This result can also be expressed in terms of carrier phase offsets using the equivalence between shifts in the time domain and phase offsets in the frequency domain. A first set of N orthogonal signals is represented in phase by N complex spreading codes:

$$f_1(\phi)\{e^{j\theta 1}, e^{j\theta 2}, \ldots, e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N}, \ldots, e^{j(N-1)\cdot 2\pi k/N}\}$$

A second set of N orthogonal signals is represented in phase by N complex spreading codes:

$$f_2(\phi)\{e^{j\theta' 1}, e^{j\theta' 2}, \ldots, e^{j\theta N}\} = \{e^{j(0+\Delta\phi)}, e^{j(2\pi k/N+\Delta\phi)}, \ldots, e^{j((N-1)\cdot 2\pi k/N+\Delta\phi)}\}$$

where $\Delta\phi=\pi/N$.

The superposition signal **110**D in FIG. **1**B can be thought of as a superposition of complex-weighted carriers in a carrier set **105**D or a sum of the superposition signals **110**A, **110**B, and **110**C. The carrier set **105**D represents a sum of the carrier sets **105**A, **105**B, and **105**C. The complex amplitudes of carrier set **105**D can be characterized by a complex-weight vector $w=[w_1, w_2, \ldots, w_N]$. Each value w_n of the weight vector w corresponds to a particular carrier frequency f_n. The values w_n can be derived from a complex addition of carriers in the carrier sets **105**A, **105**B, and **105**C. The values w_n can be derived from summing complex numbers representing the magnitude and phase of each carrier in the carrier sets **105**A, **105**B, and **105**C.

CI signals demonstrate both excellent frequency resolution and excellent time resolution. A CI signal is composed of multiple narrowband carriers that allow it to be resolved into its frequency components. When observed in the time domain, a basic CI signal is very narrow, enabling it to be easily separated from other CI signals and to resolve the channel's multipath profiles.

Because the period and width of the pulse envelope depends on the amplitudes, relative phases, and frequency separation of the CI carriers, the frequency of each carrier may be changed without affecting the pulse envelope as long as the amplitudes, relative phases, and frequency separation are preserved. Thus, frequency hopping and frequency shifting of the carriers does not affect the temporal characteristics of the superposition signal, such as superposition signal **110**A. Tapering the amplitude distribution of the CI carriers broadens the main-lobe width and reduces the amplitude of the side lobes.

A CI signal has a number of carrier signals that may each have a bandwidth that is less than the coherence bandwidth of the communication channel. The coherence bandwidth is the bandwidth limit in which correlated fading occurs. The total bandwidth of the CI signal preferably exceeds the coherence bandwidth.

CI carriers corresponding to any particular user, channel, or data symbol may be spaced in frequency by large amounts to achieve a large system bandwidth relative to the coherence bandwidth. In this case, CI uses frequency to achieve uncorrelated fading. However, any diversity parameter or combination of diversity parameters may be used to achieve uncorrelated fading over the system bandwidth, or even between individual carriers.

The system bandwidth of a group of CI carriers may be selected relative to the coherence bandwidth of one or more subchannels, such as spatial sub-channels. Carriers that are closely spaced in frequency may have uncorrelated fading if they are transmitted from different locations or have different degrees of directivity. CI carriers transmitted from different locations may have different fades over each spatial sub-channel and therefore, can benefit from diversity combining at a receiver (not shown).

Phase shifts applied to an n^{th} carrier to separate a k^{th} channel from adjacent channels are given by:

$$\phi_{kn}=\pi k n f_s(\Delta t)+\phi^0_{kn}=\pi k n/N+\phi^0_{kn}$$

where ϕ^0_{kn} is an initial phase-offset corresponding to the n^{th} carrier and the k^{th} channel. The values of Δt depend on whether the channel spacing is orthogonal or quasi-orthogonal.

Although FIG. **1**A and FIG. **1**B illustrate an in-phase superposition of carrier signals, this example can be extended to other superpositions of CI. For example, the time offset Δt (and the corresponding carrier phase shifts ϕ_{kn}) for adjacent channels may be applied to CI implementations that do not have in-phase superpositions. The time offsets Δt (and thus, the phase shifts ϕ_{kn}) derived in this case are also relevant to CI implementations that process the received carriers separately. When each carrier is processed separately, phase-offset coding (in addition to the phase offsets ϕ_k, used to separate channels) may be used to reduce or minimize the peak of the superposition signal.

The carrier sets **105**A, **105**B, and **105**C have phase offsets corresponding to a pulse-width duration. However, any type of orthogonal (e.g., non-overlapping) or quasi-orthogonal (e.g., overlapping) spacing may be provided. Carrier sets having quasi-orthogonal (or non-orthogonal) spacing may be processed with multi-user (or multi-channel) detection techniques or with any other type of interference-suppression technique.

FIG. **1**A and FIG. **1**B illustrate several levels of signal decomposition that reduce a complex time-domain signal into simple components. The time-domain pulses may be scaled and positioned to produce a predetermined time-domain signal indicative of an information signal, coding, and at least one transmission protocol. Multiple frequency components may be weighted to produce an information signal having predetermined time-domain characteristics. Similarly, multiple frequency components that comprise the pulses may be selected and weighted to impart predetermined characteristics to the pulses. The scale of the components selected for signal processing can be selected to provide a desired granularity for the information architecture.

Modulation of the pulses, the carriers, or both may be performed over the duration of the signals shown in FIG. **1**A and FIG. **1**B. Carrier modulation may be performed over a pulse-repetition period, a pulse duration, or any multiple or fraction of either. In some cases, guard intervals, guard bands, and/or cyclic prefixes may be provided to CI signals.

3. CI Codes

CI codes, as used herein, may include basic CI codes or advanced CI codes. CI codes are based on phase relationships between orthogonal carriers, such as illustrated by samples **220** to **225** shown in FIG. **2**A.

Basic CI codes of the present invention can be derived from phase relationships between orthogonal carrier frequencies. FIG. **2**A illustrates first and second orthogonal sinusoidal waveforms **201** and **202**. Each waveform **201** and **202** has an integer number of wavelengths over a particular symbol interval T_s. The first waveform **201** frequency f_1 is six cycles per symbol interval T_s. The second waveform **102** frequency f_2 is five cycles per symbol interval T_s.

The samples **220** to **225** of waveform **202** are selected at intervals of Δt_1 corresponding to periods **210** to **215** of waveform **201** over a symbol interval $T_s=6\Delta t_1$. In this case, the waveforms **201** and **202** are aligned in phase at times t=0 and $t=T_s$. At $t=\Delta t_1$, sample **221** occurs at 5/6 of waveform **202** period Δt_2. Each sample **220** to **225** can be represented by a value on a unit circle in the complex plane. For example, FIG. **3**A shows a complex-plane representation of samples **220** and **221**.

Since the sampling frequency f_1 exceeds the frequency f_2 of the sampled waveform **202**, the phase shift of each successive sample **220** to **225** falls short of a full cycle of waveform **202**. The waveforms **201** and **202** are orthogonal due to selection of an appropriate symbol interval T_s that causes the samples **220** to **225** to be distributed uniformly across the unit circle in the complex plane, as illustrated by FIG. **4**A. The sample values **220** to **225** cancel when they are summed.

FIG. **2**B illustrates a first waveform **201** sampled at intervals **230** to **235** relative to a sampling frequency f_2 of a second waveform **202**. A symbol interval is expressed by $T_s=5\Delta t_2$. Each sample **240** to **244** corresponds to a phase shift that is greater than a full cycle of waveform **201**, as illustrated by FIG. **3**B. The orthogonality of the waveforms **201** and **202** ensures that the samples **240** to **244** are distributed uniformly around the unit circle in the complex plane, as shown in FIG. **4**B. Samples **240** to **244** collected over a symbol interval T_s cancel when summed.

FIG. **4**C shows a normalized complex-plane representation of samples (collected at a sampling rate $f_{sample}=f_n$) of a desired waveform having a frequency f_n. Since $f_{sample}=f_n$, the samples always occur on the same part of the unit circle in the complex plane. Thus, the samples sum constructively. In this example, the samples occur at the peaks of the desired waveform and thus, occur on the real axis in the complex plane. The number of samples N_s per symbol interval T_s is expressed by:

$$N_s=f_{sample}T_s=(f_o+nf_s)/f_s$$

The number of samples per waveform period (1/A) is 1.

Nearby waveform frequencies $f_{n\pm n'}$ can be expressed as: $f_{n\pm n'}=f_o+(n\pm n')f_s$. The number of samples per period of a nearby waveform can be expressed as:

$$N_{n\pm n'}=\frac{f_{n\pm n'}}{f_{sample}}=1\pm\frac{n'f_s}{(f_o+nf_s)}$$

In the complex plane, the sampled values shift by an amount:

$$\phi_{n\pm n'}=\pm\frac{n'f_s}{(f_o+nf_s)}2\pi\text{ radians}$$

N_s samples collected throughout the symbol interval T_s are distributed uniformly on a unit circle in the normalized complex plane unless $f_{n\pm n'}$ is an integer multiple of f_n. The case in which $f_{n\pm n'}=mf_n$ (where m is some integer) can be avoided by appropriately frequency converting the received signal(s) and/or the sampling rate to ensure that the vector sum of the samples is zero.

CI codes can be used as direct-sequence codes, multicarrier codes (e.g., MC-CDMA), etc. Applications of CI codes can be extended to any application of conventional binary direct sequence codes, including, but not limited to, spread spectrum, multiple access, channel coding, encryption, and interference mitigation. CI codes may be applied across any set of orthogonal or quasi-orthogonal diversity-parameter values or subspaces.

Basic CI codes can be generated from phase relationships indicated by vector precession in the complex plane, such as shown in FIG. **4**A. CI coding can be applied to circular, elliptical, and linear polarization. CI polarization codes may be based on vector precession in a two- or three-dimensional polarization plane. Advanced CI codes may be based on basic CI polarization codes. Similarly, vector rotation in a plane or a higher-dimension field of orthogonal bases may be used to generate basic and/or advanced CI codes. The basic family of CI codes is generated from an M×M matrix of elements having phases ϕ_{nm} described by:

$$\phi_{mn}=2\pi mn/M+2\pi f_o m/f_s M,$$

where m and n are row and column indices, respectively. M may have any positive integer value. The second term in ϕ_{mn} is an optional phase shift applied to all terms in a row. The phase-shift ϕ_{mn} may correspond to a carrier frequency offset f_o and a sub-carrier separation f_s. A basic CI code c_m of length N can include a row or column vector consisting of terms:

$$c_m=e^{im\phi'}\sum_{n=0}^{N-1}e^{imn\phi}\hat{n}$$

where $\phi=2\pi/M$ and $\phi'=2\phi f_o/f_s M$.

Some of the CI codes are complex-conjugate pairs. For example, correlations between CI codes are expressed by the following relationship:

$$\text{corr}_{m,m'}=\left(\frac{1}{M}\right)e^{i(m+m')\phi'}\sum_{n=0}^{M-1}e^{in(m+m')\phi}$$

The correlations are non-zero for (m+m')=M.

