DUAL-CARRIER MODULATION OF COFDM WITH LABELING DIVERSITY TO REDUCE PAPR

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ABSTRACT

Dual-carrier modulation (DCM) is used to implement a species of tone reservation to reduce the PAPR of COFDM, wherein the reserved tones convey coded digital data (CDD) a second time. The same CDD is conveyed by carriers in a lower-frequency sub-band of the COFDM and by carriers in a higher- frequency sub-band. Each pair of carriers conveying the same CDD are separated by a sub-band width, enabling receivers better to ameliorate the effects of multipath reception. There is labeling diversity between the QAM symbol constellations that respectively govern modulation of carriers in the lower- frequency sub-band and modulation of carriers in the higher-frequency sub-band, which labeling diversity is designed to reduce PAPR of the COFDM. The labeling diversity also improves bit-error ratio (BER) for increased-size QAM symbol constellations used to increase CDD throughput despite the halving of CDD throughput owing to the use of DCM.

KEYWORDS

OFDM modulation, Peak-to -average power ratio, Dual carrier modulation, Labeling Diversity, QAM symbol constellation mapping.

1. PRELIMINARY COMMENTS

Drawing figures 1, 2, 3, 4, 5, 6, 7 and 8 each depict mapping of a respective QAM symbol constellation descriptive of modulation of sets of carriers that are used for conveying coded digital data (CDD) in a COFDM signal. Each of these QAM symbol constellations has its lattice-point labels (LPLs) each located in one of four quadrants, which quadrants can be named according to their positions relative to an in-phase axis **I** and a quadrature-phase axis **Q**. The upper right quadrant in each of Figs. 1 – 8 is referred to as the (+I,+Q) quadrant. The lower right quadrant in each of Figs. 1 – 8 is referred to as the (+I,-Q) quadrant. The lower left quadrant in each of Figs. 1 – 8 is referred to as the (-I,-Q) quadrant. The upper left quadrant in each of Figs. 1 – 8 is referred to as the (-I,+Q) quadrant. Similar nomenclature is applied to the 256QAM symbol constellations depicted in drawing figures 11, 12, 13 and 14. Similar nomenclature is also applied to the central portions of 256QAM symbol constellations of Figs. 11 and 12, as depicted in Figs. 9 and 10 respectively.

2. USING DCM TO IMPROVE RECEPTION OF COFDM SIGNALS DURING MULTIPATH AND/OR NARROWBAND INTERFERENCE

In some species of COFDM using dual-carrier modulation (DCM), the OFDM subcarriers in each pair of them conveying the same coded digital data (CDD) are separated a uniform distance from each other so as to fall in the lower and the higher halves of a frequency spectrum respectively. [1], [2], [3]. Such separation improves reliability of reception, especially when there are narrow-band interferences or are selective frequency drop-outs in signal strength owing to multipath reception.

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When only one of the OFDM carriers in each pair of them conveying the same CDD is received in strength, the receiver can choose to recover CDD just from that carrier. When both of the OFDM carriers in each pair of them conveying the same CDD are received in strength, the receiver can combine the respective CDD recovered from each of those OFDM carriers in sucha pair of them.

DCM halves the throughput of CDD in a COFDM signal, as compared to COFDM with the same number of carriers that use individual carrier modulation (ICM). To allay reduced CDD throughput, the size of the QAM symbol constellations governing the modulation of the DCM COFDM carriers conveying CDD can be made larger than the size of the QAM symbol constellations governing the modulation of the ICM COFDM carriers. By way of example, a DCM COFDM signal may use 16QAM of its carriers that convey CDD, in order to provide CCD throughput equivalent to an ICM COFDM signal that uses QPSK (or 4QAM) of its carriers that convey CDD.

3. Using DCM to Improve Bit-Error Ratio (BER) of Received COFDM Signals

Drawing figures 1 and 2, below, illustrate dissimilar respective mappings of two sets of square 16QAM symbols transmitted parallelly in time in a representative DCM COFDM signal. [3]. The two mappings describe superposition-coded modulation (SCM), which accommodates reduction of the PAPR of DCM COFDM signal as described *infra*.

The Fig. 1 and Fig. 2 mappings are designed to improve the BER of coded digital data (CDD) that a DCM COFDM signal receiver obtains from bit-reliability averaging (BRA) of the parallel-in-time CDD signals recovered by de-mapping the dual-mapped 16QAM symbol constellations that govern the DCM. To obtain such improvement, the LPLs of lattice points in the Fig. 2 SCM-mapped 16QAM symbol constellation mirror the LPLs of similarly positioned lattice points in the Fig.1 SCM-mapped QAM symbol constellation.

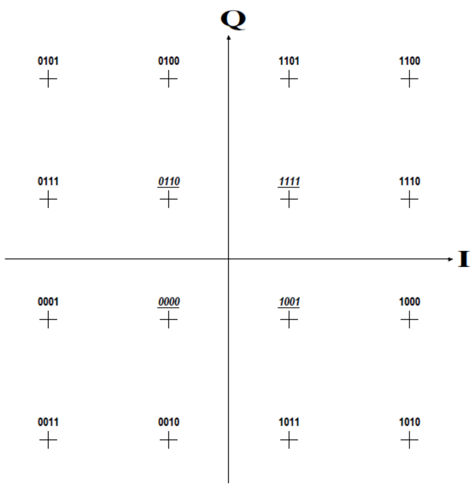

Fig. 1 "Basic" SCM-mapped 16QAM symbol constellation

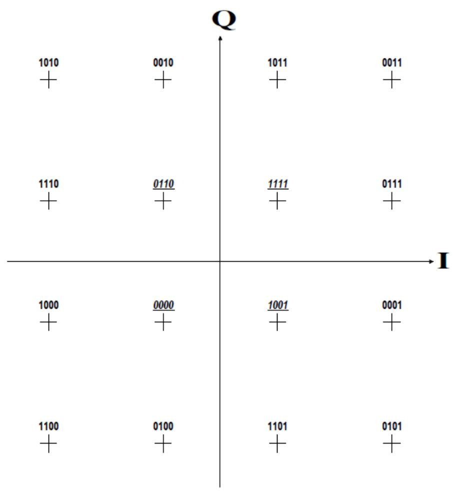

Fig. 2 An SCM-mapped 16QAM symbol constellation having LPLs that mirror the LPLs of the Fig. 1 16QAM symbol constellation

The following observations can be made concerning DCM COFDM signal that uses 16QAM of its carriers that convey CDD, in order to provide CCD throughput equivalent to an ICM COFDM signal that uses QPSK (or 4QAM) of its carriers that convey CDD, presuming the QAM symbol constellations to be square and to have uniform spacing between lattice points therein that are labeled with respective lattice-point labels (LPLs). (These conditions are met when DCM COFDM signal employs the 16QAM symbol constellations depicted in Figs. 1 and 2 to govern modulation of its carriers that convey CDD.) The bit-error ratio (BER) of the CDD segments recovered from COFDM using such 16QAM of its carriers is considerably higher thanthe BER of the CDD segments recovered from COFDM using QPSK of its carriers.

