Trellis-Coded Complementary Code Keying for High-Rate Wireless LAN Systems

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Abstract—In high-rate wireless LAN, complementary code keying (CCK) is adopted in the IEEE 802.11b standard to support data rates up to 11 Mbps, much higher than the 2-Mbps data rate in the previous wireless LAN standard. Due to less-than-ideal characteristics of the CCK codewords, the CCK performs quite poorly in large-delay-spread multipath channels. In this letter, a new modulation scheme that combines the trellis coding with the CCK modulation is proposed. This scheme is shown, through simulation, to achieve much better error rate performance in medium-to-large channel delay spread environments.

Index Terms—Orthogonal modulation, trellis coding, wireless LAN.

I. INTRODUCTION

R ECENTLY, M-ary orthogonal modulation has received much attention and has been adopted in many CDMA systems [1]. Another application of the M-ary orthogonal modulation is in extending the original IEEE 802.11 wireless LAN standard to a high-rate physical layer standard using complementary code keying (CCK) [2], [3], which is a derivative of the M-ary orthogonal modulation. Because of its better multipath immunity and backward compatibility with the previous standard based on the direct-sequence spread spectrum (DSSS) technique, the 8-chip CCK modulation is adopted as the new high-rate physical layer standard (IEEE 802.11b).

Even though CCK does preserve many advantages of the M-ary orthogonal modulation, it lost the orthogonality among symbol codewords in the process of extending from real-valued codewords to complex-valued codewords with a view to increasing the number of codewords, and thus the achievable bit rate. So in the IEEE 802.11b standard, an optional half-rate scheme was proposed, and it performs quite well under severe ISI channels and wide-coverage environments. In this half-rate CCK scheme, the number of codewords is reduced from 256 to 16 and these 16 codewords are truly orthogonal to each other.

In this letter we proposed a new technique, called coded-CCK modulation, that applies multi-dimensional trellis coding [4] to the original CCK codewords and thus achieves much better performance while sacrificing only a small fraction of the transmission bit rate. With this technique, the nonorthogonal 256 codewords in the CCK modulation are partitioned into eight sets of 32 mutually orthogonal codewords. Then a convolutional code, with either rate 1/3 or 2/3, is used to encode one or two information bits in a symbol. The three encoded bits, together with five uncoded information bits, make up the eight bits that map to a CCK codeword.

The proposed technique is evaluated using functional simulation of a system with a typical indoor wireless multipath channel [5] and a maximum-likelihood receiver with pre-correlator rake combining [6]. Simulation results show that the proposed trellis-coded-CCK modulation scheme achieves a much better packet-error-rate performance than the original CCK modulation in the IEEE 802.11b standard and is able to operate reliably in large delay spread environments as the half-rate CCK scheme. Moreover, in medium delay spread settings, the proposed coded-CCK modulation performs almost as well as the half-rate CCK modulation while achieving a bit rate that is 50% higher than the half-rate CCK scheme.

II. CODED-CCK MODULATION

A. CCK Modulation

CCK is a variation of the M-ary orthogonal modulation in that it uses quaternary complex-valued chips instead of binary real-valued chips in its codewords [3]. In the eight-chip complementary code keying, there are 256 8-chip codewords specified by the eight information bits in a symbol. The possible codewords are given by

\[ \left( c^1(\phi)1+c^2(\phi)2+c^3(\phi)3+c^4(\phi)4), c^1(\phi)1+c^2(\phi)2+c^3(\phi)3+c^4(\phi)4\right) \]

where \( \phi1, \phi2, \phi3, \) and \( \phi4 \) all can assume four possible values: 0, 0.25, 0.5, or 0.75. These eight information bits designate one of the possible 256 codewords for the current symbol. Note that \( \phi1 \) is present in all eight chips, so it simply rotates the entire codeword. In the IEEE 802.11b standard, a chipping rate of 11 MHz is adopted, thus giving a bit rate of 11 Mbps, which is 5.5 times that of the original DSSS-based IEEE 802.11 standard.

In the M-ary orthogonal modulation, the orthogonality among codewords provides a foundation for good performance in transmission error rate. Unfortunately, the complex-valued codewords in CCK modulation are not truly orthogonal among themselves. Table I shows the statistics of cross correlation magnitude between a particular CCK codeword and all 256 codewords. Four codewords with identical \( \phi1, \phi2, \phi3, \) and \( \phi4 \) have maximum cross correlation magnitude. Ideally, all other 252 codewords should have zero cross-correlation magnitude (i.e., orthogonal), however, there are actually more than one hundred codewords that have nonzero cross correlation. This nonorthogonality among CCK codewords reduces tolerance...
to noise and intersymbol interference. In the following, a new technique called coded-CCK is proposed to improve the performance in multipath fading channels and to provide more options for data rates.

To improve the performance of the CCK modulation in multipath fading channels, the IEEE 802.11b standard [2] specifies a half-rate CCK scheme with only 16 mutually orthogonal codewords. In this scheme, \( \phi_4 \) again can assume four values, \( \phi_2 \) and \( \phi_4 \) both can assume 0 or \( \pi \), while \( \phi_3 \) is fixed at 0. With the reduction in the number of codewords, orthogonality is preserved and error rate performance improved, though the achievable bit rate is halved.

### B. Trellis Coding on CCK Modulation

Examination of the CCK receiver data reveals that erroneous decisions often result from a combined effect of nonorthogonal (large cross-correlation magnitude) codewords and ISI due to multipath fading. Using the principle of trellis-coded modulation on multidimensional signal constellations [7], we propose to look upon the CCK codewords as vertices on a 16-dimensional hypercube and apply signal constellation partition. The 256 CCK codewords are partitioned into eight subsets, each with 32 mutually orthogonal codewords.

