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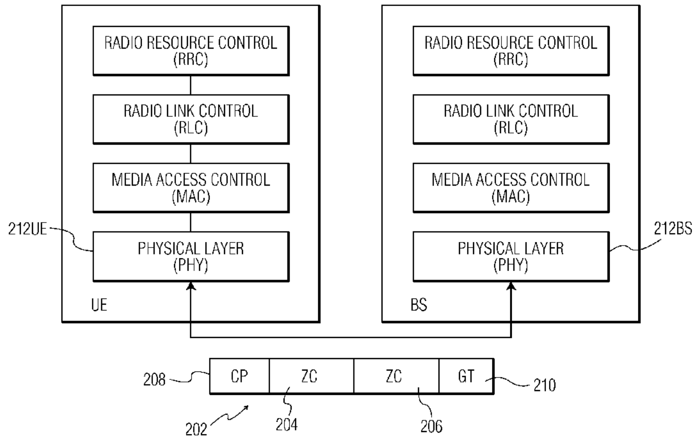

FIG. 2

(57) Abstract: A random access preamble scheme involves generating first and second preambles, each preamble having at least two Zadoff-Chu (ZC) sequences, with the ZC sequences of the first preamble being different from the ZC sequences in corresponding positions of the second preamble. For example, between two different preambles that each have two different ZC sequences, the first ZC sequences of the two preambles are different from each other and the second ZC sequences of the two preambles are different from each other. In another embodiment, a receiving scheme involves transforming received ZC sequences into transformed ZC sequences. In an embodiment, the received ZC sequences are transformed by correlating the received ZC sequences with their one chip cycle-shifting sequence. Transformed ZC sequences can be used for correlation detection in a multi- user wireless communications system.

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DESCRIPTION

RANDOM ACCESS PREAMBLE AND RECEIVING SCHEMES FOR WIRELESS COMMUNICATIONS SYSTEMS

The present invention relates to wireless communications systems, more particularly to preamble and receiving schemes used in wireless communications systems.

A mobile cellular phone system re-uses frequency spectrum by dividing spatial coverage into cells, each cell re-using the same frequency spectrum. Fig. 1 illustrates this in simple fashion, showing cell 102 with base station (BS) 104 and user equipment (UE) 106A, 106B, and 106C. In practice, a UE is a communication device making use of cellular phone technology, such as for example a cell phone, or a computer with a wireless card. A UE may be stationary, or may be in a moving vehicle. For simplicity, only three UEs are illustrated in cell 102, but in practice there will be a much larger number of such devices within any single cell.

Various signaling schemes may be employed to allow multiple UEs sharing a cell to communicate with a BS in the cell. Examples include TDMA (Time Division Multiple Access), FDMA (Frequency Division Multiple Access), CDMA (Code Division Multiple Access), and OFDMA (Orthogonal Frequency Division Multiple Access), to name a few. Some systems may utilize one signaling scheme for downlink communication (BS to UE), and another signaling scheme for uplink communication (UE to BS). Furthermore, a system may utilize different signaling schemes depending upon the information exchanged between a UE and a BS. For example, setting up a call between a UE and a BS may utilize a different signaling scheme than for the case in which the call has already been set up and voice or data content is in the process of being exchanged.

Current and future-contemplated cellular phone systems make use of a random access channel (RACH). A RACH is a contention-based communication channel, used to carry random access transmissions. For some cellular systems, the RACH channel may use the ALOHA protocol. However, other contention-based protocols may be used. The RACH channel when discussed at the physical layer (PHY) level may be referred to as a PRACH (Physical Random Access Channel).

A RACH channel may be used when a UE wishes to set up a connection with the BS in order to place an outgoing call. The RACH channel may be used for various signal processing purposes, such as for timing adjustments (synchronization), power adjustments, and resource requests, to name just a few. As a specific example, power adjustment may make use of the so-called open-loop power control protocol. In this protocol, a UE transmits a preamble to the BS, and if the BS does not acknowledge the preamble, then the UE transmits the preamble again, but at a higher power. This process continues until the received signal strength at the BS is strong enough for reception, at which point the BS sends an acknowledgement to the UE. Future RACH channels may utilize other protocols for power adjustment.

A PRACH burst comprises a random access (RA) preamble to identify the random access attempt. A RA preamble comprises a signature and a cyclic prefix, where the cyclic prefix is appended to the signature to help mitigate ICI (Inter-Channel Interference) and ISI (Inter-Symbol Interference). A UE may choose a specific RA preamble based upon a contention-based protocol. It has been proposed in the 3GPP LTE (3rd Generation Partnership Project Long Term Evolution) specification that a Zadoff-Chu (ZC) sequence is to be used for a RA signature. 3GPP is a collaboration agreement established in December 1998 for the purpose of establishing a specification for the 3G (3rd Generation) mobile phone system. 3GPP LTE is a project within the 3GPP to improve the UMTS (Universal Mobile Telecommunication System) mobile phone standard. See http://www.3gpp.org.

A mobile UE is subject to a Doppler frequency offset (DFO) when moving relative to the BS. For a high mobility UE, the resulting DFO may cause unacceptable detection errors in decoding the ZC sequences, resulting in a high false alarm rate. Some repetition-based schemes have been proposed in order to improve detection performance, but it is believed that such schemes do not completely overcome the DFO problem, especially under relatively severe DFO conditions.

A random access preamble scheme involves generating first and second preambles, each preamble having at least two Zadoff-Chu (ZC) sequences, with the ZC sequences of the first preamble being different from the ZC sequences in corresponding positions of the second preamble. For example, between two different preambles that each have two different ZC sequences, the first ZC sequences of the two preambles are different from each other and the second ZC sequences of the two preambles are different from each other. This ZC sequence diversity among preambles ensures ZC sequences from different UEs can be used at the same base station for correlation detection. In another embodiment, a receiving scheme involves transforming received ZC sequences into transformed ZC sequences. In an embodiment, the received ZC sequences are transformed by correlating the received ZC sequences with their one chip cycle-shifting sequence. Transformed ZC sequences can be used for correlation detection in a multi-user wireless communications system.

This summary is provided to introduce a selection of concepts in a simplified form that are further described below in the description of embodiments. this summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

Fig. 1 illustrates a prior art cellular phone system.

Fig. 2 illustrates protocol stacks for a UE and a BS, and a preamble structure, according to an embodiment of the present invention.

Fig. 3 illustrates a flow diagram according to an embodiment of the present invention.

Fig. 4 illustrates N different RACH preambles, 1, 2, 3,…N, in which the ZC sequences in corresponding positions are different from each other.

Fig. 5 depicts a RACH preamble that includes a cyclic prefix, two ZC sequences, and a guard time.

Fig. 6 depicts a RACH preamble with M ZC sequences.

Fig. 7 illustrates another flow diagram according to an embodiment of the invention.

Fig. 8 illustrates a mapping scheme in which a ZC sequence is transmitted via a single OFDM symbol.

Fig. 9 illustrates a mapping scheme in which the last chip of the previous ofdm symbol is inserted at the beginning of the latter ofdm symbol.

Fig. 10 is a graph of the probability of an incorrect detection (miss-detection) on the y-axis vs. the frequency offset (f_offset) on the x-axis.

Throughout the description, similar reference numbers may be used to identify similar elements.

In the description that follows, the scope of the term “some embodiments” is not to be so limited as to mean more than one embodiment, but rather, the scope may include one embodiment, more than one embodiment, or perhaps all embodiments.

Before describing the embodiments, a ZC sequence is described. A ZC sequence of length N may be represented as $\{a_u(k), k = 0, 1,\ldots, N-1\}$, where u is an index, $u = 0, 1,\ldots, N-1$, and may be referred to as the sequence index. A ZC sequence $\{a_u(k), k = 0, 1,\ldots, N-1\}$ may be generated by the expression:

$$a_u(k) = \exp(-j\pi u \frac{k(k+1)}{N}), k = 0,1,\ldots,N-1.$$

From the above expression, it is seen that $a_u(k)$ is periodic in the index u with a period equal to N. It is also readily observed from the above expression that the DFT (Discrete Fourier Transform) of a ZC sequence is another ZC sequence. That is, the DFT maps a ZC sequence into another ZC sequence of the same length. Consequently, the properties of the ZC sequences are the same whether considered in the time domain or in the frequency domain. For notational convenience, the ZC sequence $\{a_u(k), k = 0, 1,\ldots, N-1\}$ will be denoted by a_u.

Embodiments may be described with respect to the simplified protocol stack illustrated in Fig. 2, where a PRACH burst, labeled 202, is illustrated having a preamble comprising two ZC sequences, labeled 204 and 206. In addition to the two ZC sequences, PRACH burst 202 comprises cyclic prefix 208 and guard time 210. During guard time 210, PRACH burst 202 has no transmission. Embodiments may be implemented at the physical layer of a UE, labeled PHY layer 212UE, to provide bursts with preambles comprising two ZC sequences; and embodiments may be implemented at the physical layer of a BS, labeled PHY layer 212BS, to recover the preamble so as to identify the random access attempt. Some or all of the functions of a physical layer in either a UE or BS may be implemented by one or more ASICs (Application Specific Integrated Circuit), or by a FPGA (Field Programmable Gate Array), to name two examples.