CI codes may have polyphase and/or multi-magnitude values. A CI code set may include one or more binary code vectors corresponding to at least one conventional binary-phase code. In the case where CI codes include complex-valued chips, the real and imaginary parts may be impressed upon different orthogonal parameters. For example, a magnitude corresponding to a real value may be modulated on an in-phase carrier component, whereas a corresponding imaginary value may be modulated on a quadrature-phase carrier component.

Orthogonal components may include, but are not limited to, perpendicular linear polarizations, left-hand and right-hand circular or elliptical polarizations, orthogonal polarization-spin frequencies, subspaces (e.g., spatial, directional, temporal, phase, polarization, etc.), orthogonal frequencies, orthogonal time intervals, direct-sequence codes, etc. Modulation may include phase modulation, amplitude modulation, frequency modulation, polarization modulation, time-offset modulation, or any combination thereof.

Phase shifts corresponding to CI code chips may be impressed upon a single carrier or onto multiple carriers. In one embodiment, phase shifts are impressed relative to a transmitted or locally generated reference phase. In another embodiment, differential phase modulation (DPM) is employed. In one embodiment, DPM is employed on a single carrier. In another embodiment, DPM is applied to a multicarrier transmission protocol. In one embodiment, each phase shift is conveyed as a phase differential between at least two carriers.

CI codes may be applied to ordinary direct-sequence (e.g., DSSS or DS-CDMA), MC-CDMA, OFDM, coded OFDM, Discreet Multitone, Wavelength Division Multiplexing (WDM), ultra-dense WDM, Multi-tone CDMA, Multi-code spread spectrum, or any of the CI protocols. In the case where CI codes are used in a multicarrier transmission protocol, phase-shift coding may be accomplished in any of several ways. Each carrier may be phase shifted with respect to each chip of a CI code chip sequence. Each carrier may be modulated with respect to any single-carrier modulation scheme. Each carrier may be modulated with one or more CI code chip encoded subcarriers. Each carrier may be provided with at least two diversity parameters that are modulated to convey real and imaginary parts of CI codes chips.

Multicarrier signals may be defined by any set of substantially orthogonal diversity-parameter values. These diversity parameters may include, without limitation, frequency, phase space, polarization (including linear, circular, elliptical) in two or three dimensions, mode, code (e.g., DS and/or CI), time, any type of subspace, and any combination thereof.

Advanced CI codes can involve one or more types of processing applied to basic CI codes. Some examples of advanced CI codes include matrices resulting from processing basic CI codes with a Hadamard-Walsh matrix, matrices derived from Hadamard-Walsh/CI matrices, and expanded CI matrices based on Hadamard-Walsh matrix expansion.

The basic CI codes can be combined (with each other or with other direct-sequence codes) to form other families of polyphase and/or poly-magnitude CI codes. In any set of CI codes, the chip sequences may be truncated, appended, rearranged, concatenated, etc., to generate orthogonal or quasi-orthogonal chip sequences. Codes of similar or different lengths may be concatenated. Different chip sequences may be combined in such a way that at least one chip sequence is interleaved with chips from at least one other code.

CI code vectors may be multiplied by other code vectors including, but not limited to, direct-sequence codes, complementary codes, and/or other CI codes. Groups of CI code chips may be modulated (scaled and/or shifted) with respect to other code chips. A CI code may be overlayed with a long code, a Hadamard-Walsh code, a Barker code, a Gold code, a Kasami code, a Golay code, a CI code, or some other code. CI coding may include multiple levels of coding wherein at least one set of code chips modulates at least one other set of code chips.

Basic CI codes form an orthonormal basis. New orthonormal bases can be generated by linearly combining CI codes of a particular length. More advanced permutations of CI codes may also be provided to form orthonormal bases. The orthonormal bases may be multiplied by code chips of other sequences, such as Hadamard-Walsh, Gold, CI, etc.

Data symbols may be mapped to CI codes to provide channel coding. For the purpose of mapping, bi-orthogonal CI codes may be generated by including a code set multiplied by the value −1. CI codes may be used to generate trans-orthogonal (e.g., simplex) codes. Quasi-orthogonal mapping may be performed by phase shifting or scaling the CI codes. A second set of orthogonal CI codes may be generated by rotating the phase of a first code set by $\pi/2$, thus providing in-phase and quadrature CI codes.

CI-coded symbols may be decoded by correlating a coded signal with a complex-conjugate code. A received signal may be processed with an FIR filter having coefficients set appropriately to decode a desired signal. The received signal may be sampled and summed. Optionally, samples of the received signal may be weighted prior to being summed to compensate for any of various effects, such as channel distortions, transmitter-side encoding (e.g., to reduce PAPR), jamming, etc. Weighting may be performed with respect to one or more optimization processes in which weights are adjusted with respect to at least one measurement, such as signal to noise, signal to noise plus interference, probability of error, BER, received signal power, etc.

The received signal may be phase shifted with respect to chip phases of a decoding signal. If a received signal includes multiple samples per chip interval, the chip samples may be time shifted with respect to the chip phases of the decoding signal. The samples corresponding to each chip may be cyclically shifted with respect to a decode chip sequence. Subsequent processing, such as sampling, adding, comparison, and/or decision making (hard and/or soft) may be performed to evaluate data symbols measured after the decoding process.

FIG. **5**A shows a set of 16 octonary code vectors C(n) resulting from multiplying an 8×8 basic CI code matrix $CI_{8\times8}$ by rows of an 8×8 Hadamard-Walsh matrix $HW_{8\times8}$. An 8×8 matrix resulting from a product of a matrix $CI_{8\times8}$ by a row of matrix $HW_{8\times8}$ includes two binary-phase 8-chip codes (which correspond to rows of matrix $HW_{8\times8}$), two quaternary-phase code vectors, and four octonary-phase code vectors including two complex-conjugate pairs. The 16 code vectors C(n) are selected from octonary-phase vectors in matrices resulting from products of vectors of $HW_{8\times8}$ with CI code matrix $CI_{8\times8}$.

FIG. **5**B shows auto correlations and cross correlations of the 16 octonary codes C(n) shown in FIG. **5**A. The correlation relationships may be used to choose orthogonal or quasi-orthogonal code sets from the codes C(n). For example, the codes C(1), C(1)*, C(2), C(2)*, C(4), C(4)*, C(7), and C(7)* form an orthogonal eight-code set. The code pair {C(1), C(1)*} has zero cross correlation with C(2), C(2)*, C(4), C(4)*, C(7), and C(7)* and thus, can be used with these codes to provide orthogonal code sets. Code C(1) has a non-zero cross correlation with codes C(1)*, C(5), and C(6)*. Thus, an orthogonal set may include codes C(1) and C(5), and exclude codes C(1)* and C(6)*. The codes C(3), C(3)*, C(5), C(5)*, C(6), C(6)*, C(7), and C(7)* form another orthogonal eight-code set. Codes C(7), C(3), C(8), C(4), C(1), C(5), C(2), and C(6) form yet another orthogonal eight-code set. Many other code sets, including quasi-orthogonal codes, are possible.

Orthogonal and quasi-orthogonal code sets may be implemented separately or simultaneously. Code sets may include combinations of different M-ary polyphase codes. An M-ary code set may include codes with a code length (i.e., number of code chips) that is less than or greater than M. Code sets may include numbers of codes that are less than or greater than the code lengths. Code sets may include same-length and/or different-length codes.

Although basic CI codes and one family of advanced CI codes are described herein, many other implementations of coding based on CI are clearly anticipated. CI code sets may be selected or manipulated to provide cross-correlation values that are shifted by $\pi/2$. CI codes may be used to generate bi-orthogonal and/or trans-orthogonal CI code sets. CI codes may include linear combinations of other CI codes. CI codes may be derived from Hadamard-Walsh matrix expansion, code concatenation, code interleaving, code superposition, and/or weighted code superposition wherein weights are applied to one or more code chips. A CI code may include at least one set of CI matrix elements, such as a row, a column, a diagonal, and/or matrix elements selected with respect to some predetermined pattern.

CI code chips may be cyclically shifted, swapped, or otherwise re-ordered. CI codes may be implemented as multi-level codes with one or more codes that are not necessarily CI codes. Multiple codes including at least one CI code may be interleaved. CI codes may be interleaved with same length or different length codes. CI codes may be implemented in block coding, convolutional coding, turbo coding, any other form of channel coding, encryption, multiple-access coding, spread-spectrum coding, peak-power mitigation, etc. CI codes may be implemented with orthogonal coding, quasi-orthogonal coding, bi-orthogonal coding, trans-orthogonal coding, or any combination thereof.

CI codes may be generated by convolving at least one set of CI codes with at least one other set of codes, including one or more of the following: CI codes, binary direct-sequence codes, channel codes, spreading codes, multiple-access codes, etc. CI codes may be provided with one or more parity-check symbols formed from linear combinations of data symbols and/or code chips.

FIG. **6**A illustrates basic components of a CI-code generator **603**. A CI-symbol generator **609** generates a plurality of CI symbols that are coupled to a symbol combiner **610**. The symbol combiner **610** groups the CI symbols to generate one or more CI codes.

A CI-symbol generator, such as the CI-symbol generator **609**, includes any algorithm, system, or device adapted to generate a plurality of CI symbols. CI symbols may include basic CI symbols. CI symbols may be discreet-valued or continuous-valued numbers or functions. CI symbols may be values derived from at least one invertible transform function, such as a Fourier transform, a Laplace transform, a Walsh transform, a wavelet transform, etc. CI symbols may include linear combinations of other CI symbols, linear combinations of CI symbols with other code symbols, CI symbols modulated with code sequences from a predetermined code set including one or more of the following: spread-spectrum codes, multiple-access codes, channel codes, encryption codes, multi-level codes, compression codes, hybrid codes, invertible-transform codes, and CI codes.

A CI symbol combiner, such as the symbol combiner **610**, includes any algorithm, system, or device adapted to group CI symbols to generate at least one CI chip sequence. A symbol combiner may append, concatenate, interleave, shift, puncture, or re-order one or more symbol sets. A symbol combiner may combine CI symbols with other symbols. A symbol combiner may provide a CI chips sequence with at least one parity-check symbol.

FIG. **6**B illustrates a CI transmitter adapted to generate at least one CI-coded information signal. A CI encoder **600** encodes at least one input information signal relative to at least one CI code produced by a CI code generator **603**. CI coded information signals are optionally coupled to a transmission system **602** that may include a pre-transmission processor (not shown).

FIG. **6**C illustrates basic components of a CI decoder that include a CI code generator **603** and a coherent combiner **605** adapted to decode at least one CI-encoded signal with respect to at least one code generated by the CI code generator **603**. Optionally, the decoder may be coupled to a front-end receiver processor **604** that provides the at least one CI-encoded signal to the decoder.

Channel coding provides signal transformations that are designed to improve communication performance by enabling transmitted signals to better withstand the effects of various channel impairments (e.g., noise, fading, interference). CI channel coding may include waveform coding and/or structured sequences. CI waveform coding (such as M-ary signaling, orthogonal coding, bi-orthogonal coding, trans-orthogonal coding, etc.) transforms waveforms to make them less subject to error. CI-structured sequences transform a data sequence into one or more sequences having structured redundancy. Redundant bits are used for detecting and/or correcting errors.