The bits of the LPLs of the 16QAM symbol constellations that describe finer spatial resolution have 6 dB greater likelihood of error in the presence of additive white Gaussian noise (AWGN)than the bits of the LPLs of the QPSK symbol constellations. This is simply because the stripes in 16QAM symbol constellation space these finer-spatial-resolution bits define are half the size of the stripes in QPSK symbol constellation space that each bit of its LPLs defines.

The bits of the LPLs of the 16QAM symbol constellations that describe coarser spatial resolution also have greater likelihood of error in the presence of additive white Gaussian noise(AWGN) than the bits of the LPLs of the QPSK symbol constellations. This is because bits of the LPLs of the 16QAM symbol constellations that describe finer spatial resolution add to the AWGN to increase likelihood of error in the bits of the LPLs of the 16QAM symbol constellations that describe coarser spatial resolution.

(These conditions are met when DCM COFDM signal employs the 16QAM symbol constellations depicted in Figs. 1 and 2 to govern modulation of its carriers that convey CDD.) The initial two bits of LPLs of the Fig. 1 "basic" SCM-mapped 16QAM symbol are less likely to be in error than the final two bits of these LPLs, supposing transmission over a channel afflicted by AWGN. The final two bits of LPLs of the Fig. 2 "basic" SCM-mapped 16QAM symbol are less likely to be in error than their initial two bits, supposing transmission over a channel afflicted by AWGN. When both carriers of the DCM COFDM signal are received, BRA will average each less-reliable bit with a more-reliable bit, rather than with another less-reliable bit. This tends to reduce the number of bit errors in the CDD recovered by the BRA, as compared with DCM in which each pair of carriers conveying the same segment of CDD use similar 16QAM mapping. [3].

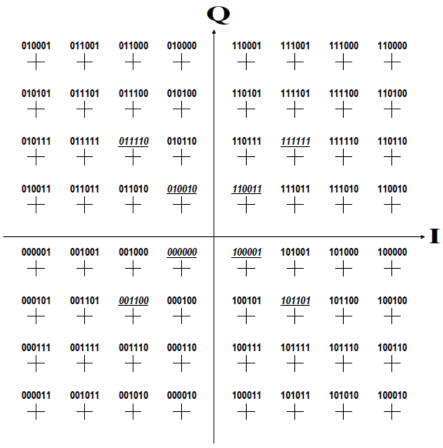

Fig. 3 "Basic" SCM-mapped 64QAM symbol constellation

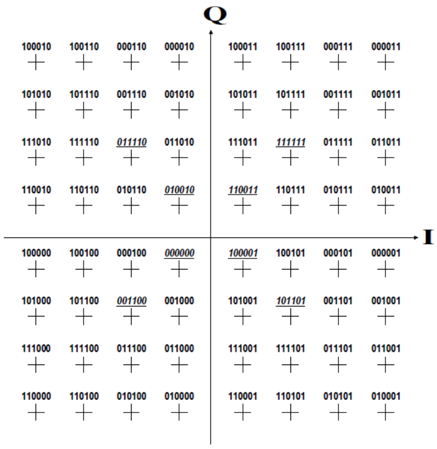

Fig. 4 An SCM-mapped 64QAM symbol constellation having LPLs that mirror the LPLs of the Fig. 3 64QAM symbol constellation

Drawing figures 3 and 4, above, illustrate dissimilar respective SCM mappings of two sets of square 64QAM symbols transmitted parallelly in time in a representative DCM COFDM signal.

The Fig. 3 and Fig. 4 mappings are designed to improve the BER of CDD that a DCM COFDM signal receiver obtains from bit-reliability averaging (BRA) of the parallel-in-time CDD signals recovered by de-mapping dual-mapped 64QAM symbol constellations. Accordingly, the LPLs of lattice points in the Fig. 4 SCM-mapped 64QAM symbol constellation mirror the LPLs of correspondingly positioned lattice points in the Fig. 3 "basic" SCM-mapped 64QAM symbol.

In general, a DCM COFDM signal may use $2^{4(N+1)}$QAM of its carriers that convey CDD, N being a positive integer, in order to provide CCD throughput equivalent to an ICM COFDM signal that uses $2^{2(N+1)}$QAM of its carriers that convey CDD. The BER of the CDD segments recovered from ICM COFDM using such $2^{4(N+1)}$QAM of its carriers is considerably higher than the BER of the CDD segments recovered from ICM COFDM using $2^{2(N+1)}$QAM of its carriers.

E. g., BER of the CDD segments recovered from ICM COFDM using 256QAM of its carriers is considerably higher than the BER of the CDD segments recovered from ICMCOFDM using 16QAM of its carriers. BER of the CDD segments recovered from ICM COFDM using 4096QAM of its carriers is considerably higher than the BER of the CDD segments recovered from ICMCOFDM using 64QAM of its carriers.

Depicting respective SCM mappings of two sets of square 256QAM symbol constellations withbinary-number LPLs of readable font size presents difficulty with the page formatting of ***IJWMN.*** Also, the information in such a mapping is too voluminous to be readily assimilated by a casual reader. Reference [3] presents similar SCM mappings of square 256QAM symbol constellations useful in DCM COFDM, quadrants of which constellations are shown on respective sheets of drawing.

Each of the four quadrants of square QAM symbol constellations larger than QPSK (or 4QAM) can be considered to consist of four sub-quadrants: an innermost sub-quadrant closest to the center of the symbol constellation, an outermost sub-quadrant farthest from that center. and two other sub-quadrants that are referred to as flanking sub-quadrants. Drawing figures 5 and 6, following, depict the innermost sub-quadrants of dissimilar respective mappings of two sets of square 256QAM symbols transmitted in parallel in a representative DCM COFDM signal.

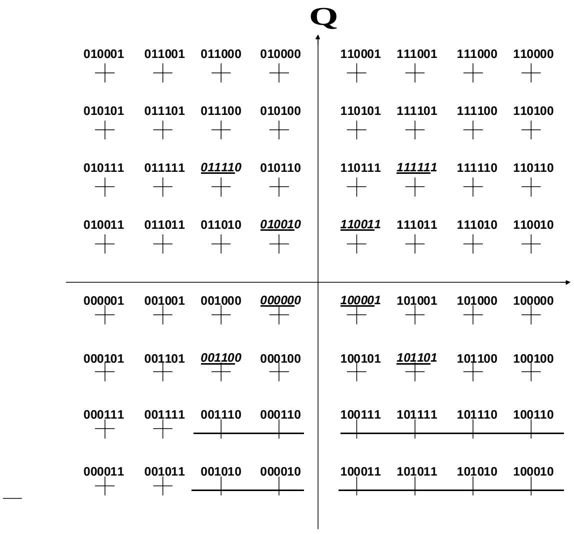

Fig. 5. Innermost sub-quadrants of "Basic" SCM-mapped 256QAM symbol constellation

