Preamble Design for Millimeter-Wave Single Carrier WPANs

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Abstract—In this paper we present preamble design for millimeter-wave single carrier wireless personal area networks. Several factors are considered for a successful preamble design, such as sequence complexity, operation range, associated delay, robustness to frequency offset. Complementary Golay sequences are selected, which combine flexibility and performance. Simulation results indicate at optimum threshold level, it is possible to reduce both false alarm probability and miss detection probability less than $10^{-3}$ in non-line-of-sight channels.

Keywords: Millimeter-wave, 60 GHz, WPAN, IEEE 802.15.3c, Golay Sequences.

I. INTRODUCTION

Recently, there is an increasing interest both in academia and industry for wireless personal area networks (WPANs), which are intended for short-distance (i.e. less than 10 meters) wireless communications [1]. The reason of this interest is the demand for higher data rates in indoor networks, for faster wireless internet access and high quality video streaming. Possible frequency bands for WPANs are 2.4 GHz band, millimeter-wave band (60 GHz) and UWB band. Among these bands, there are 3 main reasons to use 60 GHz band. First, it provides 7 GHz unlicensed spectrum both in USA and in Japan [6], [7]. Second manufacturers can provide inexpensive 60 GHz circuits and components for consumer devices and last but not least, oxygen absorption at those frequencies limits interference from outside sources.

Several standardization bodies started their efforts for 60 GHz WPAN or WLANs including IEEE’s 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c (802.15.3c)[2],[3],[4]. Throughout the standardization process, three main PHY layer design alternatives emerged, SC-PHY, which is based on single-carrier transmission and HSI-PHY and AV-PHY, which are based on orthogonal frequency division multiplexing (OFDM) transmission. The three PHYs are all optimized for different applications. As stated in [5], “The SC-PHY is optimized for low power, low cost and complexity. The HSI-PHY is optimized for low-latency, bi-directional data connectivity. The AV-PHY is optimized for the delivery of uncompressed, lossless audio and video content with low latency.” For interoperability between those PHYs, a SC-PHY beacon should be sent periodically by the device, which controls the piconet, which makes SC-PHY design more crucial than the others.

In 802.15.3c system each data frame is divided in three sections; preamble, header and payload. In this paper, we are focusing on preamble section of SC-PHY, which is required for frame detection, synchronization and channel estimation.

The proposed preamble is based on binary Golay sequences [8]. Golay sequences are specified by pairs of complementary sequences. In addition, a simple correlator design is possible for Golay sequences [9], [10]. For example, a correlator consists of $M$ delay circuits, $M$ inverters and $2M$ adders for binary Golay sequences with a length of $2^M$. For channel estimation, Golay sequences were proposed in the past [11], [12], [13] and their practical use in 60 GHz SC-PHY is studied and compared with Chu sequences in [14]. However the performance of Golay sequences for frame detection, was not studied in detail. In this paper we will study the performance of Golay sequences in realistic non-line-of-sight channel model through simulations, including the effects of RF impairments such as frequency offset. We are suggesting to use moving average method to reduce memory requirements of the detector. Before the simulation results, in the next section we explain shortly, the preamble design of SC-PHY. Section III is reserved for the explanation of the simulation model. Section IV show performance results. Conclusions are stated in Section V.

II. SYSTEM MODEL

Figure 1 shows the frame format of a SC-PHY 60 GHz system, which is composed of three major components: the PHY preamble, the frame header and the MAC frame body (frame payload plus frame check sequence). The frame header is composed of a base frame header (PHY header, scrambled MAC header, scrambled header check sequence, and Parity bits), and an optional frame header (scrambled MAC sub-header, scrambled header check sequence, and parity bits). The optional header is used when different payloads are aggregated. The system parameters are shown in Table 1.

In Figure 2 we show preamble structure. Main function of preamble in 60 GHz system is to aid receiver algorithms such as frame synchronization, channel estimation, frequency recovery, timing acquisition. In addition, it provides information on header rate and channel estimation sequence length.
Fig. 1. Frame format.

Fig. 2. Preamble structure.

### TABLE I

<table>
<thead>
<tr>
<th>System Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol Rate</td>
<td>1728 Mcps</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>216 MHz</td>
</tr>
<tr>
<td>Channel center frequencies</td>
<td>58.32, 60.48, 62.64 and 64.8 GHz</td>
</tr>
<tr>
<td>Pulse shaping filter</td>
<td>Root-raised cosine</td>
</tr>
<tr>
<td>Roll-off factor</td>
<td>0.25</td>
</tr>
</tbody>
</table>

There are three different preamble types. Long preamble is the most robust preamble, therefore it is used during critical transmissions such as beacon and command frames. Medium preamble is the robust option for data transmission frames, especially, when there is no synchronization between the transmitter and the receiver. Short preamble designed for situations, during which there is synchronization between devices, such as continuous streaming. Before explaining each part of the preamble, we will focus on Golay sequences used in the preamble.