From its definition, a ZC sequence is a sequence of complex numbers. As is well known, a complex number may be transmitted over a channel in the sense that its real component modulates the in-phase component of a bandpass signal, and the imaginary component modulates the quadrature component of the bandpass signal. Demodulation recovers the in-phase and quadrature components. In the case of OFDMA, an IDFT (Inverse Discrete Fourier Transform) is performed on the ZC sequences making up a UE RACH burst, followed by cyclic prefix insertion, and then up-conversion to an RF (Radio Frequency) carrier. Upon reception, the RF signal is down-converted to a baseband signal (complex-valued with in-phase and quadrature components), the cyclic prefix is removed, and a DFT is performed to recover the ZC sequences.

ZC sequences 204 and 206 in RACH burst 202 of Fig. 2 may be represented, respectively, by a_{u1} and a_{u2}. That is,

$$a_{u1}(k) = \exp(-j\pi u_1 \frac{k(k+1)}{N}, k = 0,1,\ldots,$$

and

$$a_{u2}(k) = \exp(-j\pi u_2 \frac{k(k+1)}{N}, k = 0,1,\ldots.$$

To avoid a subscript to a subscript, the index u_1 is written as $u1$ when serving as a subscript to ZC sequence 204. A similar remark applies to $u2$ and ZC sequence 206. Alternatively, the ZC sequences may be identified as ZC_{u1} and ZC_{u2}.

For a RACH burst having a preamble comprising the ZC sequences a_{u1} and a_{u2}, let $\hat{a}_{u1}$ denote the sequence at a BS recovered from the ZC sequence a_{u1}, and let $\hat{a}_{u2}$ denote the sequence at the BS recovered from the ZC sequence a_{u2}.

According to some embodiments, the preamble for a UE RACH burst comprises two ZC sequences with sequence indices u_1 and u_2 such that $0 \leq u_1 -$

$u_2 \leq N - 1$, where the difference $\Delta u \equiv u_1 - u_2$ identifies the UE RACH random access. At the BS, each term of the recovered sequence $\hat{a}_{u1}$ is divided by a corresponding term of the recovered sequence $\hat{a}_{u2}$ to yield a quotient sequence. If this quotient sequence yields a ZC sequence, then the index of the resulting quotient sequence is identified with Δu, and the random access attempt is thereby identified. In other words, if for each $k = 0, 1, \ldots, N - 1$, the quotient $q(k) \equiv \hat{a}_{u1}(k) / \hat{a}_{u2}(k)$ is such that $q(k) \equiv a_v(k)$, where $\{a_u(k), k = 0, 1, \ldots, N - 1\}$ is a ZC sequence of index v, then the difference Δu identifying the UE RACH random access is estimated as $\Delta u = v$.

The above description may be represented by the diagram of Fig. 3. The functions indicated by 302, 304, and 306 are performed by the UE. Two ZC sequences are generated (302) at the UE, denoted as a_{u1} and a_{u2}, followed by an IDFT (304). A cyclic prefix is inserted (306) after the preamble comprising a_{u1} and a_{u2}, and the RACH burst is transmitted over channel 308. The functions indicated by 310, 312, 314, 316, and 318 are performed by the BS. The cyclic prefix is removed (312), followed by a DFT (312). The sequences $\hat{a}_{u1}$ and $\hat{a}_{u2}$ are recovered (314). A division is performed (316) with $\hat{a}_{u1}$ the dividend and $\hat{a}_{u2}$ the divisor. Correlation Detection 318 identifies the resulting quotient as a ZC sequence, and the index of the quotient ZC sequence indentifies the UE random access.

It is expected that the above-described embodiments help mitigate DFO in the identification of a UE random access. This may be shown as follows. For an ideal OFDMA channel (noiseless and without ISI and ICI), the received sequences due to DFO may be expressed as:

$$\hat{a}_{u1}(k) = \exp(-j\pi u_1 \frac{k(k+1)}{N}) \exp(j2\pi\Delta f \frac{kT}{N}), k = 0,1,\ldots,N\,,$$

and

$$\hat{a}_{u2}(k) = \exp(-j\pi u_2 \frac{k(k+1)}{N})\exp(j2\pi\Delta f \frac{kT}{N}), k = 0,1,...,N,$$

where Δf is the frequency offset due to the Doppler shift in frequency and T is the length (in time) of a ZC sequence. The above expressions assume that the relative velocity of the UE to the BS is substantially constant over the signal time duration T. Dividing $\hat{a}_{u1}(k)$ by $\hat{a}_{u2}(k)$ for each k = 0, 1,..., N, yields the quotient sequence q, where:

$$q(k) \equiv \frac{\hat{a}_{u1}(k)}{\hat{a}_{u2}(k)} = \exp(-j\pi\Delta u \frac{k(k+1)}{N}) = a_{u1-u2}(k) = a_{\Delta u}, k = 0,1,...,N.$$

The phase factors $\exp(j2\pi\Delta f \frac{kT}{N}), k = 0,1,...,N$, in the expressions for $\hat{a}_{u1}$ and $\hat{a}_{u2}$ due to DFO are seen to cancel out upon division, so that the quotient sequence q is readily identified with the ZC sequence $a_{\Delta u}$. Furthermore, because the smallest period of each ZC sequence is N, and because the difference in sequence indices Δu is chosen by the UE to belong to the set of integers [0, N – 1], the UE random access is identified without ambiguity.

For a given preamble overhead, the above-described embodiment trades off the number of unambiguous preambles against the effects of DFO. For example, if the length of a preamble in symbols is denoted by N_P, then prior art systems using a single ZC sequence of length N_P allow for N_P unambiguous UE RACH random accesses in a cell, but at the expense of sensitivity to DFO. By using two ZC sequences in a preamble as in the above-described embodiment, the length of each ZC sequence is $N_P/2$ (assuming for ease of discussion that N_P is even) so that $N_P/2$ unambiguous UE RACH random accesses may be accommodated, but it is expected that such embodiments have greater robustness against the effects of DFO.

By using more than two ZC sequences in a preamble, a larger number of unambiguous random accesses in a cell may be accommodated, but false alarm rates may go up for such shorter ZC sequences. For example, some embodiments may be designed to have three ZC sequences, say a_{u1}, a_{u2}, and a_{u3}, and two quotient sequences may be derived, $q_{\Delta u1} = \hat{a}_{u1} / \hat{a}_{u2}$ and $q_{\Delta u2} = \hat{a}_{u2} / \hat{a}_{u3}$. The second sequence index difference, Δu_2, allows for additional degrees of freedom in identifying a UE RACH random access. However, the length of each ZC sequence is now reduced to (assuming N_P is odd) $N_P/3$, which increases the false alarm rate for a particular ZC sequence. Consequently, such types of embodiments trade off the number of allowable unambiguous random accesses against the undesirable properties of shorter ZC sequences.

Various modifications may be made to the described embodiments without departing from the scope of the invention as claimed below. For example, in the above-described embodiments, the first ZC sequence in a preamble was defined as the first (in order) sequence in a preamble when reading from left to right as shown in burst 202 in Fig. 2. However, this was merely chosen for convenience. Other embodiments may be described in which the “first” ZC sequence is the second (in order) sequence in a preamble, and the “second” ZC sequence is the first (in order) sequence in the preamble.

Furthermore, it should be appreciated that the ZC sequences are periodic in their sequence indices, with a period equal to N. This implies that $a_u = a_v$ if u is congruent to v modulo N. Accordingly, in describing the embodiments, the sequence indices may be restricted to the set of integers $[0, N-1]$ without loss of generality when describing ZC sequences. With this in mind, the embodiment of Fig. 3 may be generalized to where the difference Δu may be chosen from a set S of N integers, where no two integers in the set S are congruent modulo N to each other.

Utilizing two ZC sequences with different sequence indexes as described above with reference to Figs. 2 – 4 works well for additive white Gaussian noise

(AWGN) channels. However, the above-described technique does not take into account practical radio channel characteristics such as time-variation and multiple paths (i.e., multi-path fading). In situations where the DFO is relatively large, the channel impulse response of the different ZC sequences tends to vary greatly. As a result of the variation in the channel impulse response, the above-described division operation can cause new interference. For example, assume that two received ZC sequences, ZC_{u1} and ZC_{u2}, are expressed as:

$$\begin{cases} \hat{ZC}_{u1}(k) = h_1^k \exp\left(-j\pi u_1 \frac{k(k+1)}{N_G}\right) + S_1 \\ \hat{ZC}_{u2}(k) = h_2^k \exp\left(-j\pi u_2 \frac{k(k+1)}{N_G}\right).\exp\left(-j2\pi\Delta f \frac{N_{dif}T_s}{N_G}\right) + S_2 \end{cases}$$

where h_1^k, h_2^k represent the frequency domain channel impulse responses, S_1 and S_2 represent the respective inter-carrier interference (ICI) of the two ZC sequences, N_G is the length of the respective ZC sequences, Δf is the DFO, T_s is the sampling period, and N_{diff} is the time difference between the two ZC sequences. Without considering the ICI, the result of a division operation can be expressed as:

$$ZC_{u1-u2}(k) = \hat{ZC}_{u1}(k) / \hat{ZC}_{u2}(k) = \frac{h_1^k}{h_2^k} \exp\left(-j\pi (u_1 - u_2) \frac{k(k+1)}{N_G}\right) \exp\left(-j2\pi\Delta f \frac{N_{dif}T_s}{N_G}\right)$$

Given the expression of the division operation, it can be seen that for a radio channel exhibiting fast variation, h_1^k and h_2^k will lead to significant deterioration in receiver performance.