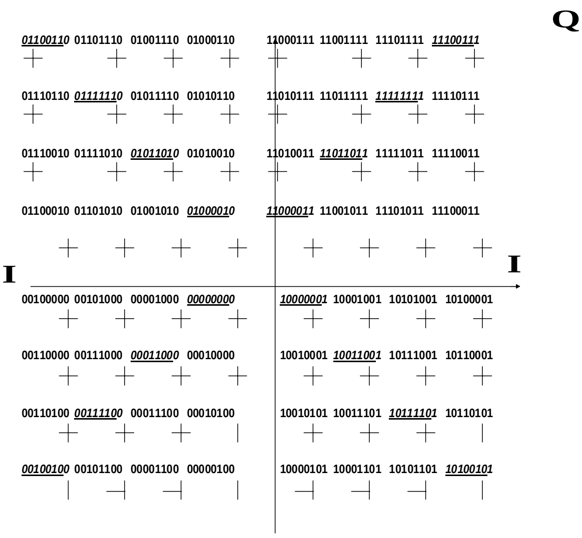

Fig. 6. Innermost sub-quadrants of ana SCM-mapped 256QAM constellation having LPLs that mirror LPLs of lattice points in Fig. 5 that are similarly positioned

Note that the binary-number LPLs of corresponding lattice points in Fig. 5 and Fig. 6 mirror each other, so as to reduce the number of bit errors in the CDD recovered by BRA in a DCM COFDM signal receiver.

4. USING DCM TO REDUCE PAPR OF COFDM SIGNALS

Reference [3] describes respective SCM mappings of two sets of similar-size QAM symbols transmitted parallel in time, which mappings have labeling diversity between them that is designed to reduce significantly the peak-to-average-power ratio (PAPR) of DCM COFDM signals. Reference [3] points out that: reductions in PAPR can be larger if the QAM symbol constellations are not simply Gray mapped, but rather are mapped in accordance with superposition-coded modulation (SCM). In SCM the four quadrants of square QAM symbol constellations are each Gray mapped independently from the others and from the pair of bits in the map label specifying that quadrant. SCM was previously employed for purposes other than minimizing PAPR of DCM COFDM signals. [4]. Drawing figures 7 and 8, following, depict SCM-mapped 16QAM symbol constellations, either one of which can be used together with the Fig. 1 SCM-mapped 16QAM symbol constellation in a DCM COFDM signal with PAPR closeto 0 dB. [3].

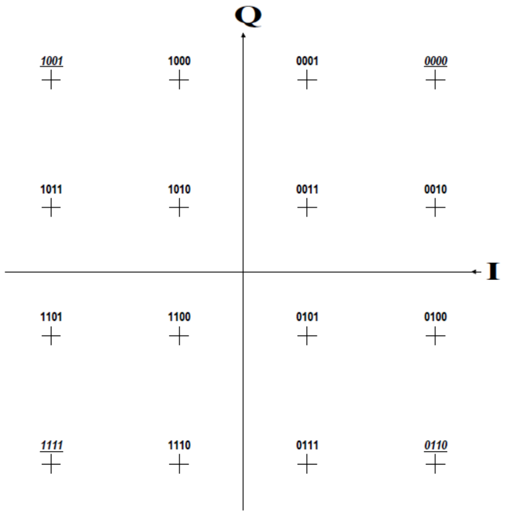

Fig. 7 An SCM-mapped 16QAM symbol constellation for reducing PAPR of dual-mapping with the Fig. 1 or Fig. 2 16QAM symbol constellation

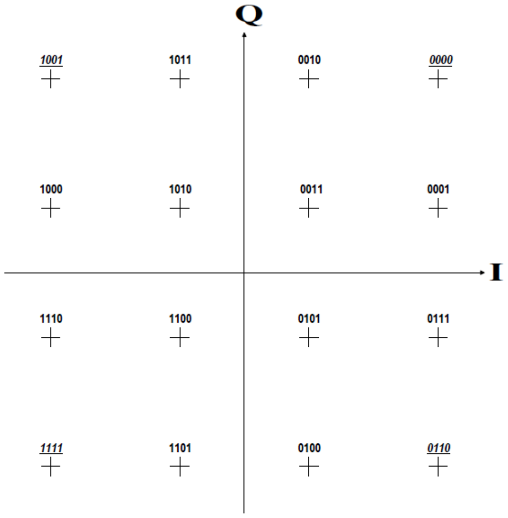

Fig. 8 An SCM-mapped 16QAM symbol constellation for reducing PAPR of dual-mapping with the Fig. 1 or Fig. 2 16QAM symbol constellation

The 16QAM symbol constellation in Fig. 7, above, is derived in the following way from the 16QAM symbol constellation in Fig. 1. A diagonal translation of the (+I,+Q) quadrant of the Fig. 1 symbol constellation generates the (-I,-Q) quadrant of the Fig. 7 symbol constellation. A diagonal translation of the (+I,-Q) quadrant of the Fig. 1 symbol constellation generates the (-I,+Q) quadrant of the Fig. 7 symbol constellation. A diagonal translation of the (-I,-Q) quadrant of the Fig. 1 symbol constellation generates the (+I,+Q) quadrant of the Fig. 7 symbolconstellation. A diagonal translation of the (-I,+Q) quadrant of the Fig. 1 symbol constellation generates the (+I,-Q) quadrant of the Fig. 5 symbol constellation. These diagonal translations move the LPLs associated with the four high-energy carriers at the outer-corner lattice points inthe Fig. 1 symbol constellation so as to be associated with the four low-energy carriers at the most-central lattice points in the Fig. 2 symbol constellation. These diagonal translations movethe LPLs associated with the four low-energy carriers at the most-central lattice points in the Fig. 1 symbol constellation so as to be associated with the four high-energy carriers at the outer-corner lattice points in the Fig. 7 symbol constellation.

The 16QAM symbol constellation in Fig. 8 is derived, as follows, from the 16QAM symbol constellation in Fig. 7. Each of the four quadrants in the 16QAM symbol constellation in Fig. 7is twisted (out of plane) 180^o around its diagonal axis that reaches to the intersection of theI axis and the Q axis of the symbol constellation.

The Fig. 1 SCM-mapped 16QAM symbol constellation purposely has its four palindromic LPLs clustered about its center. The mirroring of the LPLs of the Fig. 1 SCM-mapped 16QAM symbol constellation in the correspondingly positioned LPLs of the Fig. 2 SCM-mapped 16QAM symbol constellation leaves these four palindromic LPLs in place. Accordingly, eitherone of the Fig. 7 and Fig. 8 SCM-mapped 16QAM symbol constellations can be used together with the Fig. 2 SCM-mapped 16QAM symbol constellation in a DCM COFDM signal with PAPR also being close to 0 dB. These DCM COFDM signals will have lower BER than the DCM COFDM signals that use the Fig. 1 SCM-mapped 16QAM symbol constellations with theFig. 7 or the Fig. 8 SCM-mapped 16QAM symbol constellation.