CI coding may include replacing a data set with an orthogonal codeword set. In one embodiment, a CI coder may multiplex multiple coded data symbols together by providing an orthogonal codeword set. A CI codeword set may be selected in which each codeword vector has zero projection onto all other CI codeword vectors except for its complex conjugate. A decoder may include multiple matched filters (or equivalent systems or algorithms) that output zero unless a corresponding encoded data symbol is received.

FIG. **7** illustrates a relationship between CI symbol values w_n and data symbols s_n. CI code chip values are arranged in columns with respect to phase spaces, such as phase space (column) **701**. A phase space may be analogous to a pulse position. The phase spaces (e.g., pulse positions) may be orthogonal or quasi-orthogonal. Thus, the number of CI symbols w_n may differ from the maximum number of data symbols s_n. Each data symbol value s_n is impressed upon a phase space such that each set of CI code chip values in that phase space expresses the value of the corresponding data symbol s_n. Each code chip value is analogous to a complex weight applied to a particular CI carrier. A superposition of these carriers produces a CI waveform (e.g., pulse) bearing the data symbol value s_n.

A CI superposition waveform bearing multiple data-symbol/pulse-position characteristics can be created by applying weights to CI carriers that correspond to sums of carrier weights for each data-symbol/pulse-position. Similarly, each CI symbol, such as symbol w_2, corresponds to a summed row of data-bearing CI code chips, such as row **703**. The code chips may be transmitted over multiple time intervals, carrier frequencies, polarizations, and/or other orthogonal diversity parameter values.

Decoding may include any appropriate inverse of the coding operation represented by FIG. **7**. For example, to extract an n^{th} data-symbol value s_n from a vector of received CI symbol values w, the complex conjugate of a vector of the n^{th} phase space (or CI code) values w_n may be correlated with the received CI symbol vector w. Equivalent decoding processes may be performed. The decoding process may be performed with respect to one or more combining techniques, such as, but not limited to, MMSE, EGC, maximum likelihood combining, or any combination thereof. Decoding may include turbo decoding.

FIG. **8**A illustrates basic components of a CI coding system and a CI decoding system. A data symbol stream **801** is processed by a CI symbol generator **820** that outputs a plurality of CI symbol values w_n representing a coded version of the data symbols s_n. The symbols w_n may be interleaved by an optional interleaver **804** prior to being prepared for transmission into a communication channel **899** by a pre-transmission processor (not shown) in a transmission system **805**. The symbols w_n are typically multiplexed onto one or more diversity-parameter spaces prior to transmission.

A receiver system **806** couples transmitted signals from the channel **899**, and a front-end receiver processor (not shown) performs any necessary processing, such as filtering, amplification, demultiplexing, de-spreading, decoding, and/or beam forming, prior to outputting an IF or baseband digital signal. Optionally, channel compensation **807** may be performed to mitigate effects of channel distortion and/or interference. Any necessary de-interleaving processes **808** may be performed prior to processing by a CI symbol decoder **830**. The decoder **830** processes received CI symbols w'_n to produce data-symbol estimates **801'**. The data-symbol estimates **801'** may be output to additional signal-processing systems (not shown).

The CI Symbol Generator **820** converts a predetermined number of input data symbols s_n to a plurality of CI code symbols w_n. This conversion may involve summing information-modulated CI code chips. A first step in a CI symbol generation process may include generating code chips and/or acquiring code chips stored in memory or received from an input data stream. Code chips may be generated from a reduced set (e.g., an orthonormal basis) of code chips or code vectors.

A second step in a CI symbol generation process involves impressing at least one data symbol s_n onto at least one set of code chips. The code chips may be multiplied, phase shifted, modulated, or otherwise impressed with data symbol values s_n. The code chips may represent a phase space, such as a pulse position. Optionally, the code chips may be provided with phase offsets, such as for crest-factor reduction or encryption.

A third step in a CI symbol generation process involves combining the code chips to produce one or more CI code symbols w_n. FIG. **7** illustrates how rows of information-modulated CI code chips are summed to produce CI code symbols w_n. Predistortion may be provided applying channel-compensation weights to the CI code symbols w_n.

The decoder **830** processes received CI symbols w'_n to produce data-symbol estimates **801'**. A first step in a CI decoding method includes generating code chips and/or acquiring code chips stored in memory or received from an input data stream. Code chips may be generated from a set of orthonormal codes or a subset of chips comprising one or more orthonormal codes.

A second step in a CI signal processing method includes combining or correlating at least one vector of the code chips with a vector of the received data symbols w'_n. A correlation process may include a scalar multiplication between the code chip vector and the received data symbol vector followed by combining (e.g., integrating) the products. Another embodiment of correlation includes adding together selected samples over a predetermined symbol interval T_s. Additional processing may be performed to produce estimates of the transmitted data symbols.

The decoder **830** may perform various types of combining, such as weighted combining as part of an MMSE, EGC, maximal likelihood, or any other performance-based optimization process. The decoder **830** may perform channel compensation. The decoder **830** may include a front-end receiver processor (not shown).

The bandwidth requirements for bi-orthogonal CI codes are half of the requirements for comparable orthogonal codes. Bi-orthogonal codes have slightly better performance over orthogonal codes because antipodal signal vectors have better distance properties than orthogonal signals. Trans-orthogonal (e.g., simplex) codes, when compared to orthogonal and bi-orthogonal codes, require the minimum SNR for a particular symbol error rate. Channel codes may be overlaid onto multiple-access codes. Depending on the processing gain of the multiple-access codes, channel coding may not require additional bandwidth.

FIG. **8**B shows a system diagram of a CI transceiver. An information source **851** provides data symbols to a CI coder/interleaver **852**. A modulator **853** modulates the coded symbols onto one or more carriers that are transmitted by a transmitter **805** into a communication channel **899**. The channel **899** may be characterized by AWGN and/or multipath. Other channel distortions may be considered. A receiver **806** couples the transmitted signals out of the channel **899**. A demodulator **863** retrieves symbols from the received signal. A CI decoder/de-interleaver **862** decodes (and de-interleaves, if necessary) the received symbols into information symbols that are optionally processed in an information processor or sink **861**.

In one embodiment, the coder **852** maps data symbols to CI code words using a look-up table. In another embodiment, the CI code words are generated with respect to each data symbol. Codeword generation may be performed with a CI code generation matrix G. CI codes of a given set of CI code words may be constructed from a combination of linearly independent code vectors that form the CI code generation matrix G.

Although code generation is described with respect to basic CI codes, orthonormal basis vectors and a corresponding CI code generation matrix may be constructed for advanced CI codes. Each code in a basic CI code set can be defined by a different number of full rotations in the complex plain. For example, an orthonormal basis for a set of N=64 basic CI codes can be defined by the CI code generation matrix:

$$G = \begin{bmatrix} C(\text{rotations} = 1) \\ C(\text{rotations} = 2) \\ C(\text{rotations} = 4) \\ C(\text{rotations} = 8) \\ C(\text{rotations} = 16) \\ C(\text{rotations} = 32) \end{bmatrix}$$

where C(rotations=m), m=0, 1, . . . , N−1, is a code vector corresponding to:

$$C(m)=e^{im\Phi'}(1,e^{im\Phi},e^{i2m\Phi}, \ldots ,e^{i(N-1)m\Phi})$$

Since this basic CI code set is totally defined by G, the coder **852** needs to store only k rows of G instead of 2^k vectors of the CI code matrix. Furthermore, since the first half of each row vector C(m) of G is the same as the second half (except C(l)'s first and second halves differ by a factor of −1), the coder **852** and decoder **862** need only store one half of each row vector C(m).

A CI receiver may perform error detection using any of several techniques. Symmetry relationships between the first and second halves of a received code can be exploited to determine whether an error occurred. Other relationships between code symbols may be used to provide error detection and/or correction. For example, adjacent CI code symbols (except for the all-ones code) are typically not identical. Depending on the code, the values of adjacent code symbols change in a predetermined way. For example, adjacent code chips of an m^{th} basic code C(m) differ by $e^{im\Phi}$.

A parity-check matrix H (defined by the equation, $GH^T=0$) can be used to test whether a received vector is a member of a codeword set. The decoder **862**, upon detecting an error, may perform forward error correction and/or request a retransmission. Preferably, the decoder **862** estimates the transmitted code vector using some optimizing strategy, such as the maximum-likelihood algorithm. The receiver may erase ambiguous signals. The decoder **862** may implement error correction to correct erasures and/or errors.

It is preferable that the coder **852** select codes that maximize the Hamming distance between codes. An advantage of using polyphase codes is that they provide a superior Hamming distance compared to binary codes. For example, (n,k)=(8,3) binary code has an n-tuple space of $2^n=2^8=256$ binary words, of which $2^k=2^3=8$ are code words. An octonary-phase (m=8) (8,3) code has an n-tuple space of $2^m=2^{64}$ octonary words. The fraction of words that are code words decreases dramatically with increasing values of m. When a small fraction of the n-tuple space is used for code words, a large Hamming distance can be created.

CI codes may be processed as cyclic codes, which are described in many prior-art references, such as B. Sklar, *Digital Communications, Fundamentals and Applications*, Prentice-Hall, Inc., New Jersey, 1988. For example, components of a CI code vector $C=(C_0, C_1, \ldots, C_{N-1})$ can be treated as coefficients of a polynomial U(X), as follows:

$$U(X)=u_0+u_1X+u_2X^2+\ldots+u_{N-1}X^{N-1}$$

where $X=e^{i2\pi nk/N}$, where k is the order of the code: k=0, 1, . . . , N−1. Well-known cyclic code processing may then be performed.

4. CI Networks

FIG. **9**A illustrates a tree network that may be implemented in aspects of the present invention. Transmissions passed to one or more nodes in the network may be branched off, or routed, to a plurality of nodes. Routing may include processing any combination of network addresses conveyed in headers and network addresses conveyed by codes (e.g., spreading codes, multiple-access codes, channel codes, etc.).

Network addresses may provide routing information and/or directions. For example, multiple addresses may convey one or more paths between a source node and a destination node. Various types of control information may be included in a code. For example, certain codes may convey priority information, identify the type of data payload, and/or otherwise tag the transmission.

FIG. **9**B illustrates a network design that permits a plurality of communication paths to each node. Multiple network connections between a source node and a destination node may be provided for redundancy. Alternatively, each path may be selected based on one or more criteria, such as channel conditions and load balancing.

FIG. **9**C illustrates a network design adapted to provide array processing performance advantages. A plurality of nodes **926**, **927**, **902**, **920**, **921**, and **922** are adapted to provide complex-weighted transmissions to at least one destination node, such as nodes **931** and **932**. For example, a data sequence addressed to node **931** is routed to nodes **926**, **927**, **902**, **920**, **921**, and **922**, which provide appropriate weights to the data transmission to generate a phase front **941** that converges at the destination node **931**. Similarly, appropriate delays or complex weights may be provided to transmissions to produce a coherent phase front **942** that converges at destination node **932**. Signals received by the nodes **926**, **927**, **902**, **920**, **921**, and **922** may be combined with respect to any combining technique, including optimal combining.