Define the following four vectors:

\[
\begin{align*}
\mathbf{u}_1 &= (+ + + + - - - -) \\
\mathbf{u}_2 &= (+ + - - + + + -) \\
\mathbf{u}_3 &= (+ - + - + + - -) \\
\mathbf{u}_4 &= (+ + + - - - + -)
\end{align*}
\]

where “+” denotes 1 and “-” denotes \(-1\). The codewords in the first subset are given by

\[
\mathbf{u}_1^{\phi_1} \otimes \mathbf{u}_2^{\phi_2} \otimes \mathbf{u}_3^{\phi_3} \otimes \mathbf{u}_4
\]

where \( \phi_1, \phi_2, \phi_3 \) = 0 or 1; the zeroth power of a codeword is the all-one codeword, and \( \otimes \) denotes element-wise product. There are eight such codewords and multiplying each of them by one of the four possible \( \phi^{\phi_1} \) terms yields all 32 codewords in this subset. Note that the cross correlation of any two codewords in this subset is zero. Therefore, all 32 codewords in this subset are mutually orthogonal. Other seven subsets have the same structure except that their subset leaders are different from that of the first subset.

Two convolutional codes are adopted: one with rate 1/3 and the other with rate 2/3. The convolutional codes are used to apply constraint on the transmitted CCK codeword sequence, more precisely the subset sequence. Since both codes have a constraint length of four, they are called Con(3,1,4) coded-CCK and Con(3,2,4) coded-CCK, respectively (see Fig. 1 for their trellis diagrams). In these schemes, either one or two information bits are convolutional encoded into three coded bits. Then these three coded bits and the five other uncoded information bits make up the eight bits that select one of the 256 CCK codewords. Therefore for the two coded-CCK schemes the bit rates are 3/4 and 7/8 that of the original CCK modulation, respectively.

To decode the coded-CCK symbols, soft-decision Viterbi algorithm is adopted in the receiver. Since all codewords are of the same magnitude (vertices on 16-dimensional hypercube), correlation between the received symbol and a codeword scales monotonically with the distance between that received symbol and the codeword (larger correlation indicates smaller distance). In the coded-CCK receiver, correlations of the received 8-chip symbol and all 256 codewords are first computed as soft decisions, which are then fed to the Viterbi decoder for further processing, i.e., branch metric computation, survivor path and path metric update, and best path trace back [8].

### III. Simulation Results

In this section, functional simulation of the four CCK schemes are conducted for different RMS-delay-spread channels. The transmitted data in the simulation are packetized; one packet consists of 192 Barker symbols in the preamble/header part and 1000 CCK symbols in the high-rate data part [2]. One CCK symbol carries 8, 7, 6, and 4 information bits in the CCK, Con(3,2,4) coded-CCK, Con(3,1,4) coded-CCK, and half-rate CCK schemes, respectively. Following the IEEE 802.11 standard requirement, packet error rate (PER) is used as the performance index in the simulation. An error packet is declared when there exists one or more erroneous bits in the demodulated packet.

The channel model proposed by Saleh and Valenzuela [5] is used to generate channels with various RMS delay spread values. Due to the short duration of a packet (less than 1 ms) and characteristics of indoor environments, the channel is assumed stationary throughout a packet. For each case in the simulation, 200 different channels are generated and under each channel condition ten packets with different data are transmitted.
The receiver consists of a channel estimator, carrier recovery phase-locked loop, phase rotator, pre-correlator rake combiner [6], correlators, and the extra Viterbi decoder. The channel estimator and the carrier recovery loop estimate the channel impulse response and the carrier phase/frequency error respectively using the 11-chip Barker symbols in the preamble part of a packet. Since the channel is assumed stationary throughout a packet, the estimation then is used by the rake combiner and the phase rotator to perform path-diversity combining and carrier alignment on the data part, respectively. All the aforementioned blocks operate at sample rate (44 MHz) or chip rate (11 MHz), while the Viterbi decoder operates at symbol rate (1 MHz). Moreover, since the number of states in the trellis diagrams is only eight, the coded-CCK decoding complexity is only a small portion of the whole receiver.

Fig. 2 shows the simulated performance of the four modulation schemes in 65-, 100-, 150-, and 226-ns delay spread channels. Under 65-ns channel delay spread condition, all four schemes have acceptable performance (IEEE 802.11 standard requires an 8% PER). In 100-ns delay spread channels, the PER of the CCK scheme rises above 40% while the other three schemes still have acceptable PER. In 150-ns delay spread channels, the Con(3,1,4) coded-CCK scheme and the half-rate CCK scheme can still meet the PER specification. In 226-ns delay spread channels, only the half-rate CCK scheme still has an acceptable performance with PER around 10%–15%.

To sum up, the optimal modulation schemes for environments with channel RMS delay spread around 65, 100, 150, and 226 ns are CCK, Con(3,2,4) coded-CCK, Con(3,1,4) coded-CCK, and half-rate CCK, respectively. The two coded-CCK schemes proposed in this letter can achieve good performance in indoor multipath fading environments with medium to large channel RMS delay spread while sacrificing only a small fraction of the data rate.

IV. CONCLUSION

In this letter, we proposed a new technique that applies trellis coding to the CCK codewords used in the IEEE 802.11b high-rate wireless LAN standard. By partitioning the nonorthogonal CCK codewords into sets of mutually orthogonal codewords and apply convolutional code to the possible set sequence, the proposed coded-CCK can achieve improvement in communication performance. When combined with the existing IEEE standard, the coded-CCK modulation can provide an alternative for medium-to-large delay spread indoor environments with more than 50% data rate increase than the half-rate CCK modulation specified in the IEEE standard.

REFERENCES