Drawing figures 9 and 10, following, depict SCM-mapped 64QAM symbol constellations, either one of which can be used together with the Fig. 1 SCM-mapped 16QAM symbol constellation in a DCM COFDM signal to reduce PAPR 2.92 dB to be close to 0.86 dB. [3],

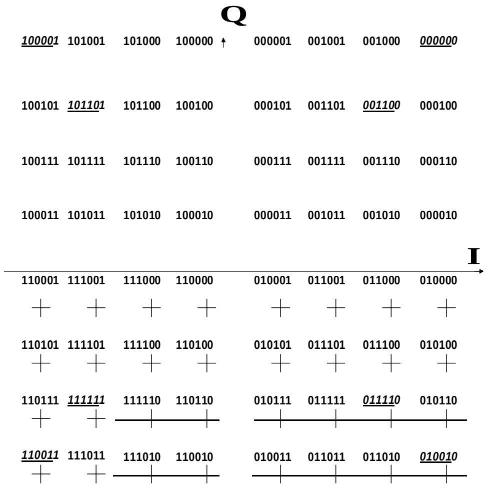

Fig. 9 An SCM-mapped 64QAM symbol constellation for reducing PAPR of dual-mapping with the Fig. 3 or Fig. 4 64QAM symbol constellation

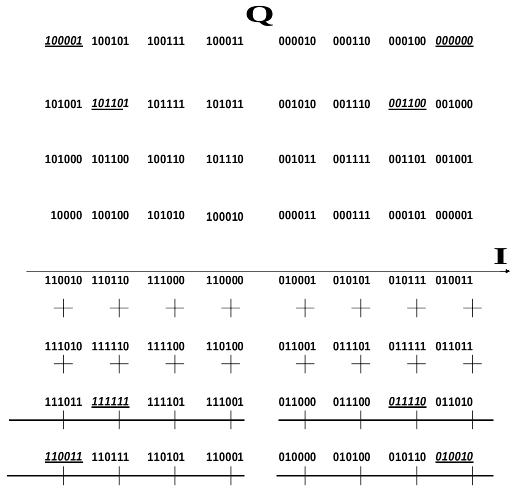

Fig. 10 An SCM-mapped 64QAM symbol constellation for reducing PAPR of dual-mapping with the Fig. 3 or Fig. 4 64QAM symbol constellation

The 64QAM symbol constellation in Fig. 9, above, is derived from the 64QAM symbol constellation in Fig. 3 in the following way. A diagonal translation of the (+I,+Q) quadrant of the Fig. 3 symbol constellation generates the (-I,-Q) quadrant of the Fig. 9 symbol constellation. A diagonal translation of the (+I,-Q) quadrant of the Fig. 3 symbol constellation generates the (-I,+Q) quadrant of the Fig. 9 symbol constellation. A diagonal translation of the (-I,-Q) quadrant of the Fig. 3 symbol constellation generates the (+I,+Q) quadrant of the Fig. 7 symbolconstellation. A diagonal translation of the (-I,+Q) quadrant of the Fig. 3 symbol constellation generates the (+I,-Q) quadrant of the Fig. 9 symbol constellation. These diagonal translations move the LPLs associated with the four high-energy carriers in the outermost sub-quadrant of the Fig. 3 symbol constellation so as to be associated with the four low-energy carriers in the innermost sub-quadrant of the Fig. 9 symbol constellation. These diagonal translations move the LPLs associated with the four low-energy carriers innermost sub-quadrant of the Fig. 3 symbol constellation so as to be associated with the four high-energy carriers in the outermost sub- quadrant of the Fig. 9 symbol constellation.

The 64QAM symbol constellation in Fig. 10 is derived, as follows, from the 64QAM symbol constellation in Fig. 9. Each of the four quadrants in the 64QAM symbol constellation in Fig. 9is twisted (out of plane) 180^o around its diagonal axis that reaches to the intersection of theI axis and the Q axis of the symbol constellation.

The Fig. 3 SCM-mapped 64QAM symbol constellation purposely has its eight palindromic LPLs positioned in the following way. A respective pair of the palindromic LPLs is positioned along the diagonal of the innermost sub-quadrant of each of the (+I,+Q), (+I,-Q), (-I,-Q), and (+I,+Q) quadrants of that symbol constellation, which diagonal touches the centerpoint of the symbol constellation. The mirroring of the LPLs of the Fig. 3 SCM-mapped 64QAM symbol constellation in the correspondingly positioned LPLs of the Fig. 4 SCM-mapped 64QAM symbol constellation leaves these four palindromic LPLs in place. Accordingly, either one of the Fig. 9 and Fig. 10 SCM-mapped 64QAM symbol constellations can be used together with the Fig. 4 SCM-mapped 64QAM symbol constellation in a DCM COFDM signal with PAPR also being close to 0.86 dB. These DCM

COFDM signals will have lower BER than the DCM COFDM signals that use the Fig. 3 SCM-mapped 64QAM symbol constellations with the Fig. 9 or the Fig. 10 SCM-mapped 64QAM symbol constellation.

Drawing figures 11, 12, 13 and 14 on the following four pages each depict a complete 256QAM symbol constellation with decimal-number labeling of its 256 lattice points, rather than binary- number labeling, because the 8-bit binary number labels are difficult to fit in a single-page figure. Also, patterns of the LPLs regarding the reduction of PAPR in DCM COFDM will likelybe more easily discerned by casual readers of this paper.

The central portion of the complete 256QAM symbol constellation with decimal-number labeling depicted in Fig. 11 corresponds to that central portion depicted with binary-number labeling in Fig. 5. The final six bits of binary-number LPLs for the complete SCM-mapped 256QAM symbol constellation of Fig. 11 would define a Gray-mapped 64QAM symbol constellation, as included within each quadrant of that 256QAM symbol constellation.

The central portion of the complete 256QAM symbol constellation with decimal-number labeling depicted in Fig. 12 corresponds to that central portion depicted with binary-number labeling in Fig. 6. The final six bits of the binary-number LPLs of the complete SCM-mapped 256QAM symbol constellation of Fig. 12 would define a Gray-mapped 64QAM symbol constellation included within each quadrant of that 256QAM symbol constellation.

The 256QAM symbol constellation in Fig. 13 is derived from the Fig. 11 symbol constellation, as follows. A diagonal translation of the (+I,+Q) quadrant of the Fig. 11 symbol constellation generates the (-I,-Q) quadrant of the Fig. 13 symbol constellation. A diagonal translation of the(+I,-Q) quadrant of the Fig. 11 symbol constellation generates the(-I,+Q) quadrant of the Fig. 13 symbol constellation. A diagonal translation of the (-I,-Q) quadrant of the Fig. 11 symbol constellation generates the (+I,+Q) quadrant of the Fig. 13 symbol constellation. A diagonal translation of the (-I,+Q) quadrant of the Fig. 11 symbol constellation generates the (+I,-Q) quadrant of the Fig. 13 symbol constellation. These diagonal translations move the LPLs associated with the 64 high-energy carriers in each of the four outermost sub-quadrants of the Fig. 11 symbol constellation so as to be associated with the 64 low-energy carriers in each of thefour innermost sub-quadrants of Fig. 13 symbol constellation. These diagonal translations movethe LPLs associated with the 64 low-energy carriers in each of the four innermost sub-quadrantsof the Fig. 11 symbol constellation so as to be associated with the 64 high-energy carriers in each of the four outermost sub-quadrants of the Fig. 13 symbol constellation.