In order to take into account practical channel characteristics such as time-variation and multipath fading, improved de-correlation performance is achieved if the two ZC sequences and the result of a division operation between the two ZC sequences (i.e., the quotient) can be used in correlation detection at the receive side. In order to ensure that both ZC sequences of a preamble and the quotient of the two ZC sequences can be used in correlation detection, the ZC sequences of one RACH preamble are different from the ZC sequences in corresponding positions of other RACH preambles. For example, between two different preambles that each have two different ZC sequences, the first ZC sequences of the two preambles are different from each other and the second ZC sequences of the two preambles are different from each other. In an embodiment, ZC sequence diversity among preambles is ensured by setting *N* to an integer that cannot be evenly divided by an integer from 2 to M. Per-preamble ZC sequence diversity enables preambles from different UEs to be easily distinguished from each other. In another embodiment, the per-preamble ZC sequence diversity is extended to more than two preambles. That is, the ZC sequences in corresponding positions among a group of more than two preambles are all different from each other. Fig. 4 illustrates N different RACH preambles 402 (identified as preambles 1, 2, 3,...N), with each preamble including a cyclic prefix 408, two ZC sequences 404 and 406, and a guard time 410. Among the N different preambles, the ZC sequences in corresponding positions are different from each other. That is, ZC sequence 11 (ZC_{11}), ZC_{21}, and ZC_{N1} are different from each other and ZC_{12}, ZC_{22}, and ZC_{N2} are different from each other. In an embodiment, in order to employ both of the ZC sequences of a preamble for de-correlation, the ZC sequences and the quotient are uniquely identifiable by an index. For example, if the ZC sequences are identified as ZC_{s1}, ZC_{s2}, where s = 1, 2, 3,...,N, then ZC_{s1}, ZC_{s2}, and ZC_{s2}/ZC_{s1} should be uniquely defined by the index s.

As described above, the ZC sequences in different preambles are selected such that the division operation between different received ZC sequences in a first preamble yields a result that is different from the division operation between different ZC sequences in a second preamble. In still another embodiment, this division-result diversity is extended to more than two preambles, e.g., to the N preambles depicted in Fig. 4.

In an embodiment, within a preamble, one ZC sequence of the preamble has a sequence index, u, and the other ZC sequence has a sequence index that is an integer multiple of u, e.g., 2u. An exemplary embodiment of such a preamble is described with reference to Fig. 5. Fig. 5 depicts a RACH preamble 502 that includes a cyclic prefix 508, two ZC sequences 504 and 506, and a guard time 510. In the RACH preamble of Fig. 5, ZC sequence 504 has a sequence index u and ZC sequence 506 has a sequence index 2u, where $0 \leq u \leq N - 1$.

In the embodiment of Fig. 5, the RACH preamble includes two different ZC sequences. In another embodiment, one RACH preamble includes more than two ZC sequences, for example, M ZC sequences. Fig. 6 depicts a RACH preamble with M ZC sequences, in which ZC sequence 504 has a sequence index u, ZC sequence 506 has a ZC sequence index 2u, ZC sequence 512 has a ZC sequence index 3u, and ZC sequence 514 has a ZC sequence index Mu.

In an embodiment, the number of available RACH preambles should be as large as possible. A large RACH preamble space enables more UEs to randomly access the wireless resources of the base station.

Receiving Scheme

In accordance with another embodiment of the invention, a receiving scheme involves transforming received ZC sequences into transformed ZC sequences. In an embodiment, the received ZC sequences are transformed by correlating the received ZC sequences with their one chip cycle-shifting sequence. The transformed ZC sequences are referred to herein as the ZC transforms, ZCT. A ZC transform is less influenced by radio channel variation because the channel characteristics of adjacent sub-channels vary slightly and can be transformed into a positive real numbers from complex numbers. Additionally, a ZC transform can be uniquely identified by its corresponding sequence index, u, and the ZC transform has a good self-correlation characteristic. Transformed ZC sequences can be used for correlation detection as described in more detail below.

An example of a receiving scheme that utilizes ZC transformation of received ZC sequences is described with reference to Fig. 7. Assume two different ZC sequences 504 and 506 are generated at the transmit side of a UE (not shown). At the transmit side, the ZC sequences go through an IDFT 304 and a cyclic prefix is inserted after the preamble at 306. A RACH burst, including the two ZC sequences is then transmitted over the channel 308. At the receive side, the cyclic prefix is removed at 310, followed by a DFT 312. The received sequences, identified as $Z\hat{C}_u$, $Z\hat{C}_{2u}$, are recovered at 314 and then provided to the correlation detection unit 340 and to the transformation unit 342. The transformation unit transforms the received ZC sequences into transformed ZC sequences, $Z\hat{C}T_u$, $Z\hat{C}T_{2u}$. In the embodiment of Fig. 7, the received ZC sequences are transformed via a correlation operation with one chip cycle-shifting although different transformation operations are possible. The transformation operation can be expressed as:

$$\begin{aligned}
&Z\hat{C}T_u(k) = Z\hat{C}_u(k) \cdot Z\hat{C}_u^{\,*}(k-1) \\
&Z\hat{C}T_{2u}(k) = Z\hat{C}_{2u}(k) \cdot Z\hat{C}_{2u}^{\,*}(k-1) \\
&k = 0 \sim N_G - 1
\end{aligned}$$

Since $Z\hat{C}_u(k)$ and $Z\hat{C}_u(k-1)$ are transmitted on adjacent sub-carriers, the channel impulse responses of the two ZC sequences are quite close to each other and therefore the correlation operation can eliminate the channel impulse responses, e.g., S_1 and S_2.

In addition to the transformation operation, a division operation is conducted using the two ZC transforms to generate another ZC transform, identified as $ZCT_u^{'}$. For example, as indicated in Fig. 7, the two ZC transforms are provided to the division unit 344, which implements a division operation. In the embodiment of Fig. 7, the division unit implements the division operation using a correlation operation although other techniques are possible. Including the ZC transforms, $Z\hat{C}T_u$, $Z\hat{C}T_{2u}$, and the quotient from the division operation, ZCT_u', a total of five ZC sequences are generated at the receive side from the two received ZC sequences. The five ZC sequences are indicated in Fig. 7 as: $Z\hat{C}_u$, $Z\hat{C}_{2u}$, $Z\hat{C}T_u$, $Z\hat{C}T_{2u}$, and ZCT_u'.

In an embodiment, the five ZC sequences are different from the ZC sequences at corresponding positions of other RACH preambles and the five ZC sequences can be used alone or in combination for correlation detection. Corresponding local de-correlation sequences 346 maintained at the receive side (e.g., the base station 104) are identified in Fig. 7 as:

ZC_u

ZC_{2u}

$ZCT_u = ZC_u(k) \cdot ZC_u(k-1)$

$ZCT_{2u} = ZC_{2u}(k) \cdot ZC_{2u}(k-1)$

ZCT_u'.

The five ZC sequences that are recovered and/or generated on the receive side are useful in dealing with different types of interference/noise. For example, the received ZC sequences, $Z\hat{C}_u$ and $Z\hat{C}_{2u}$, are useful for dealing with Gaussian noise and the ZC transforms, $Z\hat{C}T_u$ and $Z\hat{C}T_{2u}$, and the quotient of the ZC transforms, ZCT_u', are useful for dealing with channel variation and DFO.

At the receive side, different combinations of the ZC sequences can be selected for use in correlation detection depending on the actual transmission environment. Alternatively, a fixed set of ZC sequences (e.g., all five ZC sequences) can be used in correlation detection regardless of the actual transmission environment. Although the receive side operations, which include ZC sequence transformation, are described with reference to the two different ZC sequences of Fig. 5, the receive side operations are applicable to other schemes that use ZC sequences. For example, the receive side operations, which include ZC sequence transformation, are applicable to the ZC sequence scheme described above with reference to Figs. 2 – 4 as well as other multiple ZC sequence or single ZC sequence preamble schemes.

Zadoff-Chu Mapping

In accordance with an embodiment of the invention, when a ZC sequence is transmitted using more than one OFDM symbol, the ZC mapping scheme is adjusted. In an embodiment, the last chip of a previous OFDM symbol is inserted at the beginning of a latter OFDM symbol. A description of this technique as applied in a 3GPP LTE environment is described below with reference to Figs. 8 and 9.