Nodes in a wireless network may generate weighted transmissions (or process received signals) to perform various types of array processing. Individual nodes may include one or more transceiver (e.g., antenna) elements. Array-processing operations may include combinations of local and global processing. For example, diversity combining may be performed at each multi-element node and signals from each node may be combined in a central processor to perform sub-space (i.e., directional) processing. Other combinations of local and global processing may be employed.

Array processing may include space-time processing, space-frequency processing, beam forming, null steering, blind-adaptive processing, long baseline interferometry, frequency-diversity interferometry, etc. Array processing may be performed to achieve any combination of sub-space processing (i.e., increased capacity) and diversity benefits in (i.e., improved performance). Selection of transmitting and receiving nodes in an array-processing network can be adapted to changing node positions, network loads, throughput requirements, user services, bandwidth availability, frequency-reuse requirements, channel conditions, etc.

FIG. **9**D illustrates a concentric ring network configuration in which a base station **900** or access point provides direct or indirect communication links to a plurality of subscriber units **901** to **935** arranged in a plurality of concentric-ring regions **951** to **953**. Subscriber units **901** to **906** in region **951** are adapted to route signals to one or more subscriber units **921** to **935** in one or more regions, such as region **953**. Similarly, subscriber units **911** to **918** in region **952** may be adapted to route signals to subscribers in other regions. In some applications, one or more subscribers may be adapted to route signals to at least one other subscriber in the same region.

Region shapes and sizes may be adapted to numbers of users and/or the geographical distributions of the users. Similarly, regions may be adapted to balance network loads. For example, subscriber power consumption and processing requirements associated with routing signals through subscribers near the base **900** can be mitigated by distributing routing operations over a larger number of subscribers. Thus, subscribers in regions **951** and **952** perform routing associated with a direct transmission from and/or to the base **900**. Similarly, the number of subscribers in primary arteries of tree networks (or other networks) can be increased. Routing functions can be assigned to subscribers based on subscriber location, subscriber load, channel conditions, and network load. The network configuration illustrated in FIG. **9**D may be integrated with other network architectures, such as tree configurations, or otherwise adapted to geographical distributions of subscribers and other network transceivers.

FIG. **9**E illustrates a network configuration adapted to the geographic distribution of a plurality of subscribers **921** to **926** and **931** to **936** located along a roadway. In this case, there are two routing paths **961** and **962** provided by subscriber routing. Network configurations, including transmission paths, may be adapted to subscriber distributions and channel conditions. For example, urban channel environments are typically characterized by a waveguide grid. Thus, routing paths may be provided with a grid architecture in urban areas.

A transmission may include multiple levels of coding intended to be stripped off at each node along a predetermined path to a particular address. FIG. **9**F illustrates three nodes **901**, **902**, and **904**. The first node is adapted to decode a one-rotation basic CI code by applying complex-conjugate decoding of the one-rotation code. A basic CI code c_m characterized by m rotations (m<N) is expressed by the following equation:

$$c_m = e^{im\phi'} \sum_{n=0}^{N-1} e^{imn2\pi/N} \hat{n}$$

The complex-conjugate decoding essentially unwinds the code. Similarly, nodes **902** and **904** are adapted to decode two-rotation and four-rotation codes, respectively. For simplicity, the rotations are provided in a common predetermined direction.

In one aspect of the invention, each node splits a received signal into at least two signals. At least one of the split signals is decoded at the node to extract any information intended for that node. A node may be associated with one or more addresses, or codes. At least one split signal is passed through the node without any decoding. Thus, node **901** receives signals coded (or addressed) with one code rotation, node **902** receives signals coded (or addressed) with two code rotations, etc.

In another aspect of the invention, a signal input to a node is not split prior to being decoded to extract any signals intended for that node. The decoded signal is then re-encoded with respect to the complex conjugate of the decoding operation. Thus, any unwinding associated with decoding is reversed prior to re-transmission of the coded information signal. Optionally, a node transceiver may cancel or otherwise remove signals addressed to itself prior to re-encoding.

In yet another aspect of the invention, coded transmissions are coded with respect to the intended path(s) to a predetermined address, thus obviating the need for splitting or re-encoding. For example, an information signal addressed to nodes **902** and **904** input to the first node **901** is encoded with a pair of basic CI codes having three rotations and seven rotations, respectively:

$$r_{node901} = \sum_{n=0}^{N-1} (s_2(t)e^{i3n2\pi/N} + s_4(t)e^{i7n2\pi/N})\hat{n}$$

Decoding at the first node **901** unwinds the coded signals by one rotation. The decode signal is characterized by C*(1), which is the complex conjugate of code C(1). Thus, node **901** passes a coded information signal to node **902** expressed by two-rotation and six-rotation codes:

$$r_{node902} = \sum_{n=0}^{N-1} (s_2(t)e^{i2n2\pi/N} + s_4(t)e^{i6n2\pi/N})\hat{n}$$

A sum of the decoded chips yields zero because there are no input signals coded with a single-rotation code. A sum of the chips generated at node **901** is zero because the non-zero rotations cause the chip values to cancel.

Decoding with decode signal C*(2) at node **902** unwinds the coded signals by two rotations. Thus, a sum of the decoded signal at node **902** coherently combines chip values associated with signal $s_2(t)$ and cancels chip values associated with signal $s_4(t)$. Node **902** produces a coded information signal expressed by:

$$r_{node904} = \sum_{n=0}^{N-1} (s_2(t) + s_4(t)e^{i4n2\pi/N})\hat{n}$$

The values $s_2(t)$ may optionally be removed (such as by cancellation, dc-offset removal, etc.) prior to transmission to node **904**. A node transceiver at node **902** may ensure non-zero chip values prior to transmission.

Coded signals received by node **904** are processed with a complex-conjugate code C*(4) that unwinds the coded signal by four rotations. The resulting decoded signal is expressed by:

$$r_{node904'} = \sum_{n=0}^{N-1} s_4(t)\hat{n}$$

Decoding and summing the code chips at node **904** coherently combines signal values $s_4(t)$ associated with a four-rotation code C(4).

FIG. **9**G illustrates a simple tree-style CI-based network. Nodes **901**, **902**, and **904** are provided with decode signals corresponding to C*(1), C*(2), and C*(4), respectively. A branch node **903** employs a decode signal C*(3) adapted to decode signals characterized by three rotations in a predetermined direction. A signal addressed with basic CI codes corresponding to rotations of seven, three, and six are input to node **901**. Signals output by node **901** to node **902** correspond to rotations of six, two, and five. Node **902** provides a decode signal of C*(2) to its input signal. Thus, the input corresponding to two rotations is decoded and the resulting value is processed at the node **902**. The resulting output signal(s) from node **902** is expressed by rotations as four, zero, three. The zero value may characterize a substantially null signal resulting from cancellation of the decoded signal at node **902**.

Node **902** may provide a broadcast signal to nodes **903** and **904**. Alternatively, node **902** may duplicate the signal four, zero, three and provide a signal to each of the nodes **903** and **904**. In some cases, node **902** may be adapted to separate its input signal into a plurality of components relative to addresses. Each component may be forwarded directly to its intended node. In some cases, separate signals may be provided via beam forming. In other cases, some form of multiple access, including header addresses, may be employed.

FIG. **9**H illustrates a simple multipath CI-based network. Node **902** is provided with coded signals (expressed in rotations as 2, 5, 6, 3, 4). The value two is addressed to node **902**. The values five and six are addressed to nodes **903** and **904**. A fourth node **906** receives transmissions from nodes **903** and **904**. Thus, values three and four characterize paths through nodes **903** and **904**, respectively, that are addressed to node **906**. Signals received and decoded at node **906** may be combined coherently. Such combining may include optimal combining.

In some aspects of the invention, node **906** may be provided with additional decode values (e.g., C*(5)) to enhance reception. Furthermore, two or more decode values (e.g., C*(6) and C*(5)) may be exploited in appropriate combinations to provide beam forming (or equivalent array processing) operations. Various combining operations may be performed to provide any combination of interference rejection, diversity enhancement, and sub-space processing (i.e., capacity enhancement).

FIG. **9**I illustrates a plurality of nodes **901** to **905** and at least two communication paths. A first communication path includes nodes **902**, **904** and **905**. A second communication path includes nodes **901**, **903**, and **905**. In this case, the two paths illustrate communication to node **5**. Alternatively communication paths may be provided indicating communications from node **905**.

Signals arriving from the first communication path are encoded with at least one code $c_1(n)$. Similarly, the signals arriving from the second communication path are encoded with at least one code $c_2(n)$. In various applications of the invention, additional communication paths (not shown) may be provided.

The codes $c_1(n)$ and $c_2(n)$ may be address codes or they may include address codes. The codes $c_1(n)$ and $c_2(n)$ may be similar or different. Alternatively, the codes $c_1(n)$ and $c_2(n)$ may be separate (or different) from address codes. In some cases, address codes may be adapted to provide additional coding or achieve other objectives, such as, but not limited to, encryption, verification, authentication, identification, anti-jamming, and/or diversity benefits.

In one set of embodiments of the invention, redundant information signals or signals providing redundant information are routed along the multiple paths to the destination node **905**. This can provide diversity benefits. The codes $c_1(n)$ and $c_2(n)$ may include similar or different channel codes. Signals provided along the multiple paths may be decoded (if necessary) and coherently combined in a receiver at the node **905**. Combining may include one or more optimal-combining techniques. The number of transmission paths that are coherently combined is proportional to an effective processing gain of the combining process. Consequently, low-power information-bearing transmissions may be employed over the multiple transmission paths. Signals received from different paths may be processed via soft-decision processing to provide confidence measurements for symbol estimates and/or enhance channel compensation and/or iterative decoding.

In another set of embodiments, each of a plurality of signals routed along different paths to a given node may provide necessary keys (or equivalent information) necessary for decoding. For example, signals routed along a first path may provide a coded information signal to a predetermined destination. Signals routed along a second path to the same destination may provide a decode sequence to decode the coded information signal. The codes $c_1(n)$ and $c_2(n)$ may include codes that are complex conjugates of each other. The first code $c_1(n)$ may include a public key and the second code $c_2(n)$ may include a private key wherein the two codes $c_1(n)$ and $c_2(n)$ contribute the necessary code keys for decoding a coded information signal transmitted along the first and/or second paths, or along a third path. Various pluralities of codes, paths, and/or coded information signals may be employed.

The process of providing multiple decoder keys across multiple transmission paths may be part of an authentication and/or verification process. The codes $c_1(n)$ and $c_2(n)$ may include channel-specific codes that characterize the channel between at least one transceiver and the destination node **905**. The codes $c_1(n)$ and $c_2(n)$ may include channel compensation. Consequently, a channel analysis of received signals at the destination node **905** will indicate the likelihood that the signals were transmitted from known nodes, such as nodes **903** and **904**. Similarly, channel analysis may be employed to determine the local source node of a given transmission. The codes $c_1(n)$ and $c_2(n)$ may include beamforming weights.

In some aspects of the invention, channel estimation may be performed on a signal received from a transceiver attempting to access the network. Various location-finding processes (e.g., direction-of-arrival determination, geo-location tracking, triangulation, etc.) may be implemented to determine the transceiver's location relative to a set or range of allowed locations. In some applications, identification of unauthorized users may be combined with location finding.