The 256QAM symbol constellation in Fig. 14 is derived, as follows, from the 256QAM symbol constellation in Fig. 13. Each of the four quadrants in the 256QAM symbol constellation in Fig. 13 is twisted (out of plane) 180o around its diagonal axis that reaches to the intersection of the I axis and the Q axis of the symbol constellation. The BER of the CDD segments recovered from ICM COFDM using such $2^{4(N+1)}$ QAM of its carriers is considerably higher than the BER of the CDD segments recovered from ICM COFDM using $2^{2(N+1)}$ QAM of its carriers.

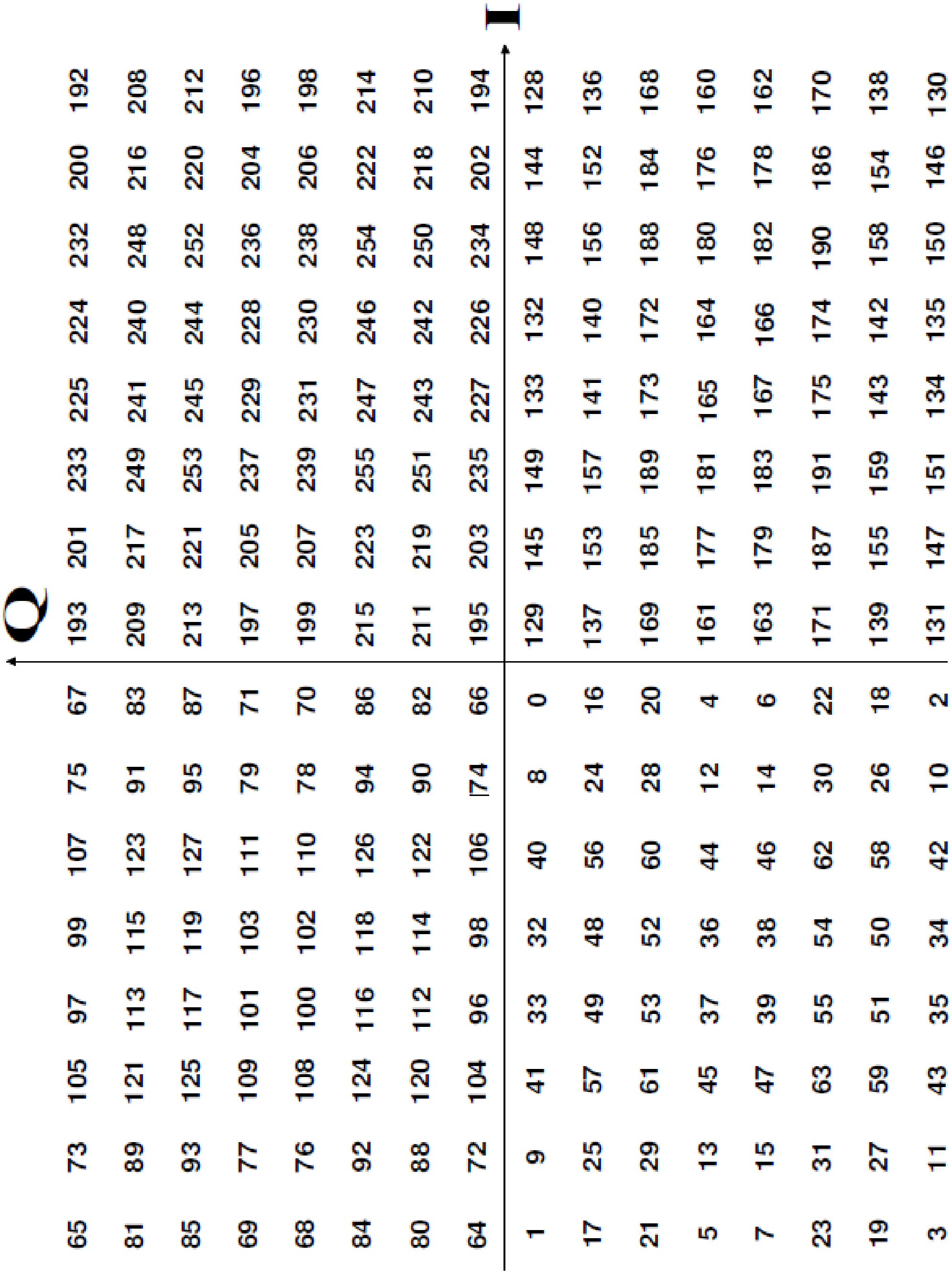

Fig. 11. "Basic" SCM-mapped 256QAM symbol constellation

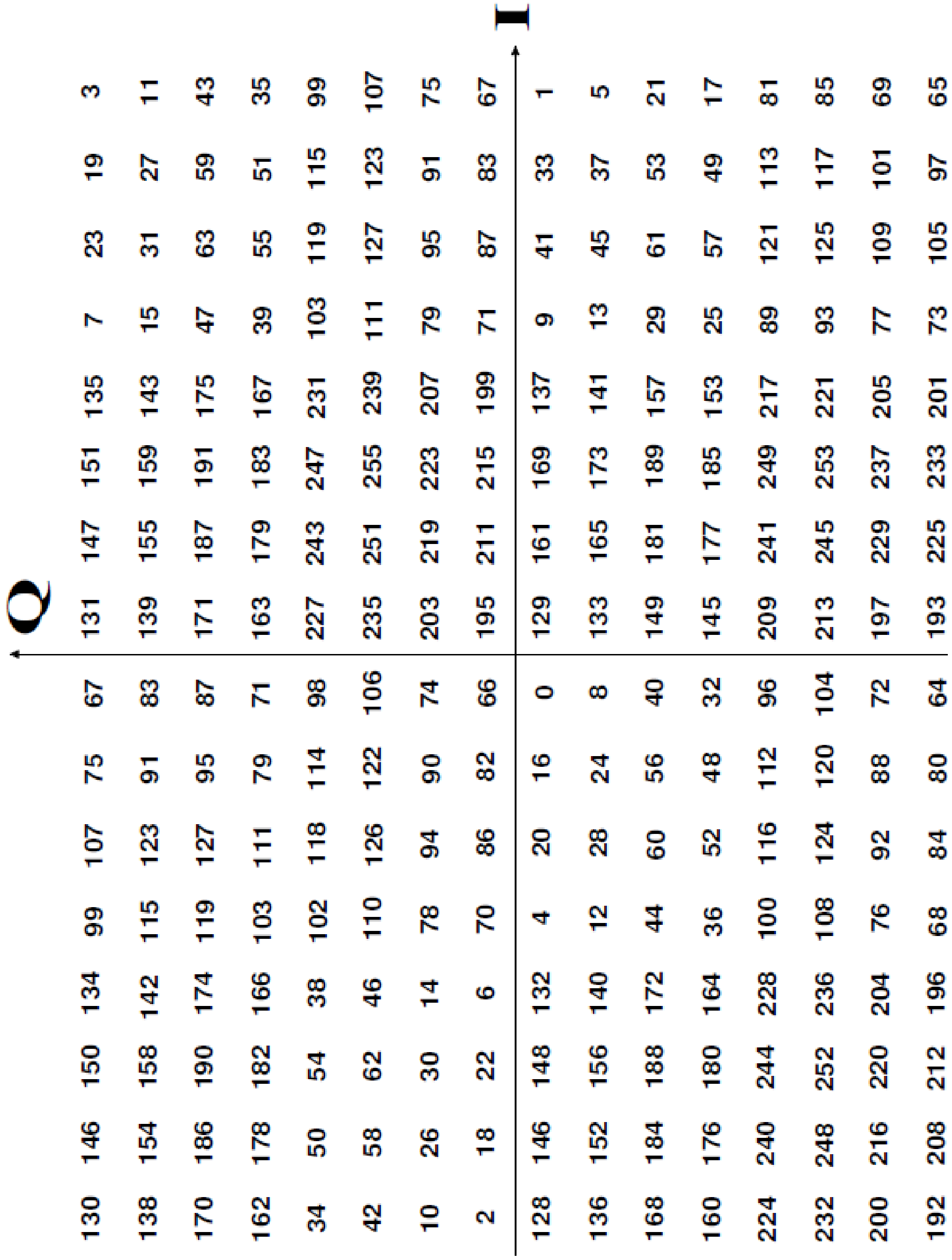

Fig. 12. An SCM-mapped 256QAM symbol constellation having LPLs that mirror LPLs of the 256 QAM symbol constellation of Fig. 11