In the above-described schemes, each ZC sequence is assumed to be transmitted through one OFDM symbol. For example, in a 3GPP LTE system, a ZC sequence with a length of 419 is transmitted on 72 sub-carriers out of 300 total sub-carriers for one OFDM symbol. However, in accordance with an embodiment of the invention, when ZC sequences are transmitted via more than one OFDM symbol, the ZC mapping scheme is revised. According to a conventional scheme, a ZC sequence is transmitted through six OFDM symbols with thirteen zeros inserted into the last OFDM symbol. Fig. 8 illustrates a mapping scheme in which a ZC sequence is transmitted via a single OFDM symbol. Using the mapping scheme of Fig. 8, the above described receiving scheme may have difficulty generating the ZC transform, $Z\hat{C}T_u(k)$. For example, for the case when *k* = 72, the ZC transform is calculated as:

$$Z\hat{C}T_u(k) = Z\hat{C}_u(72) \cdot Z\hat{C}_u^*(71)$$

When $Z\hat{C}_u(72)$ and $Z\hat{C}_u(71)$ are transmitted on different OFDM symbols and not on "adjacent" sub-carriers, the channel impulse responses of the two chips will differ greatly and cannot be eliminated through a correlation operation.

In accordance with an embodiment of the invention, the ZC mapping scheme is adjusted to include the last chip of the previous OFDM symbol at the beginning of the latter OFDM symbol. Fig. 9 illustrates a mapping scheme in which the last chip 360 of the previous OFDM symbol is inserted at the beginning of the latter OFDM symbol. The inserted chip 362 includes redundant values that are used in the ZC transformation to generate the ZC transforms. The above-described mapping scheme does not reduce the transmission efficiency of the system because insertion of the redundant chips can be offset by inserting fewer zeros in the last OFDM symbol.

Performance Analysis

A performance analysis of the above-described technique is described below. In particular, the performance of the above-described technique is compared to schemes that use multiple repeated ZC sequences. The simulation was conducted using the following parameters:

Channel: 6 paths Rayleigh (ITU TU-A)

FFT size: 300

Occupied bandwidth by RACH preamble: 1.25MHz

Fig. 10 is a graph of the probability of an incorrect detection (miss-detection) on the y-axis vs. the frequency offset (f_offset) on the x-axis. The graph includes three instances of techniques that use conventional ZC sequences and three instances that use the techniques described above with reference to Figs. 4, 5 and 7. As illustrated in Fig. 10, under higher signal-to-noise (SNR) conditions (e.g., >0dB), the above-described techniques exhibit better performance than conventional techniques. Furthermore, as the DFO grows beyond about 3 KHz, the performance of the conventional scheme sharply deteriorates while the performance of the above-described technique maintains relatively steady. Additionally, the above-described preamble and receiving techniques can significantly cancel the DFO effect, which is extremely valuable for an AWGN channel – LoS (Line of Sight) path.

Throughout the description of the embodiments, various mathematical relationships are used to describe relationships among one or more quantities. For example, a mathematical relationship or mathematical transformation may express a relationship by which a quantity is derived from one or more other quantities by way of various mathematical operations, such as addition, subtraction, multiplication, division, etc. Or, a mathematical relationship may indicate that a quantity is larger, smaller, or equal to another quantity. These relationships and transformations are in practice not satisfied exactly, and should therefore be interpreted as “designed for” relationships and transformations. One of ordinary skill in the art may design various working embodiments to satisfy various mathematical relationships or transformations, but these relationships or transformations can only be met within the tolerances of the technology available to the practitioner.

Accordingly, in the following claims, it is to be understood that claimed mathematical relationships or transformations can in practice only be met within the tolerances or precision of the technology available to the practitioner, and that the scope of the claimed subject matter includes those embodiments that substantially satisfy the mathematical relationships or transformations so claimed.

Although the subject matter has been described in language specific to structural features and methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed as example forms of implementing the claims.

CLAIMS:

1. A wireless communications system comprising:

a first physical layer to transmit a burst comprising a first preamble, the first preamble comprising a first Zadoff-Chu sequence and a second Zadoff-Chu sequence; and

a second physical layer to transmit a burst comprising a second preamble, the second preamble comprising a first Zadoff-Chu sequence and a second Zadoff-Chu sequence;

wherein the Zadoff-Chu sequences of the first preamble are different from the Zadoff-Chu sequences in corresponding positions of the second preamble.

2. The wireless communications system of claim 1 wherein a division operation of the first and second Zadoff-Chu sequences in the first preamble yields a first result and a division operation of the first and second Zadoff-Chu sequences in the second preamble yields a second result, wherein the first and second results are different from each other.

3. The wireless communications system of claim 1 wherein each Zadoff-Chu sequence of the first preamble has a length N, the first Zadoff-Chu sequence periodic in a first sequence index with period equal to N, and the second Zadoff-Chu sequence periodic in a multiple of the first sequence index with period equal to N.

4. The wireless communications system of claim 3 wherein the multiple is an integer multiple of the first sequence index.

5. The wireless communications system of claim 3 wherein the multiple is an integer multiple, M, of the first index sequence and wherein N is an integer that cannot be evenly divided by an integer from 2 to M.

6. The wireless communications system of claim 3 wherein the first Zadoff-Chu sequence of the second preamble is periodic in a first sequence index with period equal to *N*, and the second Zadoff-Chu sequence in the second preamble is periodic in a multiple of the first sequence index with period equal to *N*.

7. The wireless communications system of claim 1 wherein the first physical layer is configured to insert, within at least one of the first and second Zadoff-Chu sequences, a last chip of a first orthogonal frequency division multiplexed (OFDM) symbol at the beginning of a next OFDM symbol.

8. An apparatus comprising:

a physical layer to receive a burst comprising a preamble, and to recover from the preamble at least one Zadoff-Chu sequence;

a transformation unit configured to transform the at least one Zadoff-Chu sequence into a transformed Zadoff-Chu sequence;

a correlation detection unit configured to correlate the transformed Zadoff-Chu sequence with another Zadoff-Chu sequence.

9. The apparatus of claim 8 wherein the Zadoff-Chu transformation unit is configured to transform the at least one Zadoff-Chu sequence into another Zadoff-Chu sequence via a correlation operation with one chip cycle-shifting.

10. The apparatus of claim 9 further comprising a divider to divide the transformed Zadoff-Chu sequence by another transformed Zadoff-Chu sequence to provide a quotient sequence.

11. The apparatus of claim 10 further comprising using the quotient sequence to detect a correlation with another Zadoff-Chu sequence.

12. A method comprising:

transmitting a first burst comprising a first preamble, the first preamble comprising a first Zadoff-Chu sequence and a second Zadoff-Chu sequence; and

transmitting a second burst comprising a second preamble, the second preamble comprising a first Zadoff-Chu sequence and a second Zadoff-Chu sequence;

wherein the Zadoff-Chu sequences of the first preamble are different from the Zadoff-Chu sequences in corresponding positions of the second preamble.

13. The method of claim 12 further comprising:

recovering from the first preamble at least one Zadoff-Chu sequence;

transforming the at least one Zadoff-Chu sequence to a transformed Zadoff-Chu sequence; and

correlating the transformed Zadoff-Chu sequence with another Zadoff-Chu sequence.

14. The method of claim 13 wherein transforming the at least one Zadoff-Chu sequence comprises correlating the at least one Zadoff-Chu sequence via a correlation operation with one chip cycle-shifting.

15. The method of claim 13 further comprising:

recovering from the second preamble at least one Zadoff-Chu sequence;

transforming the at least one Zadoff-Chu sequence to a transformed Zadoff-Chu sequence; and

correlating the transformed Zadoff-Chu sequence with another Zadoff-Chu sequence.

16. The method of claim 15 further comprising dividing the first Zadoff-Chu sequence in the first preamble by the second Zadoff-Chu sequence in the first preamble to yield a first result and dividing the first Zadoff-Chu sequence in the second preamble by the second Zadoff-Chu sequence in the second preamble to yield a second result, wherein the first and second results are different from each other.

17. The method of claim 16 further comprising:

using the first result in a correlation operation; and

using the second result in a correlation operation.

18. The method of claim 12 further comprising, within at least one of the first and second Zadoff-Chu sequences of at least one of the first and second preambles, inserting a last chip of a first orthogonal frequency division multiplexed (OFDM) symbol at the beginning of a next OFDM symbol.

19. The method of claim 18 further comprising:

recovering at least one Zadoff-Chu sequence;

transforming the at least one Zadoff-Chu sequence to a transformed Zadoff-Chu sequence, wherein the at least one Zadoff-Chu sequence is transformed using the inserted last chip; and correlating the transformed Zadoff-Chu sequence with another Zadoff-Chu sequence.

20. The method of claim 12 wherein each Zadoff-Chu sequence of the first preamble has a length *N*, the first Zadoff-Chu sequence periodic in a first sequence index with period equal to *N*, and the second Zadoff-Chu sequence periodic in an integer multiple of the first sequence index with period equal to *N*, wherein the multiple is an integer multiple, M, of the first index sequence and wherein *N* is an integer that cannot be evenly divided by an integer from 2 to M.