FIG. **9**J illustrates a node **902** used in a plurality of crossing communication paths. Nodes **901**, **902**, and **904** are part of a first communication path. Nodes **911**, **902**, and **913** are part of a second communication path characterized by at least one unique diversity parameter value. In this case, the communication paths are distinguished by different carrier frequencies. Alternatively, communication paths may be differentiated by code, polarization, subspace, time, phase, subspace, or any combination thereof.

Although basic CI codes are illustrated in the exemplary network architectures, other types of codes (including, but not limited to, complex CI codes, Walsh codes, multi-code sets, multi-level (or stacked) codes, and/or codes derived from invertible transforms) may be implemented in the examples shown, as well as in variations, adaptations, permutations, and combinations of the exemplary network architectures. Network address codes may be employed for one or more additional functions, including, but not limited to, spread spectrum, multiple access, channel coding, and encryption. Network designs shown in the figures and described in the specification are intended to convey basic principles and various aspects of the invention. These network designs do not limit the scope of the invention. Consequently, various network designs may be considered as building blocks for complex network architectures.

Network designs and other aspects of the invention may be combined with prior-art network designs, systems, devices, protocols, formats, and/or methods. Such combinations are clearly anticipated and suggested. Aspects and embodiments of the invention may serve as portions of networks. Network designs, systems, and/or methods of the invention may be adapted to various types of networks, such as long-haul, short-haul, last-mile, local-area, metropolitan-area, sensor, RF-identification, tracking, ad-hoc, mobile radio, personal communication, cellular, airborne, air-ground, and/or satellite networks. Network architectures of the invention may include one or more types of multiple access. Network architectures of the invention may include any combination of addressing, including address codes and packet headers containing addresses.

FIG. **10**A illustrates a multi-level cellular architecture that may be employed by systems and methods of the present invention. At least one macro-cell **1021** is subdivided into one or more micro-cells **1031**. Various multiple-access techniques may be used to separate communications in different cells. For example, a predetermined code may be provided to transmissions within the macro-cell **1021**. Macro-cell codes may be provided for inter-cell multiple access or radio isolation. Micro-cell codes may be provided for intra-cell multiple access. Codes applied to transmissions may implement additional network functions, such as spread spectrum, encryption, authentication, channel coding, addressing, and/or interference mitigation.

In some applications, multi-level codes may be implemented. In some cases, macro-cell codes may provide greater processing gain than the micro-cell codes. For example, macro-cell codes may consist of long codes and micro-cell codes may consist of shorter channel codes and/or multiple-access codes. Either or both micro-cell codes and macro-cell codes may implement CI and/or CI-based coding. Coding may be implemented with, or as part of, array processing.

FIG. **10**B illustrates three cells **1021** to **1023** in a cellular network of the present invention. Each cell **1021** to **1023** employs a different long code C_{L1} to C_{L3}, respectively, to differentiate between communications in adjacent cells. Each cell **1021** to **1023** provides intra-cell communications with codes $C_{s1\text{-}N}$ to differentiate between subscriber units in each cell. Coding may include CI and/or CI-based codes. Additional multiple-access techniques may be employed to provide for inter-cell and intra-cell multiple access.

FIG. **10**C shows a cellular architecture of the present invention that includes a plurality of cells **1021** to **1025** and a plurality of base stations **1001** to **1005** located on cell boundaries. The base stations **1001** to **1005** may include spatially sectorized antennas to provide communication to a plurality of cells. For example, base **1002** may be adapted to service users in cells **1021**, **1022**, and **1023**.

The base stations **1001** to **1005** may be adapted to route coded information across multiple cells. For example, coded data and/or control information is routed from base **1002** to base **1003**. A coded signal may be duplicated or decomposed for routing to multiple bases or subscriber units. For example, base **1003** transmits coded information to bases **1004** and **1005**. In some applications, subscriber units, such as subscriber units **1011** and **1012** may be employed to route information between two or more base stations. In any of the implementations of the invention, transmission paths through a network may be selected based on one or more criteria, including transceiver availability, transceiver locations, network loads, channel conditions, transmission-power requirements, etc.

FIG. **10**D illustrates a cellular network of the invention including a plurality of cells **1021** to **1030**, a plurality of base stations **1000** to **1009**, and a plurality of subscriber units, such as subscriber units **1061** to **1063** and **1071** to **1073**. In this case, the bases **1000** to **1009** are located inside each cell **1021** to **1030**. Other cellular architectures may be employed.

A base station (e.g., base **1000**) may route information directly to other bases (e.g., bases **1001**, **1002**, **1004**, **1005**, and **1006**). Such direct transmissions paths are indicated by transmission paths **1041** to **1045**. A direct transmission path **1046** may be provided to a base (such as base **1009**) that is not adjacent to the originating base **1000**. A transmission between bases may be routed through intermediate bases. For example, base **1005** acts as a router for transmissions between base **1000** and bases **1007** and **1008**. Similarly, subscriber units (such as subscriber units **1071** and **1072** may be employed as routers for communications between bases (e.g., bases **1000** and **1003**), between subscribers, and/or between bases and subscribers.

5. CI Routing Systems

FIG. **11**A illustrates a CI transceiver adapted to perform routing. Transmitted signals are received by a receiver system **1101** that outputs a baseband or IF signal. The receiver system **1101** performs RF and (optionally) baseband processes typically performed to convert an RF signal to a baseband or intermediate frequency signal. For example, the receiver system **1101** may perform channel selection, filtering, amplification, frequency conversion, and A/D conversion.

A CI decoder **1102** is adapted to decode the baseband signal relative to one or more address codes intended for the transceiver. The decoder **1102** may select a signal relative to an address in a header prior to decoding. A signal processor **1103** may process the decoded signals prior to producing an output data stream. Signal processing may include one or more signal-processing operations, including, but not limited to, quantization, channel decoding, multiple access decoding, demultiplexing, formatting, demodulation, channel estimation, channel compensation, synchronization, filtering, error detection, error correction, signal-quality analysis, multi-user detection, phase jitter compensation, frequency-offset correction, time-offset correction, etc.

A control system **1104** is adapted to select, adapt, or otherwise control the operation of one or more transceiver components. For example, channel estimates and/or signal-quality analysis performed by the signal processor **1103** may be processed in the control system **1104** to adapt decoding performed by the decoder **1102**. The control system **1104** may provide power-control information to the transmission system **1106**. For example, power control may include mitigating the effects of near-far interference. Channel selection may also be performed to mitigate near-far interference. The control system **1104** may provide other types of network control. For example, CI coding may be adapted by the control system **1104**.

A CI coder **1105** is adapted to process input data bits to produce a coded signal that is coupled to a transmission system **1106**. The transmission system **1106** performs signal-processing operations typically performed to prepare a baseband signal for transmission into a communication channel. The transmission system **1106** may perform one or more processes, including, but not limited to, D/A conversion, modulation, filtering, amplification, frequency conversion, beam forming, etc.

Signals from the receiver system **1101** are coupled to a CI decoder **1112**, which may include a bank of CI decoders. The decoder **1112** decodes received signals that are to be retransmitted. The decoded signals are processed in a signal processor **1113**. The signal processor **1113** may perform similar signal-processing operations as signal processor **1103**. Additionally, the signal processor **1113** may perform duplication, addressing, signal removal, information insertion, re-routing functions, and/or transmitter **1106** control. Furthermore, the signal processor **1113** may perform pre-processing operations prior to coding in a CI coder **1115**. The coder **1115** may include a CI coder bank. A control system **1114** is adapted to select, adapt, or otherwise control the operation of one or more of the transceiver components **1112**, **1113**, and **1115**.

The control system **1114** and the coder **1115** may provide channel-compensation and/or beam-forming weights to the coded symbols. Such weights may be regarded as part of the routing process. Since routing decodes some signals that are not intended for the transceiver, the router components **1112**, **1113**, **1114**, and **1115** are isolated from the rest of the transceiver by a fire wall **1110**.

Code division duplexing or cancellation division duplexing may be employed to permit reliable reception while concurrently transmitting. Alternatively, other types of duplexing may be employed. Pseudo-random time, frequency, and/or phase codes are typically used to avoid self-jamming. However, CI codes and CI-based waveforms enable the frequency-domain processing required for optimal performance in a multipath environment while providing data redundancy (i.e., channel coding) needed to mitigate errors. Optionally, additional channel coding (e.g., block, convolutional, TCM, turbo, etc.) may be provided to CI waveforms and/or CI coding.

FIG. **11**B illustrates an alternative embodiment of a CI receiver adapted to perform routing. Many of the system components shown in FIG. **11**B are similar to components shown in FIG. **11**A and thus, are identified by corresponding reference numbers. A portion of the baseband (or IF) signal (s) produced by the receiver system **1101** is optionally processed in a processor **1119** prior to being coupled into the transmission system **1106**.

The processor **1119** may perform one or more baseband or IF processes, including, but not limited to, signal shaping, filtering, re-quantization, error detection, error correction, interference mitigation, multi-user detection, amplification, up sampling, down sampling, frequency conversion, D/A conversion, AGC, symbol remapping, etc. The processor **1119** may be adapted to perform routing functions. In some applications, the processor **1119** may perform signal duplication, addressing, signal deletion, signal insertion, signal monitoring, address adjustment, re-routing, request retransmission, update header information, and/or insert or adjust control information.

FIG. **11**C illustrates a CI transceiver adapted to decode received signals intended for the transceiver and partially decode and route signals intended for one or more other transceivers. System components shown in FIG. **11**C are similar to components shown in FIG. **11**B, as indicated by similar reference numbers.

The CI decoder **1103** applies one or more decode signals to the received baseband signal. If the received baseband signal is coded with one or more codes including complex conjugates of the one or more decode signals, a sum of decoded baseband symbols over a code period combines coherently. The combined symbols have a value associated with one or more information signals. The combined symbols may be provided as a data output after one or more optional signal-processing operations.

Symbols generated by the CI decoder **1103** are optionally processed in processor **1119** prior to being coupled to a transmission system **1106** for re-transmission. CI-encoded signals not corresponding to complex conjugates of at least one of the decode signals (i.e., not intended for the transceiver) contribute a substantially zero value to the combined symbols. The processor **1119** may be adapted to remove one or more signal components intended for the transceiver. Since the signals intended for the transceiver provide a dc offset to the individual symbols generated by the CI decoder **1106**, these signals may be removed by filtering, cancellation, or some other dc-removal process.

6. CI Routing and Control Methods

FIG. **11**D illustrates a method whereby a transceiver in a network is provided with control information **1151** that includes information used to generate one or more array-processing weights **1153**. Array processing **1153** may be integrated into one or more transceiving functions **1153**, such as transmitting, receiving, routing, and/or relay operations.

A subscriber unit (or any other network transceiver) may be adapted to provide a directional or otherwise adaptable beam pattern. A beam pattern may be considered to include any type of array processing, including, but not limited to, space-frequency processing, space-time processing, spatial interferometry, null steering, diversity combining, spatial sweeping, and/or direction-of-arrival processing. A network transceiver, such as a subscriber unit, may act as an antenna element in an array including other network transceivers. Thus, a network transceiver may provide one or more weights to its transmitted and/or received signals as part of a larger array-processing scheme. Similarly, each antenna element of a multi-element network transceiver may be regarded as a transceiver element in a larger array. Each transceiver element may be provided with weights as part of a larger array-processing scheme. Array processing may be performed relative to one or more operational characteristics and/or objectives.