All the binary-number LPLs of the Fig. 12 symbol constellation would mirror the binary number LPLs correspondingly positioned in the Fig. 11 symbol constellation. This reduces the number of bit errors in the CDD recovered by BRA in a DCM COFDM signal receiver, when the 256QAM symbol constellations of Figs. 11 and 12 govern modulation of respective sets of carriers that convey the same CDD.

Also, this reduces the number of bit errors in the CDD recovered by BRA in a DCM COFDM signal receiver, when the 256QAM symbol constellation of Fig. 12 and either of the 256QAM symbol constellations in Figs. 13 and 14 govern modulation of respective sets of carriers that convey the same CDD. This is owing to the 256QAM symbol constellations in Figs. 13 and 14 being derived from the 256QAM symbol constellation in Fig. 11.

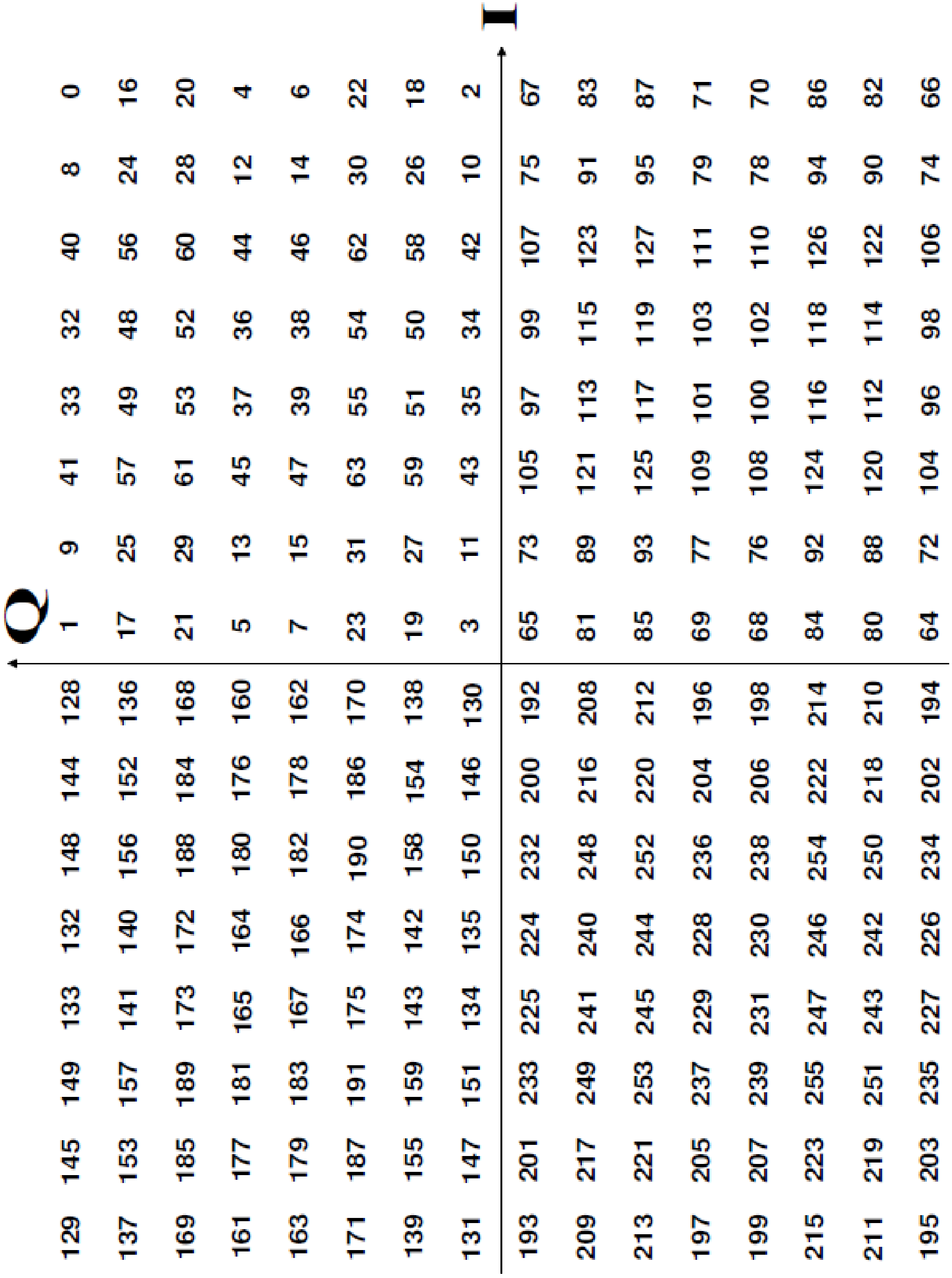

Fig. 13 An SCM-mapped 16QAM symbol constellation for reducing PAPR of dual-mapping with the 16QAM symbol constellation of Fig. 11 or Fig. 12

