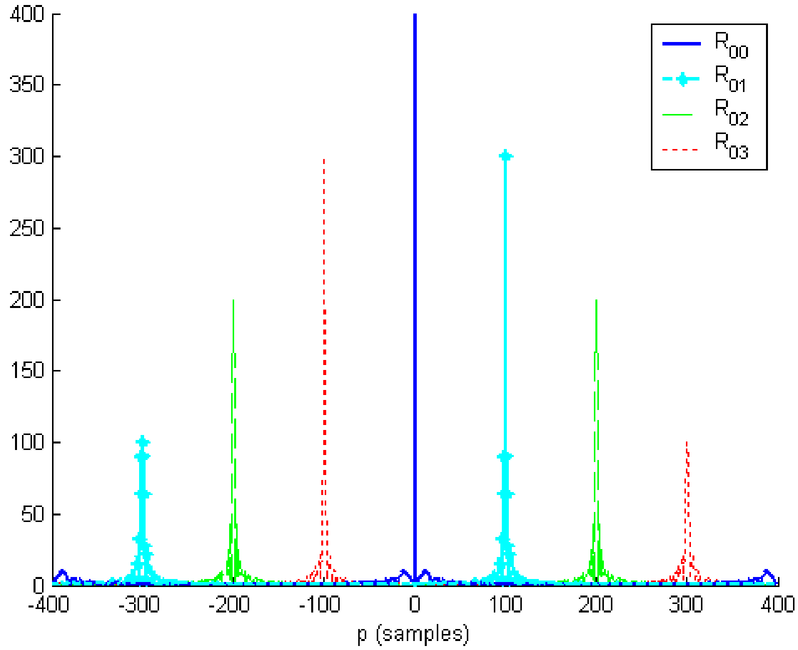

Figure 1 Absolute values of the autocorrelation and cross-correlation functions of the GCL-DFT sequences.

The detector correlates the received signal with all possible preambles in the search window. A threshold is set to give a false alarm probability of 0.0001 at a single delay. Missed detection is declared if the transmitted preamble is not detected within the true range of delays of received signal replicas. The number of concurrently transmitted preambles ranges from 1 to 4. All preambles are transmitted with independent random delays within the search window, corresponding to randomly distributed mobiles in the cell. If two or more different preambles are transmitted using the same time-frequency resources, the signal-to-noise ratio (SNR) of the observed preamble (whose probability of missed detection is evaluated) is fixed (SNR = -15 dB) and the other interfering preambles are transmitted with various power offsets to the observed preamble. However, all interfering preambles are transmitted with the same power.

As it is not yet decided whether a message will be transmitted in conjunction with the RACH preamble, we also consider RACH bursts with the preamble immediately followed by a message. The message is modelled as a random sequence of QPSK symbols; the sequence has the same length and is transmitted with the same power as the preamble. Simulation results with a message are only shown for the worst case of four transmitted RACH bursts.

The probabilities of missed detection of the observed preamble as functions of SNR are shown in Figure 2, for the case of a single transmitted preamble without message, both on AWGN and TU channels. The probabilities of missed detection of the observed preamble as functions of signal-to-interference ratio (SIR), in presence of interferers, are shown in Figures 3 and 4 for AWGN and TU channels respectively. The SIR is defined as the ratio of the power of the observed preamble to the power of any of the interfering preambles.

From Figure 2 it is clear that there is no difference in the probability of missed detection in the absence of interfering sequences between WCDMA RACH preambles and the proposed preambles. The probability of missed detection does not change when the message is sent immediately after the preamble (not shown). However, the results shown in Figures 3 and 4 clearly demonstrate significantly improved detection performance of the proposed preambles in the presence of one or several interfering sequences. For the proposed set of RACH preambles, the detection performance does not change with an increased number of interferers, whereas for the WCDMA preambles the performance deteriorates as the number of interferers

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