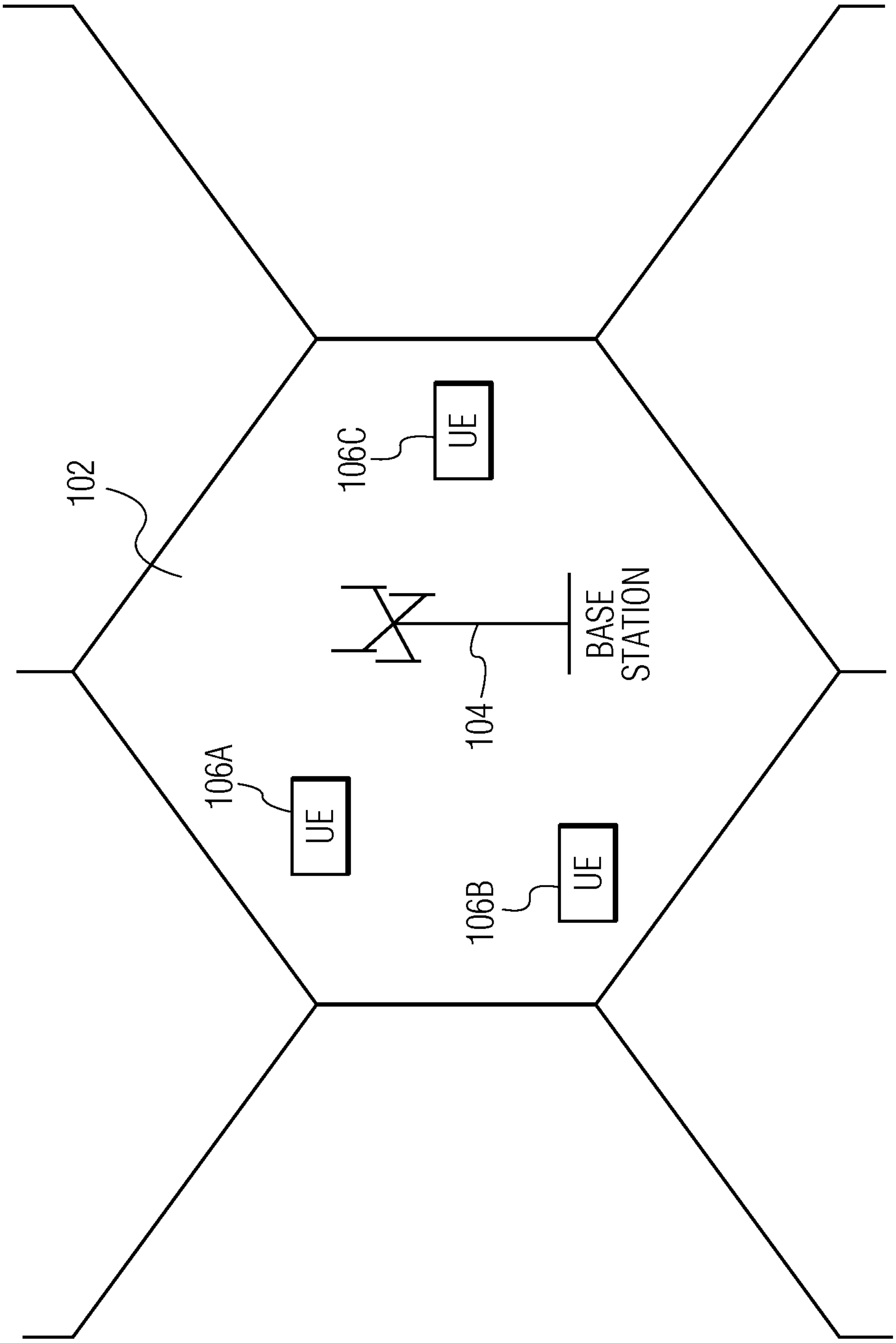


FIG. 1
PRIOR ART

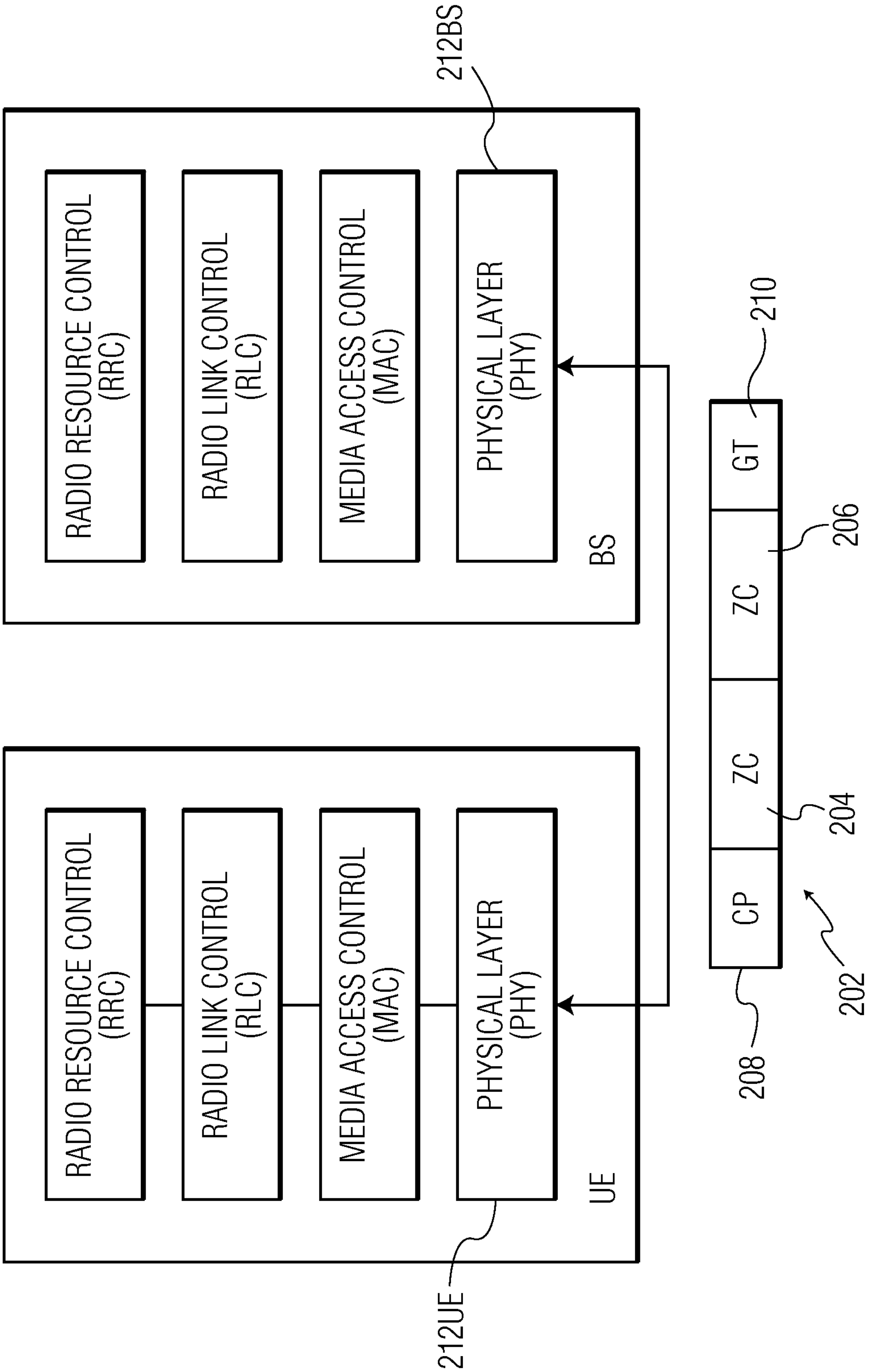

212BS
RADIO RESOURCE CONTROL (RRC)
RADIO LINK CONTROL (RLC)
MEDIA ACCESS CONTROL (MAC)
PHYSICAL LAYER (PHY)
BS
210
GT
206
ZC
ZC
204
CP
202
208
RADIO RESOURCE CONTROL (RRC)
RADIO LINK CONTROL (RLC)
MEDIA ACCESS CONTROL (MAC)
PHYSICAL LAYER (PHY)
UE
212UE