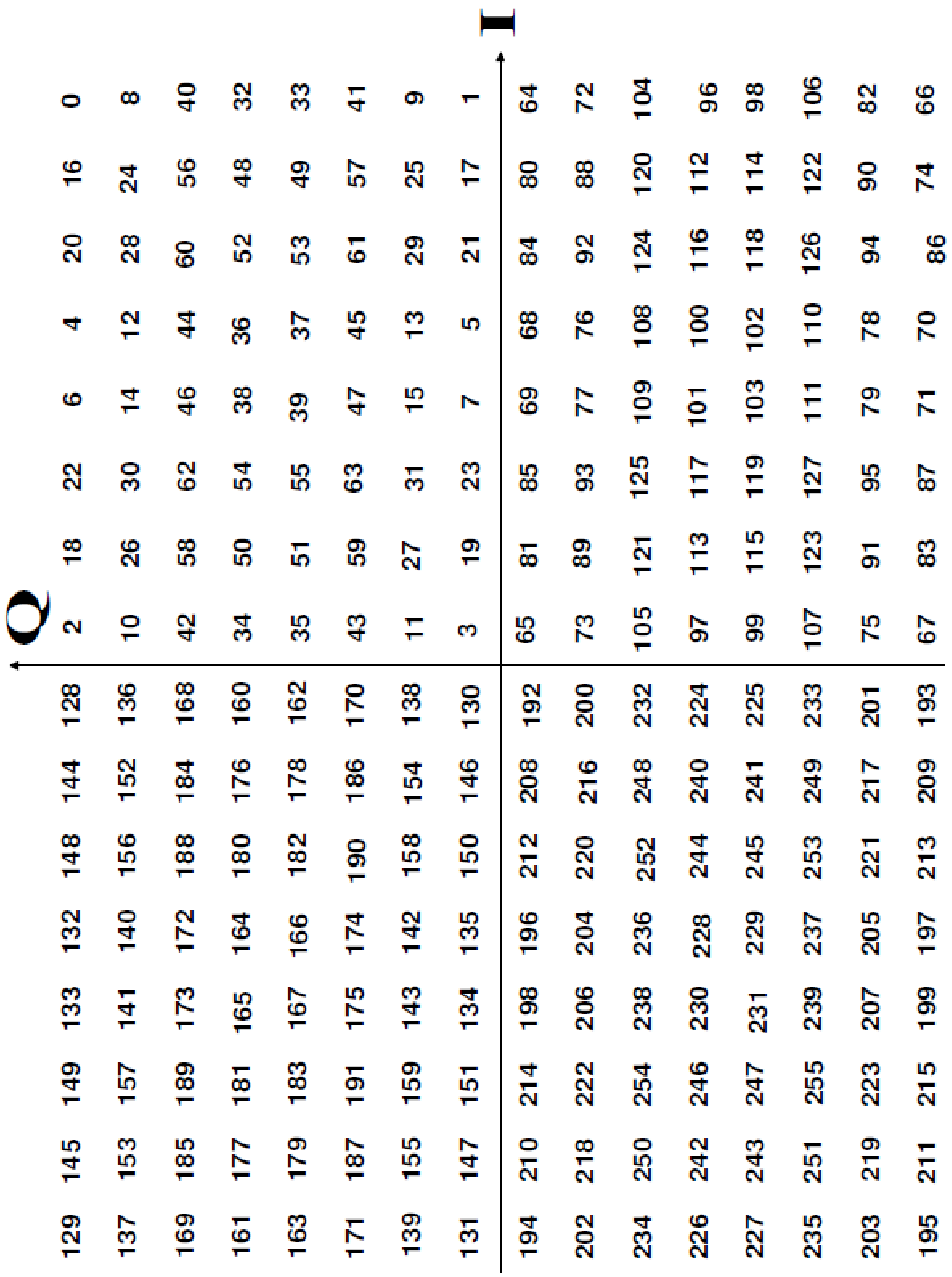

Fig. 14 An SCM-mapped 256QAM symbol constellation for reducing PAPR of dual-mapping with the 266QAM symbol constellation of Fig. 11 or Fig. 12

With appropriate labeling diversity between two SCM-mapped 256QAM symbol constellations that govern the DCM of COFDM carriers, the PAPR of a DCM COFDM signal can be reduced 2.99 dB to be close to 1.28 dB. This can be achieved using the 256QAM symbol constellation of Fig. 11 together with either of the 256QAM symbol constellations in Figs. 13 and 14 to govern modulation of respective sets of carriers that convey the same CDD.

This can also be achieved using the 256QAM symbol constellation of Fig. 12 together with either of the 256QAM symbol constellations in Figs. 13 and 14 to govern modulation of respective sets of carriers that convey the same CDD. However, this depends on the innermost sub-quadrants of the 256QAM symbol constellations of Figs.11 and 12 being of correct design,as illustrated in Fig. 5 and in Fig. 6 derived from Fig. 5.

Referring to Fig. 5, the SCM-mapped 256QAM symbol constellation purposely has its sixteen palindromic LPLs positioned therein as follows. The sixteen palindromic LPLs are grouped within four groups of four. The four palindromic LPLs in each group are positioned along the diagonal of the inner-most sub-quadrant of a respective one of the (+I,+Q), (+I,-Q), (-I,-Q), and (+I,+Q) quadrants of the 256QAM symbol constellation, which diagonal touches the centerpoint of the symbol constellation. The mirroring of the LPLs of the Fig. 5 portion of the SCM-mapped 256QAM symbol constellation in the correspondingly positioned LPLs of the Fig. 6 portion of another SCM-mapped 256QAM symbol constellation leaves these sixteen palindromic LPLs in place. Accordingly, either one of the Fig. 13 and Fig. 14 SCM-mapped 64QAM symbol constellations can be used together with the Fig. 12 SCM-mapped 64QAM symbol constellation in a DCM COFDM signal with PAPR also being close to 1.28 dB. These DCM COFDM signals will have lower BER than the DCM COFDM signals that use the Fig. 11 SCM-mapped 64QAM symbol constellations with the Fig. 13 or the Fig. 14 SCM-mapped 64QAM symbol constellation.

The procedures used for constructing the "basic" square symbol constellations of Figs. 1, 3, and 11QAM can be generalized, as follows. A square QAM symbol constellation having 2^{2N} labeled lattice points has 2^N binary-number LPLs that are palindromic (i. e., the same when read left to right in "normal" progression as when read right to left in "reverse" progression). N is a positive integer, of interest when at least two. These 2^{2N} labeled lattice points are separable into first, second, third and fourth groups of $2^{N/2}$ palindromic LPLs, each group composed of LPLs completely different from the LPLs in the three other groups.

The palindromic LPLs in the first group of them are arranged successively along the diagonal of the (+I,+Q) quadrant of the "basic" square symbol constellation, the palindromic LPLs being chosen for the first group so as to permit them to be SLM mapped entirely within the inner sub-quadrant of that (+I,+Q) quadrant. The palindromic LPLs in the second group of them are arranged successively along the diagonal of the (+I,-Q) quadrant of the "basic" square symbol constellation, the palindromic LPLs being chosen for the second group so as to permit them to be SLM mapped entirely within the inner sub-quadrant of that (+I,-Q) quadrant. The palindromic LPLs in the third group of them are arranged successively along the diagonal of the (-I,-Q) quadrant of the "basic" square symbol constellation, the palindromic LPLs being chosen for the third group so as to permit them to be SLM mapped entirely within the inner sub- quadrant of that (-I,-Q) quadrant. The palindromic LPLs in the fourth group of them are arranged successively along the diagonal of the (-I,+Q) quadrant of the "basic" square symbol constellation, the palindromic LPLs being chosen for the fourth group so as to permit them to be SLM mapped entirely within the inner sub-quadrant of that (-I,+Q) quadrant. This general procedure can be used for constructing a "basic" 1024QAM symbol constellation or for con- structing a "basic" 4096QAM symbol constellation.