Array processing may depend on one or more network parameters, such as relative location of each destination address, relative location of each transmission source, interference characteristics (e.g., origin of interference, time-domain characteristics, frequency-domain characteristics, polarization, power, etc.), channel characteristics (e.g., multipath, Doppler, etc.), link priority, link security, spectrum management, power control, and network loads. Array processing may depend on the locations of one or more network transceivers, such as relays, routers, access points, base stations, and other subscriber units. Array processing may be adapted relative to changing locations of other network transceivers, changing operational configurations, interference, frequency-reuse plans, channel conditions, power-control specifications, performance measurements (e.g., BER, probability of error, SNR, SNIR, etc.), subscriber services, information type, modulation, formatting, channel selection, multiple-access protocol, frequency band, channel bandwidth, as well as any other Physical Layer and/or MAC Layer configurations.

FIG. **11**E illustrates a method in which individual network transceivers are adapted to perform array processing relative to local conditions. A channel-estimation step **1150** provides a characterization of the propagation environment to better optimize array processing **1152** and/or CI processing. Any combination of sub-space processing (i.e., capacity enhancement) and diversity combining (i.e., signal-quality enhancement) may be performed. Array processing **1152** may be integrated into a transceiver-operations step **1153**.

FIG. **11**F illustrates an array-processing method that employs at least one central processor to provide beam-forming operations across a plurality of spatially distributed network transceivers. Signals received by the distributed network transceivers are coupled to the central processor, which performs channel estimation **1160** to characterize one or more communication channels. Various operational characteristics and/or objectives (e.g., network parameters) are evaluated **1161**. The evaluation **1161** can affect calculations of array-processing weights in a step **1162** that provides control information to a plurality of network transceivers. Alternatively, the step of providing control information **1162** may include applications of array-processing weights to signals received from and/or transmitted to the network transceivers by the central processor.

FIG. **12**A illustrates a method for providing CI-coded transmissions of information and control signals. The method described in FIG. **12**A may be performed by a subscriber unit acting as a base station in a CI network. A CI code generation process **1201** provides CI codes and/or CI-based codes for at least one information signal and at least one control signal. A control signal may provide for one or more control functions, such as, but not limited to, power control, synchronization, code assignments, priority assignments, link assignments, channel assignments, duplexing control, training-signal generation, notice of transfer of control responsibilities, and request acknowledgement. Coding processes **1202** and **1203** encode the information signal (s) and control signal(s), respectively. A transmission process **1204** provides for transmission of the coded signals.

FIG. **12**B illustrates a method for managing network control in a CI network by one or more subscriber units adapted to function as base stations. A CI transceiver acting as a base station transmits CI-coded information and control signals in a transmission step **1210**. In a network identification and communication restriction step **1211**, CI codes can be used, at least in part, to address the communication and control channels. CI codes can be allocated to restrict communications between transceivers permitted to operate in the network. CI codes can also be used to identify a radio network and each of the radio devices, as well as the type of communications being transmitted.

A duplexing step **1212** provides for management of transmission and reception. Various types of duplexing may be employed, such as time-division duplexing, frequency-division duplexing, code-division duplexing, polarization-division duplexing, etc. A CI transceiver may include a plurality of CI decoders in parallel to allow reception of more than one signal simultaneously. Similarly, transmission of coded signals may be performed simultaneously with reception when the transmitted CI codes differ from the code of the received signal. Furthermore, different CI codes may be used to encode transmissions to differentiate types of transmitted signals.

A network-control step **1213** indicates that at least one of the subscriber units becomes a network control station. A network control station initiates communications and maintains power control and time synchronization of the network in the same manner that a base station would normally function. A transfer step provides for transfer of network control from at least one subscriber to at least one other subscriber. The network control station can voluntarily transfer, or be commanded to transfer, power control and time synchronization of the network to any other radio in the network.

FIG. **12**C illustrates a network-control method of the present invention. A CI coding step **1221** provides different CI codes (such as may be used to spread a signal) to information and control signals. A network control station may provide time-division duplexing **1222** to regulate transmission and reception. A network-control step **1223** provides for network control by the network control station. Network control **1223** can include various operations, including, but not limited to, synchronization, power control, code assignment, channel assignments, channel coding, transmission-path selection, load balancing, and spectrum management.

FIG. **12**D shows a routing method of the present invention. A coding step **1231** provides a multi-address, CI-coded signal for transmission in a transmission step **1232**. The addresses may be provided by any combination of CI coding and header addressing. Transmitted signals may be routed via one or more paths through a network. A duplication step **1233** is provided when transmission paths through a node diverge. Duplicated signals are transmitted along their respective paths.

In the methods and systems of the present invention, an address may include any combination of coding and header information. A header typically includes fields that provide control information, information-processing directives, waveform identification, network identification, and/or other information for enabling and facilitating network control and information processing. Tags are typically included in a header of a transmission. An information signal may be provided with one or more tags identifying the type of transmitted information, the amount of information, coding, number of addresses, routing information, and/or any other processing or payload information.

Header fields may include frame-sequence numbers, precedence, security, and end-of-message fields. A header may include a field indicating whether an acknowledgment is required from the destination node. Acknowledgments may be requested upon receipt, reading, and/or printing of received information. An extend field may identify whether an address is an extended network address usable when the destination node corresponding to the network address has moved from one network to another network. Information may be included in the header for forwarding a message to the other network. Information may be provided for updating routing tables maintained at a node. An end-of-routing field may be provided for indicating whether a network address is the last address in a multi-address network header. Tags and/or address information may be included in a preamble of a transmission.

FIG. **13**A shows a relay method of the present invention. Received signals are decoded in a decoding step **1301** at each node. The decoding step **1301** may involve applying a code to a received signal corresponding to the complex conjugate of the node's address code. A processing step **1302** processes information signals coded with the node's address code. Processing **1302** may include summing the decoded symbols and performing hard and/or soft decisions. Information signals addressed to the node provide a de offset to the symbols of the decoded signal. This offset may optionally be removed **1303** prior to transmitting **1305** the resulting decoded signals.

FIG. **13**B illustrates an alternative embodiment of a relay method of the invention. Some of the steps in the relay method shown in FIG. **13**B are similar to the steps shown in FIG. **13**A, as indicated by similar reference numbers. A reverse-decoding step **1304** provided between steps **1303** and **1305** applies the complex conjugate of any codes applied to the received signals in the decoding step **1302**.

FIG. **13**C illustrates a transceiver processing and routing method of the invention. A decoding step **1301** processes received signals with at least one complex-conjugate code corresponding to at least one address code associated with the transceiver address and/or one or more predetermined addresses. Decoding **1301** may include one or more decoding processes, such as channel decoding, multiple-access decoding, spread-spectrum decoding, and decryption. The decoding step **1301** may optionally include a level-detect function (not shown) to verify that a received signal is present prior to decoding.

A processing step **1302** is adapted to provide one or more signal-processing steps to the decoded signals. The processing step **1302** may estimate the values of information or control signals impressed onto address codes corresponding to one or more complex-conjugate codes provided in the decoding step **1301**. For example, an adding step (not shown) may provide for coherent combining of addressed information symbols. A decision step (not shown) may follow the adding step (not shown). If any signal values are present, they may be passed to an optional error detection/correction step **1311**.

Error detection/correction **1311** may employ parity checks, trellis demodulation, convolutional decoding, block decoding, and/or any other channel decoding or error-checking technique. Errors may be corrected via receiver-side processing. Alternatively, error detection may initiate a request for re-transmission. Error detection/correction **1311** may include re-quantization, channel estimation, channel compensation, predistortion of transmissions, multi-user detection, and/or optimal combining. Error detection/correction **1311** may include decision processing, including hard decisions and/or soft decisions. Decision processing may include iterative feedback processing, such as turbo decoding.

The signal values may be provided to an optional system-function step **1312**. Confidence measures from soft-decision processes may be used to adapt receiver parameters (e.g., the processing step **1302**), such as to optimize reception. Similarly, received control information may be used to adjust receiver parameters. System functions **1312** may include AGC, adapting filter parameters, adjusting quantization constellations, and/or changing sampling parameters. System functions may also include removing symbols or values associated with one or more predetermined addresses from the input signal values.

The signal values may be provided to an optional network-function step **1313**. Network functions **1313** may be selected or adapted relative to received control information. Network functions **1313** may include routing, addressing, power control, synchronization, request re-transmission, multiple-access control, channel selection, authentication, verification, identification, link-priority assignments, load balancing, spectrum management, and/or error processing. Network functions **1313** may include adding, removing, and/or changing system control information.

Data and control information are re-encoded in a coding step **1304**. Re-encoding **1304** may include the application of one or more codes, including address codes, multiple-access codes, spreading codes, channel codes, and encryption. Coded signals are processed for transmission into a communication channel in a transmission step **1305**.

FIG. **13**D illustrates a transceiver processing and routing method of the invention. A received signal is duplicated in a duplication step **1300**. At least one duplicated signal is coupled into a decoding step **1321** that applies a complex-conjugate code to the received signal. The complex-conjugate code is related to the address code of the transceiver. The decoded signal is processed in a processing step **1322** to extract or otherwise estimate information values addressed to the transceiver.

At least one of the duplicated signals is input to a secure procedure **1310**. For example, the at least one duplicated signal is passed through a fire wall (not shown). A decoding step **1316** provides for decoding signals addressed to one or more destinations other than the current transceiver. A processing step **1318** is adapted to provide one or more signal-processing steps to the decoded signals. The processing step **1318** may estimate the values of information or control signals impressed onto address codes corresponding to the complex-conjugate code(s) provided in the decoding step **1310**.

Processed signals may be coupled to one or more optional processing steps, including error detection/correction **1311**, system function **1312**, and network function **1313** steps. The processed signals are encoded **1314** prior to being transmitted **1305**. Similarly, data input to the transceiver is encoded **1324** prior to being transmitted **1305**.

7. Scope of the Invention

In the preferred embodiments, several kinds of addressing, coding, and routing are demonstrated to provide a basic understanding of applications of CI processing in ad-hoc and peer-to-peer networks. With respect to this understanding, many aspects of this invention may vary.

For illustrative purposes, flowcharts and signal diagrams represent the operation of the invention. It should be understood, however, that the use of flowcharts and diagrams is for illustrative purposes only, and is not limiting. For example, the invention is not limited to the operational embodiments represented by the flowcharts. The invention is not limited to specific network architectures shown in the drawings. Instead, alternative operational embodiments and network architectures will be apparent to persons skilled in the relevant art(s) based on the discussion contained herein. Also, the use of flowcharts and diagrams should not be interpreted as limiting the invention to discrete or digital operation.

In practice, as will be appreciated by persons skilled in the relevant art(s) based on the discussion herein, the invention can be achieved via discrete or continuous operation, or a combination thereof. Furthermore, the flow of control represented by the flowcharts is provided for illustrative purposes only. As will be appreciated by persons skilled in the relevant art(s), other operational control flows are within the scope and spirit of the present invention.