FIG. 2

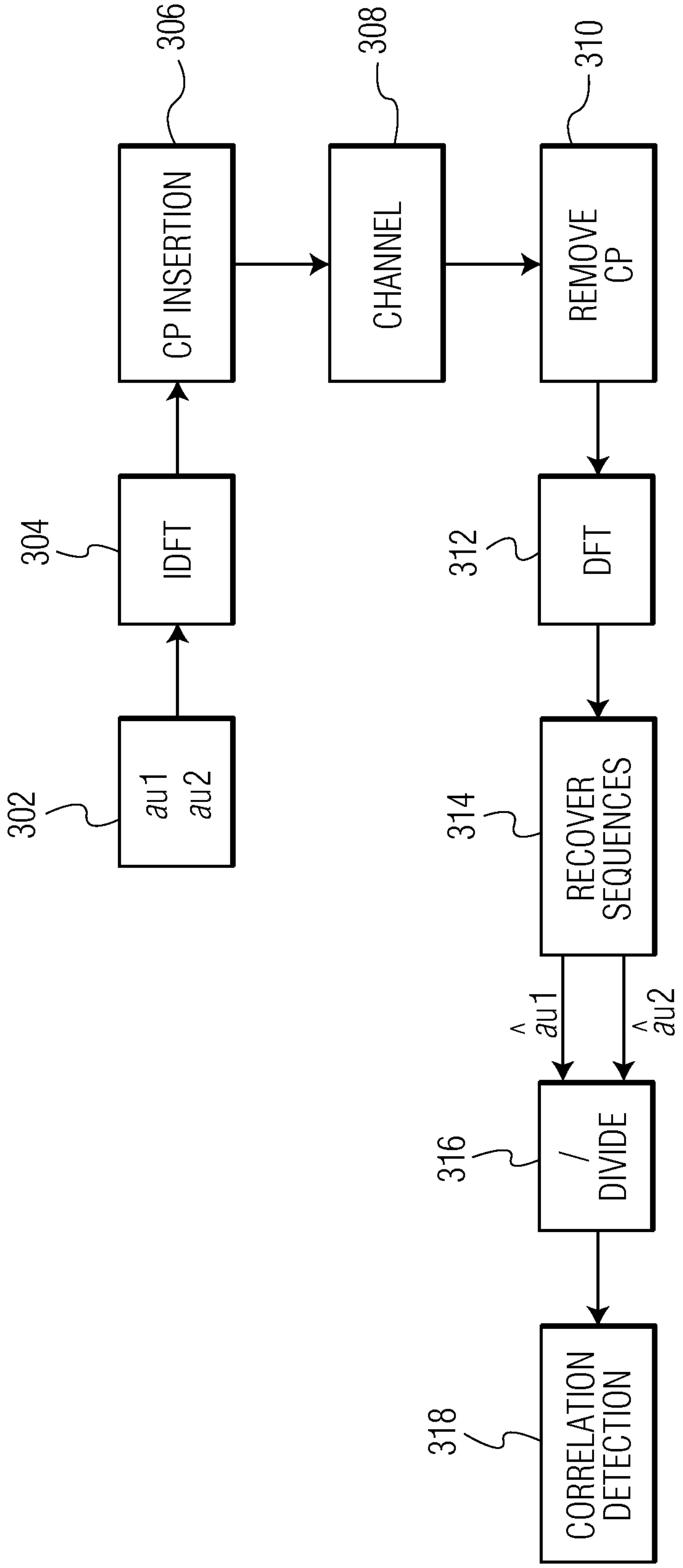

302
au1
au2
304
IDFT
306
CP INSERTION
308
CHANNEL
310
REMOVE
CP
312
DFT
314
RECOVER
SEQUENCES
^ au1
^ au2
316
/
DIVIDE
318
CORRELATION
DETECTION

FIG. 3

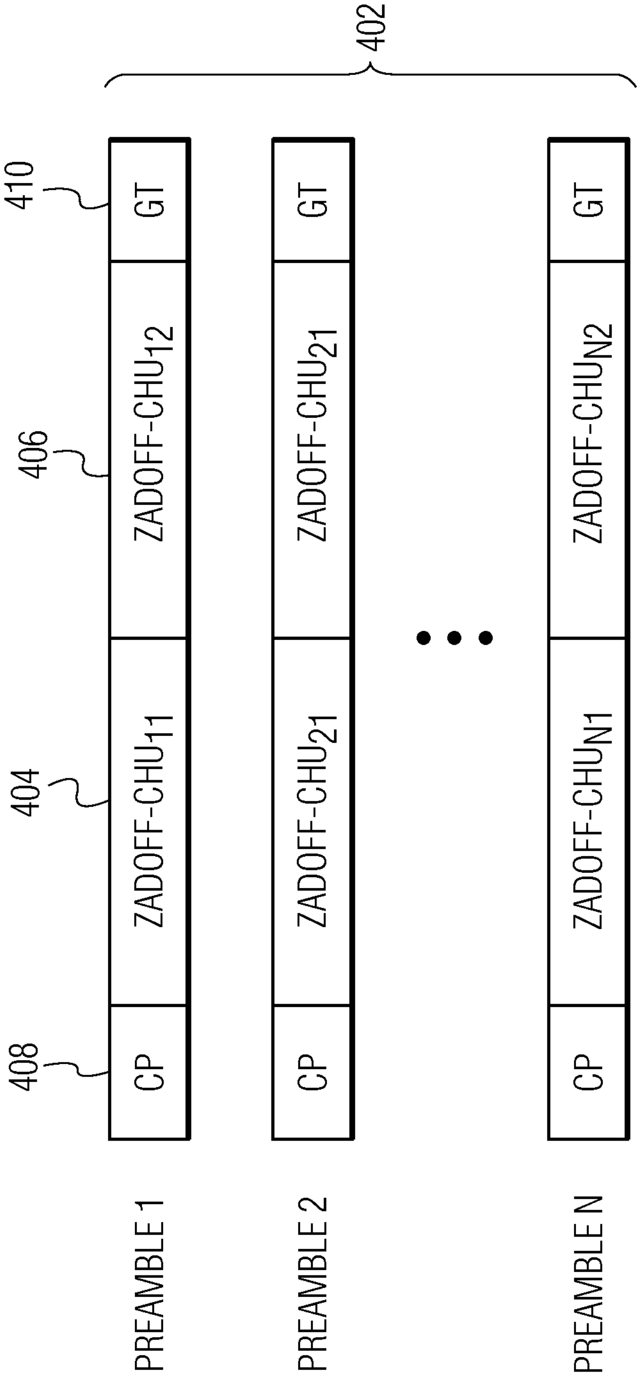
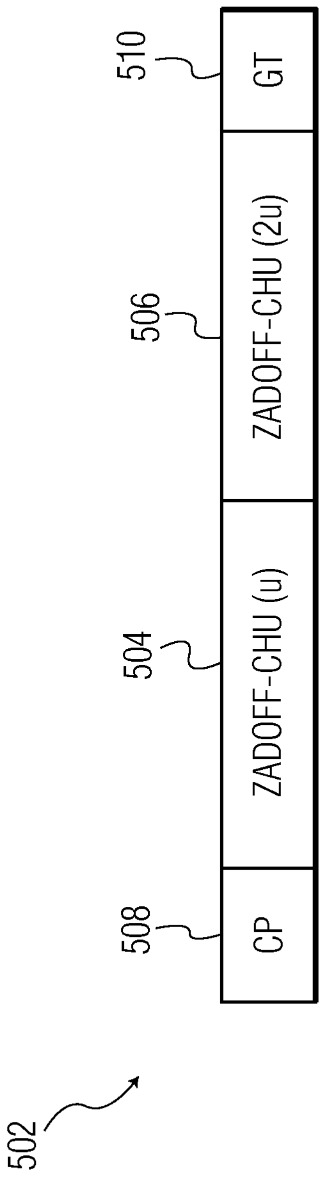

402
410
406
404
408
PREAMBLE 1
CP
ZADOFF-CHU$_{11}$
ZADOFF-CHU$_{12}$
GT
PREAMBLE 2
CP
ZADOFF-CHU$_{21}$
ZADOFF-CHU$_{21}$
GT
PREAMBLE N
CP
ZADOFF-CHU$_{N1}$
ZADOFF-CHU$_{N2}$
GT

