**IEEE P802.15**

**Wireless Personal Area Networks**

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Low Peak-to-Average Power Ratio PHY for Single Carrier

1. Hadamard Coded Modulation Concept:

Hadamard Coded Modulation (HCM) in current specification enables low Peak-to-Average Power Ratio (PAPR) implementation, which reduces the signal distortion due to the nonlinearity of LEDs, channels and amplifiers. HCM enables transmitter design with low complexity by simply operates LED array at the On and Off modes. Furthermore, the specification enables the energy-efficient waveforms such as DC reduced HCM (DCR-HCM), dispersion resistant implementation as interleaved HCM. In addition, the specification supports the application of adaptive bit and energy loading techniques as well as multiple-input multiple-output (MIMO) techniques which can leverage the additional communication capacity of multiple light sources as well as the additional communication capacity introduced by the utilization of different optical wavelengths and light polarization for communication.

1. The binary data sequence is mapped to -ary pulse amplitude modulation (PAM) symbols, where can be etc., depending on the required data rate, and assigned to vector . The vector is used to generated the signal as

Figure. 1 Illustration of fast Walsh-Hadamard transform

where is the binary Hadamard matrix of order , which is obtained by replacing by in the original bipolar Hadamard matrix, is the complement of , and the matrix forms the original bipolar Hadamard matrix. This equation can be rewritten as

where the first term is the Walsh-Hadamard transform (WHT) of vector and can be implemented using fast Walsh-Hadamard transform (FWHT). An illustration of FWHT is shown in Fig. 1. The second term is obtained from the product of a vector of all ones and **.**  The transmitter can be implemented as in Fig. 2.

Figure 2. Block diagram of the HCM transmitter using FWHT

The Hadamard transform is applied on the -ary PAM symbols using a FWHT of size , which has a complexity of . The rate of the -ary PAM HCM is the same as the simple PAM, . The constant value of is added to the output of the FWHT to ensure vector is positive. The HCM signal can be sent by modulating single LED source with varying driving current or multiple sources by switching different number of LEDs on and off based on the signal.

The decoded vector is obtained from the received vector as

which can be realized by an inverse FWHT (IFWHT) as shown in Fig. 3.

Figure 3. Block diagram of the HCM receiver using IFWHT

1. Pulse Shaping

Optional pulse shaping can be used to increase spectral efficiency. Sinc pulses can be used instead of spectral inefficient rectangular pulses to transmit HCM signals by varying the driving current of the LED. Fig. 4(a) illustrates the transmitted pulses for the three rectangular pulses shown in Fig. 4(b).



Figure 4. An HCM signal, and (b) the transmitted pulses using Sinc pulse-shaping

1. DC-reduced HCM

Optionally, the DC part of the HCM signals (before the pulse shaping) can be reduced to increase the average power efficiency. Based on the general HCM introduced in Section 2, modifications can be made to remove the DC components as follows: Set the first row of , to and does not carry any information data because the first row of HCM matrix which has all ones, represents DC. Hense, only codewords of the Hadamard matrix are modulated. In this proposed scheme called DC-reduced HCM (DCR-HCM), the average transmitted power is reduced by sending instead of **.**  The rate of the -ary PAM DCR-HCM is . The transmitter design is shown in Fig. 5.

Figure 6 shows an example of DC reduction in an HCM symbol of size , where the transmitted energy of the HCM symbol is reduced by a factor of in its corresponding DCR-HCM symbol.

The DC reduction technique decreases the probability of large amplitude of , which makes the signals less likely to be clipped by the optical source, and therefore, DCR-HCM can achieve lower BERs at lower average power levels compared to HCM in peak-power limited system.

The receiver design can be based on the general HCM design but ignoring the first symbol of the IFWHT as shown in Fig. 7.



Figure 7. Block diagram of the HCM receiver with ignored

Figure 6. (a) An HCM signal, and (b) its corresponding DC reduced signal

Figure 5. Block diagram of the DCR-HCM transmitter with set to 0

1. Cyclic prefix

Hadamard matrices consist of rows that are cyclic shifts, which increases the similarity between Hadamard codewords in dispersive channels and makes HCM vulnerable to ISI. Interleaving is an effective solution that reduces ISI by decreasing the cross-correlation of the codewords with their cyclic shifts. In this specification, as shown in Fig. 8, an optional symbol-length interleaver and a de-interleaver are used at the transmitter and receiver, respectively, to reduce the effects of inter-symbol interference (ISI) due to a dispersive channel. The interleaver is a permutation matrix, , and the deinterleaveer is its inverse, .



Figure 8. Schematic view of an interleaved HCM system for dispersive channels