In further general procedure, another square QAM symbol constellation having 2^{2N} labeled lattice points can be generated by mirroring each of the 2^{2N} binary-number LPLs of the general "basic" square QAM symbol constellation. The BER of the CDD recovered by BRA in a DCM COFDM signal receiver, when this other square QAM symbol constellation is used together with the "basic" square symbol constellation to govern the modulation of two sets of carriers, will be lower than the BER of the CDD recovered by BRA in a DCM

COFDM signal receiver, when just one of these square QAM symbol constellations governs the modulation of both sets of carriers.

Procedures analogous to those used to generate the 64QAM symbol constellations of Figs. 7 and 8, proceeding from the “basic” 64QAM symbol constellations of Fig. 3, can be applied to the general “basic” square QAM symbol constellation with 2^{2N} labeled lattice points to generate further square QAM symbol constellations of similar size. These further square QAM symbol constellations can be used together with the general “basic” square QAM symbol constellation to reduce the PAPR of a DCM COFDM signal. These further square QAM symbol constellations can be used together with a square QAM symbol constellation which has LPLs that mirror correspondingly positioned LPLs in the general “basic” square QAM symbol constellation, thereby to reduce the PAPR of a DCM COFDM signal.

To illustrate these analogous procedures, the square 64QAM symbol constellation of Fig. 4, rather than that of Fig. 3, can be chosen to be the “basic” square 64QAM symbol constellation. Further square 64QAM symbol constellations can be derived from the Fig, 4 alternative “basic” square 64QAM symbol constellation using procedures analogous to those used to derive the 64QAM symbol constellations of Figs. 9 and 10 from the 64QAM symbol constellations of Fig

3. Either of these further 64QAM symbol constellations can be used together with either of the 64QAM symbol constellations of Figs 3 and 4 in dual mapping for a DCM COFDM signal having PAPR reduced by 2.92 dB to be close to 0.86 dB.

To illustrate these analogous procedures further, the square 256QAM symbol constellation of Fig. 12, rather than that of Fig. 11, can be chosen to be the “basic” square 256QAM symbol constellation. Further square 256QAM symbol constellations can be derived from the Fig, 12 alternative “basic” square 256QAM symbol constellation using procedures analogous to those used to derive the 64QAM symbol constellations of Figs. 9 and 10 from the 64QAM symbol constellations of Fig 3. Either of these further 256QAM symbol constellations can be used together with either of the 256QAM symbol constellations of Figs 11 and 12 in dual mapping for a DCM COFDM signal having PAPR reduced by 2.99 dB to be close to 1.28 dB.

5. CONCLUDING REMARKS

Using DCM for reduction of the PAPR of COFDM is a linear procedure. The non-linearities caused by various peak-amplitude clipping schemes are avoided, together with the undesirable bandwidth widening such schemes entail. Peak-amplitude clipping schemes allow simpler COFDM signal receivers. However, the forward error-correction coding of digital data has to be able of correcting more bit errors, ones introduced by the clipping of peaks in the amplitude of COFDM signal.

Using DCM for reduction of the PAPR of COFDM allows uniform spacing between labeled lattice points in the QAM symbol constellations descriptive of modulation of the COFDM carriers. There is no polar rotation between the QAM symbol constellations governing the DCM. So, analog-to-digital conversion (ADC) and subsequent QAM demapping procedures in a COFDM signal receiver are considerably simplified.

While ADC and subsequent QAM demapping procedures need be carried out twice, parallelly in time, the receiver tends to be simpler than the receiver used when the PAPR of

COFDM is reduced by using selective mapping (SLM) procedure that allows one of just two mappings of QAM symbol constellations governing modulation of the COFDM carriers. The DCM COFDM signal receiver is simpler in that there is no need for circuitry to determine the SLM pattern, either from side information or by complicated analysis of the QAM of the carriers of a COFDM signal unaccompanied by side information. The DCM COFDM signal receiver is a fraction of the size of a COFDM signal receiver to accommodate SLM procedure allowing more than two mappings of QAM symbol constellations governing modulation of the COFDM carriers. Using SLM to reduce the PAPR of COFDM signal tends to reduce CDD throughput, owing to inclusion of side information descriptive of SLM pattern, but CDD throughput is usually reduced much less than 50%.

DCM reduces data throughput 50% compared to individual carrier modulation using similar QAM symbols for modulating a prescribed number of carriers of the COFDM signal. However, the data throughput of a DCM COFDM signal can be doubled by quadrupling the number of labeled lattice points in each QAM symbol. Doubling the number of bits in lattice point labels increases the likelihood of those bits being in error attributable to accompanying noise that resembles additive white Gaussian noise (AWGN). However, maximal ratio combining similar bits of CDD conveyed by pairs of DCM carriers reduces the likelihood of such error.

Noise resembling AWGN can originate in part from thermal noise in transmitter and receiver components and in part from errors in analog-to-digital conversion. Noise resembling AWGN can originate in part from noise introduced in the DCM COFDM signal transmission channel; e.g., atmospheric noise will affect DCM COFDM signal received over the air.

The likelihoods of bits of SCM-mapped 64QAM symbols and of SCM-mapped 256QAM symbols being in error can be as low in a properly designed receiver of DCM-COFDM signals as the likelihoods of bits of SCM-mapped 16QAM symbols being in error in a receiver for COFDM signals with individually modulated OFDM carriers. [3]. Such good BER performance during reception of a DCM-COFDM signal depends on suitable labeling diversity between the two sets of OFDDM carriers conveying similar coded digital data in that DCM-COFDM signal.

In regard to work it would be good still to do, it would be useful if reasonably precise measurements were made of the bit-error ratios available with the various new schemes of DCM COFDM signaling that are described *supra*. Also, it would be comforting to have actual measurements of the reductions in PAPR of COFDM signaling that can be using DCM, rather than predicting them simply by calculation. Presumably, reliable measurements can be made using computer simulations.

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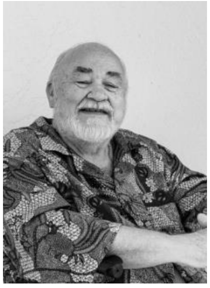

Allen Le Roy Limberg was born in Jamestown, NY, USA on Dec. 4, 1936. He received the B.E.E. degree from Union College in 1958 (Sigma Xi), the M.S.E.E. degree from University of Pennsylvania in 1964, and the J.D. degree from Seton Hall University School of Law in 1972.
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