Exemplary structural embodiments for implementing the methods of the invention are also described. It should be understood that the invention is not limited to the particular embodiments described herein. Alternate embodiments (equivalents, extensions, variations, deviations, combinations, etc.) of the methods and structural embodiments of the invention and the related art will be apparent to persons skilled in the relevant arts based on the teachings contained herein. The invention is intended and adapted to include such alternate embodiments. Such equivalents, extensions, variations, deviations, combinations, etc., are within the scope and spirit of the present invention.

Signal processing with respect to sinusoidal oscillating signals are described herein. Those skilled in the art will recognize that other types of periodic oscillating signals that can be used, including, but not limited to, sinusoids, square waves, triangle waves, wavelets, repetitive noise waveforms, pseudo-noise signals, and arbitrary waveforms.

The foregoing discussion and the claims that follow describe the preferred embodiments of the present invention. With respect to the claims, it should be understood that changes can be made without departing from the essence of the invention. To the extent such changes embody the essence of the present invention, each naturally falls within the breadth of protection encompassed by this patent. This is particularly true for the present invention because its basic concepts and understandings are fundamental in nature and can be broadly applied.

The invention claimed is:

1. A method comprising:

dividing a block of complex-valued symbols into a plurality of sets of complex-valued symbols;

transform precoding each of the plurality of sets of complex-valued symbols into a block of transform-precoded complex-valued symbols; and

generating an Orthogonal Frequency Division Multiplex (OFDM) signal comprising a plurality of OFDM subcarriers modulated by the transform-precoded complex-valued symbols, wherein the transform precoding generates a plurality of orthogonal spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

2. The method of claim **1**, wherein the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform-precoded complex-valued symbols.

3. The method of claim **2**, wherein the DFT is a fast Fourier transform (FFT).

4. The method of claim 2, wherein:

$M_{sc}^{PUSCH}=M_{RB}^{PUSCH}*N_{sc}^{RB}$;

M_{RB}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of resource blocks; and

N_{sc}^{RB} is a resource block size in the frequency domain expressed as a number of subcarriers.

5. The method of claim 4, wherein:

$M_{RB}^{PUSCH} \leq N_{RB}^{UL}$; and

N_{RB}^{UL} is an uplink bandwidth configuration expressed in multiples of N_{sc}^{RB}.

6. The method of claim 1, comprising:

mapping the block of transform-precoded complex-valued symbols to physical resource blocks assigned for transmission of a physical uplink shared channel.

7. The method of claim 6, wherein the mapping is responsive to an assignment of spectrum resources for selecting a plurality of OFDM subcarriers corresponding to at least one OFDM symbol interval.

8. The method of claim 6, wherein at least one of the transform precoding and the mapping is configured to weight each of the plurality of OFDM subcarriers with an amplitude scaling factor to adjust gain of the superposition.

9. The method of claim 6, wherein the mapping is configured to select the plurality of OFDM subcarriers according to at least one of a frequency division multiple access scheme, a time division multiple access scheme, a space division multiple access scheme, a code division multiple access scheme, and a frequency-hoping scheme.

10. The method of claim 1, comprising:

scrambling a block of bits of one subframe of a physical uplink shared channel resulting in a block of scrambled bits; and

modulating the block of scrambled bits resulting in the block of complex-valued symbols.

11. The method of claim 10, wherein the scrambling is configured to scramble the block of bits into a block of scrambled bits with at least one pseudo-noise code.

12. The method of claim 1, wherein the transform precoding is applied according to

$$z(l \cdot M_{sc}^{PUSCH}+k)=\frac{1}{\sqrt{M_{sc}^{PUSCH}}}\sum_{i=0}^{M_{sc}^{PUSCH}-1} d(l \cdot M_{sc}^{PUSCH}+i)e^{-j\frac{2\pi ik}{M_{sc}^{PUSCH}}},$$

wherein:

the block of complex-valued symbols and the block of transform-precoded complex-valued symbol comprises a plurality of resource elements;

l represents a time-domain index of each of the plurality of resource elements;

k represents a frequency-domain index of each of the plurality of resource elements;

M_{sc}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of subcarriers;

$d(l \cdot M_{sc}^{PUSCH}+i)$ represents resource elements of the block of complex-valued symbols; and

$z(l \cdot M_{sc}^{PUSCH}+k)$ represents resource elements of the block of transform precoded complex-valued symbols.

13. The method of claim 12, wherein:

the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform precoded complex-valued symbols; and

M_{sc}^{PUSCH} is a length of the DFT corresponding to the plurality of orthogonal spreading codes.

14. The method of claim 13, wherein:

each transform-precoded set of complex-valued symbols of the block of transform-precoded complex-valued symbols is a single-carrier frequency division multiple access symbol; and

said each transform precoded set of complex-valued symbols is processed by the DFT.

15. The method of claim 12, wherein:

the block of transform-precoded complex-valued symbols comprises carrier interferometry symbol values (w_n); and

the block of complex-valued symbols comprises data symbols (s_n).

16. The method of claim 15, wherein carrier interferometry code chip values are arranged with respect to a plurality of phase spaces.

17. The method of claim 16, wherein the plurality of phase spaces comprises orthogonal phase spaces.

18. The method of claim 16, wherein each of the data symbol values is impressed upon one of the plurality of phase spaces.

19. The method of claim 15, wherein the number of carrier interferometry symbol values is different than the number of data symbols.

20. The method of claim 1, wherein each of the plurality of sets of complex-valued symbols is a single carrier frequency division multiple access (SC-FDMA) symbol.

21. The method of claim 1, comprising generating a time-continuous signal defined by:

$$s_l(t)=\sum_{k=-[N_{RB}^{UL}N_{sc}^{RB}/2]}^{[N_{RB}^{UL}N_{sc}^{RB}/2]-1} a_{k^{(-)},l}e^{j2\pi(k+1/2)\Delta f(t-N_{CP,l}T_s)},$$

wherein:

N_{sc}^{RB} is a resource block size in a frequency domain express as a number of subcarriers;

N_{RB}^{UL} is an uplink bandwidth configuration express in multiples of N_{sc}^{RB};

$a_{k^{(-)},l}$ is a value of a resource element;

Δf is subcarrier spacing;

$N_{CP,l}$ is a downlink cyclic prefix length for OFDM symbol l in a slot; and

T_s is a basic time unit.

22. The method of claim 21, wherein the time-continuous signal is generated in a single carrier frequency division multiple access (SC-FDMA) symbol.

23. The method of claim 1, wherein the transform precoding generates a plurality of quasi-orthogonal complex-valued spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

24. An apparatus, comprising:

a processor; and

a non-transitory computer-readable memory communicatively coupled to the processor, the memory including a set of instructions stored thereon and executable by the processor for:

dividing a block of complex-valued symbols into a plurality of sets of complex-valued symbols;

transform precoding each of the plurality of sets of complex-valued symbols into a block of transform precoded complex-valued symbols; and generating an Orthogonal Frequency Division Multiplex (OFDM) signal comprising a plurality of OFDM subcarriers modulated with the transform-precoded complex-valued symbols, wherein the transform precoding generates a plurality of orthogonal spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

25. The apparatus of claim **24**, wherein the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform-precoded complex-valued symbols.

26. The apparatus of claim **25**, wherein the DFT is a fast Fourier transform (FFT).

27. The apparatus of claim **25**, wherein:

$M_{sc}^{PUSCH}=M_{RB}^{PUSCH}*N_{sc}^{RB}$;

M_{RB}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of resource blocks; and

N_{sc}^{RB} is a resource block size in the frequency domain expressed as a number of subcarriers.

28. The method of claim **27**, wherein:

$M_{RB}^{PUSCH}\leq N_{RB}^{UL}$; and

N_{RB}^{UL} is an uplink bandwidth configuration expressed in multiples of N_{sc}^{RB}.

29. The apparatus of claim **24**, comprising instructions for:

mapping the block of transform-precoded complex-valued symbols to physical resource blocks assigned for transmission of a physical uplink shared channel.

30. The apparatus of claim **29**, wherein the mapping is responsive to an assignment of spectrum resources for selecting a plurality of OFDM subcarriers corresponding to at least one OFDM symbol interval.

31. The apparatus of claim **29**, wherein at least one of the transform precoding and the mapping is configured to weight each of the plurality of OFDM subcarriers with an amplitude scaling factor to adjust gain of the superposition.

32. The apparatus of claim **29**, wherein the mapping is configured to select the plurality of OFDM subcarriers according to at least one of a frequency division multiple access scheme, a time division multiple access scheme, a space division multiple access scheme, a code division multiple access scheme, and a frequency-hoping scheme.

33. The apparatus of claim **24**, comprising instructions for:

scrambling a block of bits of one subframe of a physical uplink shared channel resulting in a block of scrambled bits; and

modulating the block of scrambled bits resulting in the block of complex-valued symbols.

34. The apparatus of claim **33**, wherein the scrambling is configured to scramble the block of bits into a block of scrambled bits with at least one pseudo-noise code.

35. The apparatus of claim **24**, wherein the transform precoding is applied according to

$$z(l\cdot M_{sc}^{PUSCH}+k)=\frac{1}{\sqrt{M_{sc}^{PUSCH}}}\sum_{i=0}^{M_{sc}^{PUSCH}-1} d(l\cdot M_{sc}^{PUSCH}+i)e^{-j\frac{2\pi ik}{M_{sc}^{PUSCH}}},$$

wherein:

the block of complex-valued symbols and the block of transform-precoded complex-valued symbol comprises a plurality of resource elements;

l represents a time-domain index of each of the plurality of resource elements;

k represents a frequency-domain index of each of the plurality of resource elements;

M_{sc}^{PUSCH} is a scheduled bandwidth for uplink transmission expressed as a number of subcarriers;

$d(l\cdot M_{sc}^{PUSCH}+i)$ represents resource elements of the block of complex-valued symbols; and

$z(l\cdot M_{sc}^{PUSCH}+k)$ represents resource elements of the block of transform precoded complex-valued symbols.

36. The apparatus of claim **35**, wherein:

the transform precoding spreads the block of complex-valued symbols with a plurality of orthogonal spreading codes comprising complex-valued coefficients of a discrete Fourier transform (DFT) to produce the block of transform precoded complex-valued symbols; and

M_{sc}^{PUSCH} is a length of the DFT corresponding to the plurality of orthogonal spreading codes.

37. The apparatus of claim **36**, wherein:

each transform-precoded set of complex-valued symbols of the block of transform-precoded complex-valued symbols is a single-carrier frequency division multiple access symbol; and

said each transform precoded set of complex-valued symbols is processed by the DFT.

38. The apparatus of claim **36**, wherein the time-continuous signal is generated in a single carrier frequency division multiple access (SC-FDMA) symbol.

39. The method of claim **35**, wherein:

the block of transform-precoded complex-valued symbols comprises carrier interferometry symbol values (w_n); and

the block of complex-valued symbols comprises data symbols (s_n).

40. The method of claim **39**, wherein carrier interferometry code chip values are arranged with respect to a plurality of phase spaces.

41. The method of claim **40**, wherein the plurality of phase spaces comprises orthogonal phase spaces.

42. The method of claim **39**, wherein the number of carrier interferometry symbol values is different than the number of data symbols.