FIG. 4



$0 \le u < N_G - 1$

FIG. 5

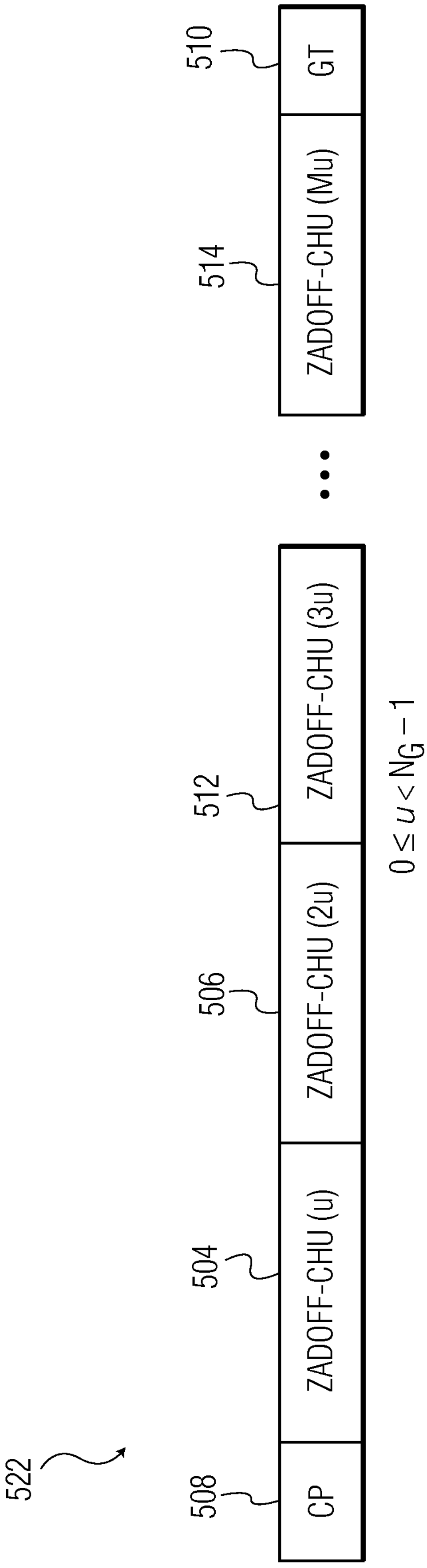

522
508
CP
504
ZADOFF-CHU (u)
506
ZADOFF-CHU (2u)
512
ZADOFF-CHU (3u)
514
ZADOFF-CHU (Mu)
510
GT
$0 \leq u < N_G - 1$

FIG. 6

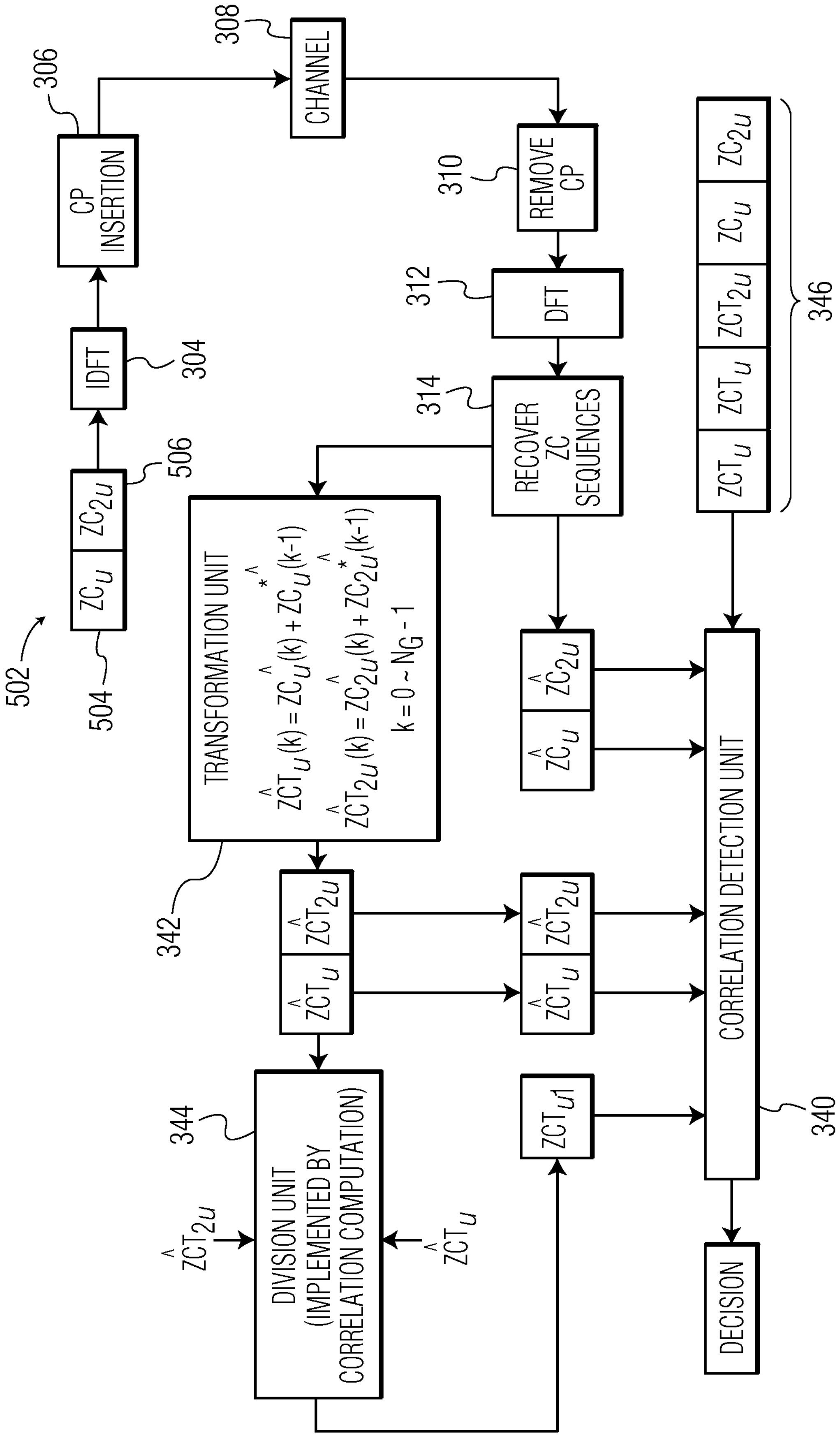

502
504
506
ZC_u
ZC_{2u}
IDFT
304
CP INSERTION
306
CHANNEL
308
REMOVE CP
310
DFT
312
RECOVER ZC SEQUENCES
314
TRANSFORMATION UNIT
$\hat{ZCT}_u(k) = \hat{ZC}_u(k) + \hat{ZC}_u^*(k-1)$
$\hat{ZCT}_{2u}(k) = \hat{ZC}_{2u}(k) + \hat{ZC}_{2u}^*(k-1)$
$k = 0 \sim N_G - 1$
342
$\hat{ZC}_u$
$\hat{ZC}_{2u}$
$\hat{ZCT}_u$
$\hat{ZCT}_{2u}$
DIVISION UNIT (IMPLEMENTED BY CORRELATION COMPUTATION)
344
ZCT_{u1}
CORRELATION DETECTION UNIT
340
DECISION
ZCT_u
ZCT_u
ZCT_{2u}
ZC_u
ZC_{2u}
346

FIG. 7

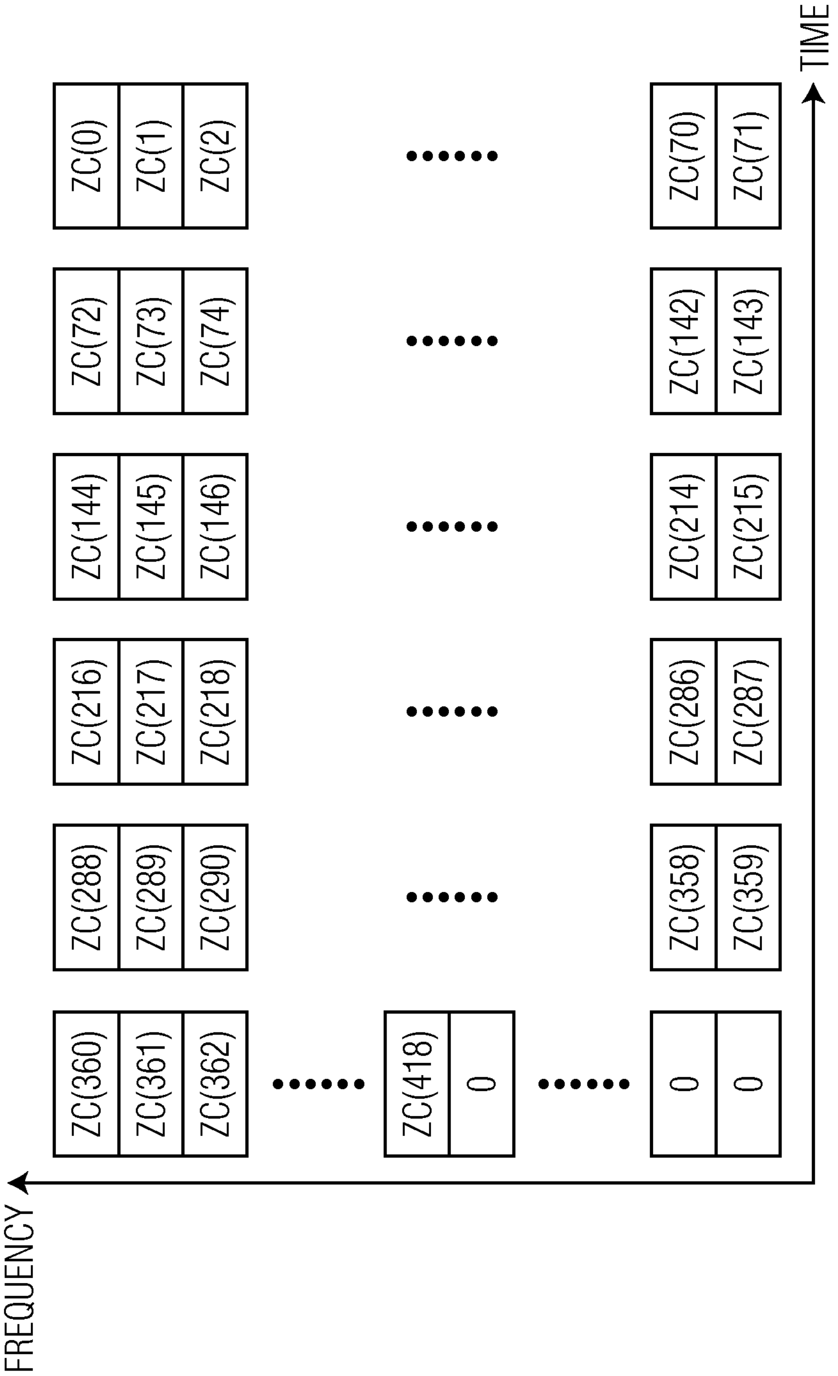
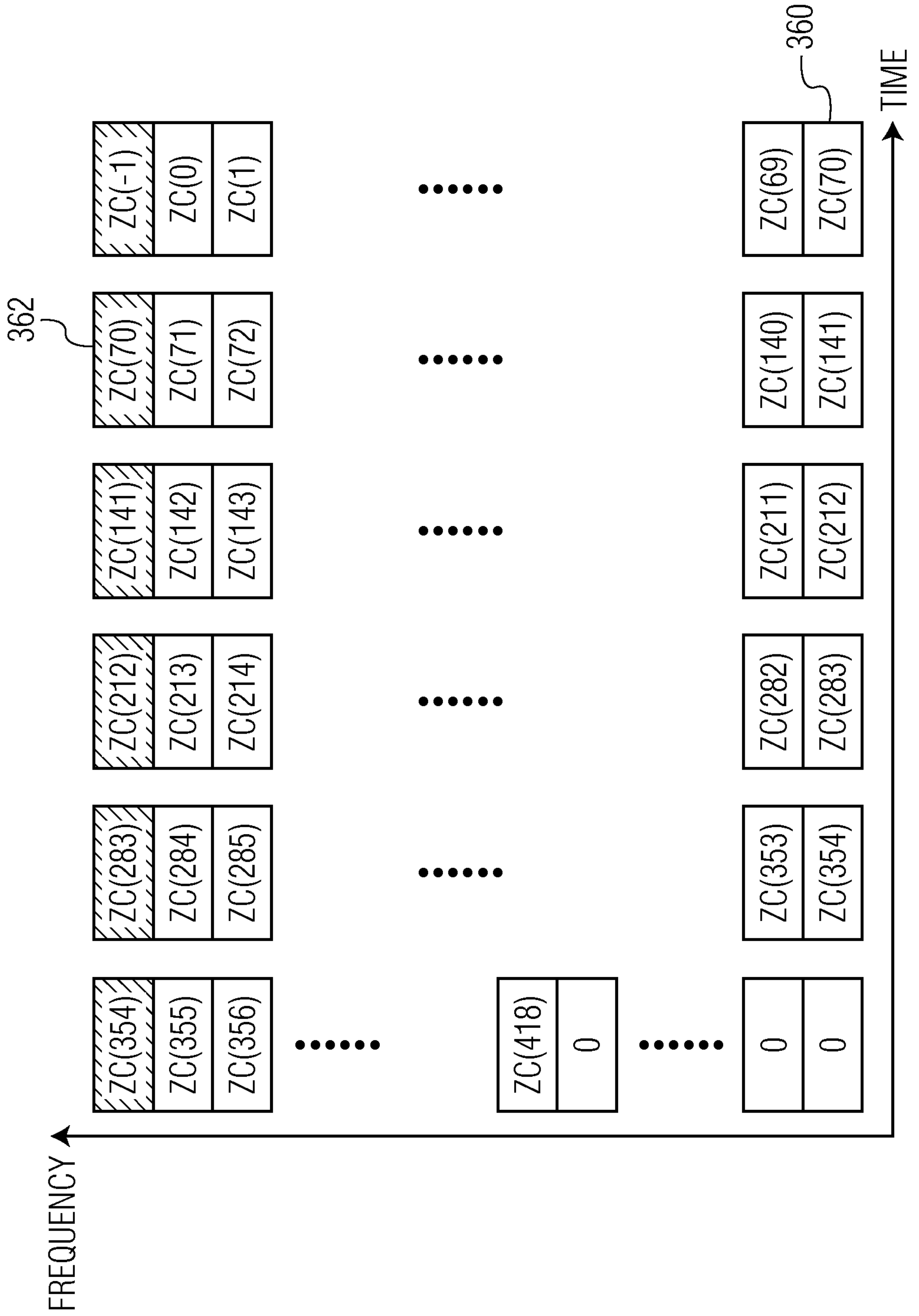


FIG. 8
PRIOR ART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360
TIME
FREQUENCY
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ZC(0)
ZC(1)
ZC(69)
ZC(70)
ZC(70)
ZC(71)
ZC(72)
ZC(140)
ZC(141)
ZC(141)
ZC(142)
ZC(143)
ZC(211)
ZC(212)
ZC(212)
ZC(213)
ZC(214)
ZC(282)
ZC(283)
ZC(283)
ZC(284)
ZC(285)
ZC(353)
ZC(354)
ZC(354)
ZC(355)
ZC(356)
ZC(418)
0
0
0

FIG. 9

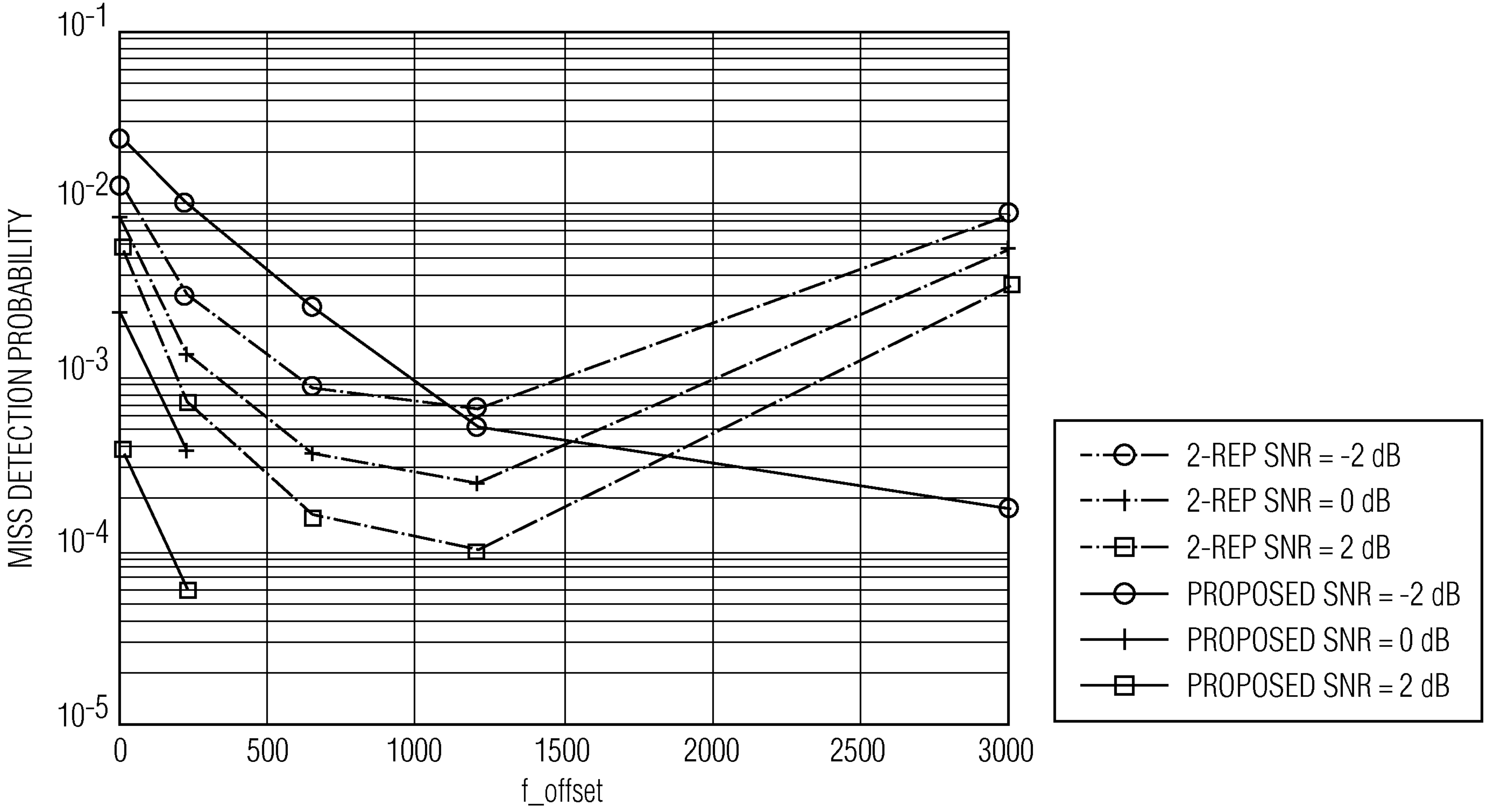
10-1
10-2
10-3
10-4
10-5
MISS DETECTION PROBABILITY
0
500
1000
1500
2000
2500
3000
f_offset
2-REP SNR = -2 dB
2-REP SNR = 0 dB
2-REP SNR = 2 dB
PROPOSED SNR = -2 dB
PROPOSED SNR = 0 dB
PROPOSED SNR = 2 dB

FIG. 10