43. The method of claim **40**, wherein each of the data symbol values is impressed upon one of the plurality of phase spaces.

44. The method of claim **24**, wherein each of the plurality of sets of complex-valued symbols is a single carrier frequency division multiple access (SC-FDMA) symbol.

45. The method of claim **24**, comprising generating a time-continuous signal defined by:

$$s_l(t)=\sum_{k=-[N_{RB}^{UL}N_{sc}^{RB}/2]}^{[N_{RB}^{UL}N_{sc}^{RB}/2]-1} a_{k(-),l}e^{j2\pi(k+1/2)\Delta f\left(t-N_{CP,l}T_s\right)},$$

wherein:

N_{sc}^{RB} is a resource block size in a frequency domain express as a number of subcarriers;

N_{RB}^{UL} is an uplink bandwidth configuration express in multiples of N_{sc}^{RB};

$a_{k(-),l}$ is a value of a resource element;

Δf is subcarrier spacing;

$N_{CP,l}$ is a downlink cyclic prefix length for OFDM symbol **1** in a slot; and

T_s is a basic time unit.

46. The apparatus of claim **24**, wherein the transform precoding generates a plurality of quasi-orthogonal complex-valued spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

47. A computer program product, comprising a non-transitory computer readable hardware storage device having computer readable program code stored therein, said program code containing instructions executable by one or more processors of a computer system to implement a method comprising:

dividing a block of complex-valued symbols into a plurality of sets of complex-valued symbols; and

transform precoding each of the plurality of sets of complex-valued symbols into a block of transform precoded complex-valued symbols; and

generating an Orthogonal Frequency Division Multiplex (OFDM) signal comprising a plurality of OFDM subcarriers modulated with the transform-precoded complex-valued symbols, wherein the transform precoding generates a plurality of orthogonal spreading codes to provide a superposition of the plurality of OFDM subcarriers with a reduced peak-to-average-power ratio.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,389,568 B1
APPLICATION NO. : 15/786270
DATED : August 20, 2019
INVENTOR(S) : Steve Shattil

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 1, Line 14:
-- 9,042,333 --
Should be changed to:
-- 8,750,264 --

Signed and Sealed this
Seventeenth Day of August, 2021

Drew Hirshfeld
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,389,568 B1
APPLICATION NO. : 15/786270
DATED : August 20, 2019
INVENTOR(S) : Steve Shattil

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Drawings

Please replace Drawing Sheet 7 of 17 with Drawing Sheet 7 of 17 as shown on the attached page

In the Specification

Column 14, Line 50-51:
Please amend -- $f(\phi) = \{e^{j\theta 1}, e^{j\theta 2},\ldots,e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N},\ldots, e^{j(N-1)\cdot 2\pi k/N}\}$ --
To read -- $f(\phi) = \{e^{j\phi 1}, e^{j\phi 2},\ldots,e^{j\phi N}\} = \{e^{j0}, e^{j2\pi k/N},\ldots, e^{j(N-1)\cdot 2\pi k/N}\}$ --

Column 14, Line 60:
Please amend -- $\{t_1, t_2,\ldots,t_{N-1}\} = \{1/f_s, 2/f_s,\ldots,(N-1)/ /f_s\}$. --
To read -- $\{t_1, t_2,\ldots,t_{N-1}\} = \{1/f_s, 2/f_s,\ldots,(N-1)/f_s\}$. --

Column 14, Line 64:
Please amend -- $\{t_1, t_2,\ldots,t_{N-1}\} = \{1/f_s, 2/f_s,\ldots,(N-1)/ /f_s\}$. --
To read -- $\{t'_1, t'_2,\ldots,t'_{N-1}\} = 1/(2Nf_s) + \{1/f_s, 2/f_s,\ldots,(N-1)/f_s\}$. --

Column 15, Line 6-7:
Please amend -- $f_1(\phi) = \{e^{j\theta 1}, e^{j\theta 2},\ldots,e^{j\theta N}\} = \{e^{j0}, e^{j2\pi k/N},\ldots, e^{j(N-1)\cdot 2\pi k/N}\}$ --
To read -- $f_1(\phi) = \{e^{j\phi 1}, e^{j\phi 2},\ldots,e^{j\phi N}\} = \{e^{j0}, e^{j2\pi k/N},\ldots, e^{j(N-1)\cdot 2\pi k/N}\}$ --

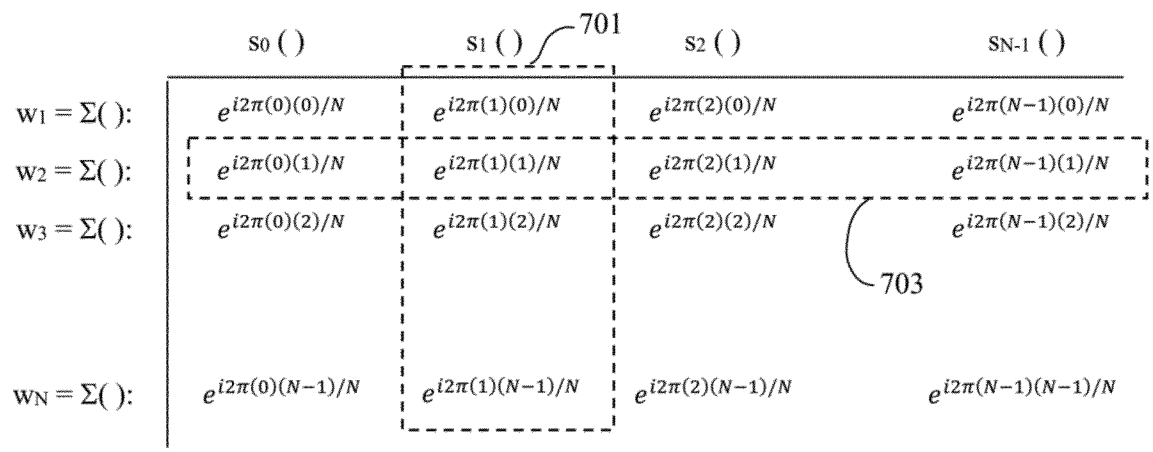
Column 15, Line 10-11:
Please amend -- $f_2(\phi) = \{e^{j\theta' 1}, e^{j\theta' 2},\ldots,e^{j\theta N}\} = \{e^{j(0+\Delta\phi)}, e^{j(2\pi k/N+\Delta\phi)},\ldots, e^{j((N-1)\cdot 2\pi k/N+\Delta\phi)}\}$ --
To read -- $f_2(\phi) = \{e^{j\phi' 1}, e^{j\phi' 2},\ldots,e^{j\phi' N}\} = \{e^{j(0+\Delta\phi)}, e^{j(2\pi k/N+\Delta\phi)},\ldots, e^{j((N-1)\cdot 2\pi k/N+\Delta\phi)}\}$ --

Column 16, Line 19:
Please amend -- offsets ϕ_k used --
To read -- offsets ϕ_{kn} used --

Signed and Sealed this
Twenty-fourth Day of August, 2021

Drew Hirshfeld
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office

Column 18, Line 28:
Please amend -- $\phi' = 2\phi f_o/f_s M$ --
To read -- $\phi' = 2\pi f_o/f_s M$ --


s0 ( )
s1 ( )
s2 ( )
sN-1 ( )
701
703
w1 = Σ( ):
w2 = Σ( ):
w3 = Σ( ):
wN = Σ( ):
$e^{i2\pi(0)(0)/N}$
$e^{i2\pi(1)(0)/N}$
$e^{i2\pi(2)(0)/N}$
$e^{i2\pi(N-1)(0)/N}$
$e^{i2\pi(0)(1)/N}$
$e^{i2\pi(1)(1)/N}$
$e^{i2\pi(2)(1)/N}$
$e^{i2\pi(N-1)(1)/N}$
$e^{i2\pi(0)(2)/N}$
$e^{i2\pi(1)(2)/N}$
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$e^{i2\pi(N-1)(2)/N}$
$e^{i2\pi(0)(N-1)/N}$
$e^{i2\pi(1)(N-1)/N}$
$e^{i2\pi(2)(N-1)/N}$
$e^{i2\pi(N-1)(N-1)/N}$

FIG. 7

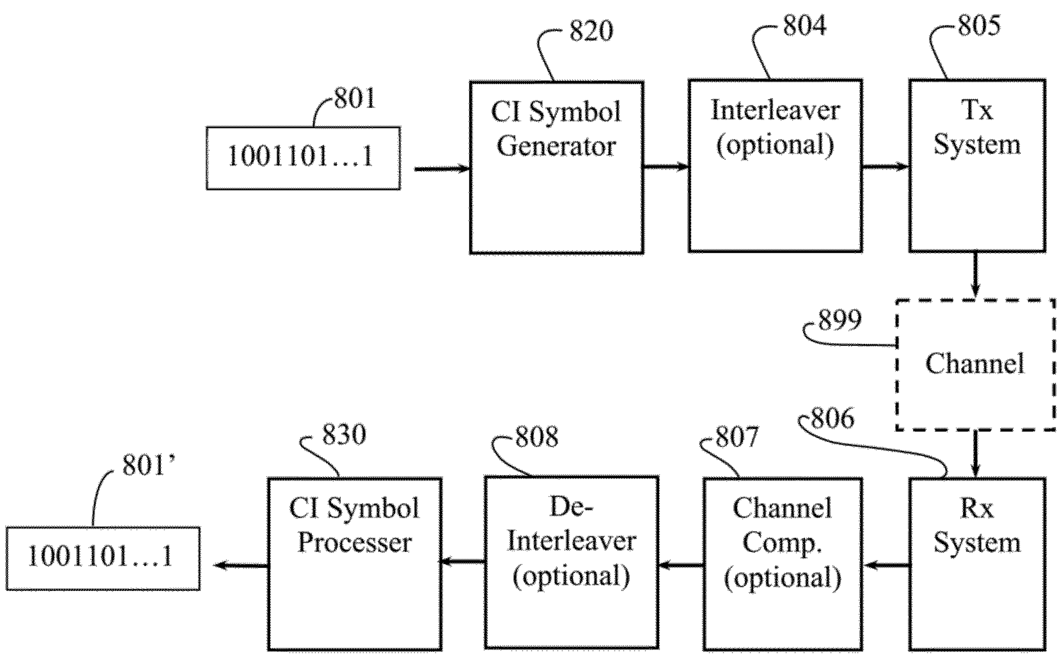
801
1001101…1
820
CI Symbol Generator
804
Interleaver (optional)
805
Tx System
899
Channel
806
Rx System
807
Channel Comp. (optional)
808
De-Interleaver (optional)
830
CI Symbol Processer
801'
1001101…1

FIG. 8A

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 10,389,568 B1
APPLICATION NO. : 15/786270
DATED : August 20, 2019
INVENTOR(S) : Steve Shattil

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

Column 1, Line 22:
-- 60 --
Should be changed to:
-- 35 --

Column 1, Line 23:
-- 60 --
Should be changed to:
-- 35 --

Signed and Sealed this
Twenty-sixth Day of October, 2021

Drew Hirshfeld
Performing the Functions and Duties of the
Under Secretary of Commerce for Intellectual Property and
Director of the United States Patent and Trademark Office