### A. Golay Sequences

Golay sequences are defined by two kinds of vectors, delay and weight vectors. A set of vectors each with length of \( M \) generates a corresponding pair of Golay sequence each with length of \( N = 2^M \). Let \( a_N = [a_N[1]a_N[2] \cdots a_N[N - 1]a_N[N]] \) and \( b_N = [b_N[1]b_N[2] \cdots b_N[N - 1]b_N[N]] \) be a complementary pair of Golay Sequences with chip length of \( N \). The pair of Golay Sequences shall be generated as following:

\[
\begin{align*}
a_N^{(0)} &= [1 \ 0 \cdots 0] \\
b_N^{(0)} &= [1 \ 0 \cdots 0] \\
a_N^{(i)} &= W[i]a_N^{(i-1)} + \text{perm}(b_N^{(i-1)}, p^{(i)}) \\
b_N^{(i)} &= W[i]a_N^{(i-1)} - \text{perm}(b_N^{(i-1)}, p^{(i)})
\end{align*}
\]
\[ p^{(i)} = \text{mod}([0 \ 1 \ \cdots \ N - 1] - D([i], N)) + 1 \]  \hspace{1cm} (5)

\[ a_N = a^{(M)}_N \]  \hspace{1cm} (6)

\[ b_N = b^{(M)}_N \]  \hspace{1cm} (7)

where \( D = [D[1] D[2] \cdots D[M]] \) is the delay vector and \( W = [W[1] \cdots W[M]] \) is the weight vector. The function \( \text{perm} \) is the permutation function. In Table 2, length 128 Golay sequences are shown. These sequences are used in synchronization, start frame delimiter and in short channel estimation sequence parts.

**TABLE II**

**LENGTH 128 GOLAY SEQUENCES IN HEXADECIMAL NOTATION**

<table>
<thead>
<tr>
<th>Sequence name</th>
<th>Sequence value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a\textsubscript{128}</td>
<td>0x30A99A0330A965FCCF5665FC30A965FC</td>
</tr>
<tr>
<td>b\textsubscript{128}</td>
<td>0x05C99C50FAC9635005C99C50FAC96350</td>
</tr>
</tbody>
</table>

In Table 3, length 256 Golay sequences, which are used only in long channel estimation sequence, are shown.

**TABLE III**

**LENGTH 256 GOLAY SEQUENCES IN HEXADECIMAL NOTATION**

<table>
<thead>
<tr>
<th>Sequence name</th>
<th>Sequence value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a\textsubscript{256}</td>
<td>0x05C99C50F5C059950C3FA6950CC059950C</td>
</tr>
<tr>
<td>b\textsubscript{256}</td>
<td>0x5396CAF5C059950C3FA6950CC059950C</td>
</tr>
</tbody>
</table>

B. Preamble Parts

As shown in Figure 2, there are 3 main parts of the preamble. Synchronization (SYNC), start frame delimiter (SFD), channel estimation sequence (CES).

1) Synchronization: The synchronization part is the longest part of the preamble, since it is for frame detection. It uses length 128, a\textsubscript{128}, sequences. The SYNC part of the long preamble consists of 64 repetitions of the Golay sequence. It has enough performance for detection of frame in non-line-of-sight channels up to 10 meters range, which we will show in the later sections. For the medium preamble, number of repetitions are chosen to be 32. Short preamble has 8 repetitions in its synchronization part.

2) Start Frame Delimiter (SFD): The SFD shall be provided to establish frame timing. The SFD shall be obtained by repeating code, a\textsubscript{128} with different SFD patterns. For the long preamble, the SFD shall be obtained by 8 code repetitions. For the medium and short preambles, 4 code repetitions shall be used. SFD patterns for the long, medium and short preambles and corresponding PHY header selections are shown in Table IV

**TABLE IV**

**SFD FOR HEADER SELECTION**

<table>
<thead>
<tr>
<th>Preamble Type</th>
<th>Header Spreading</th>
<th>SFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long</td>
<td>64</td>
<td>[-1 -1 +1 +1 -1 -1 +1]</td>
</tr>
<tr>
<td>Medium</td>
<td>8</td>
<td>[-1 +1 +1 -1 -1 +1]</td>
</tr>
<tr>
<td>Medium</td>
<td>2</td>
<td>[-1 +1 -1 +1]</td>
</tr>
<tr>
<td>Short</td>
<td>2</td>
<td>[-1 +1 -1 +1]</td>
</tr>
</tbody>
</table>

3) Channel Estimation Sequence (CES): The CES field shall be constructed from a pair of Golay complementary sequences either \( a_{256}, b_{256} \) or \( a_{128}, b_{128} \). For different preamble types, different number of code repetitions are employed in the CES. Additionally, the repeated code sequences shall be preceded by a cyclic prefix (i.e. a copy of the last 128 or 64 chips of the sequence) and followed by a cyclic postfix (i.e. a copy of the first 128 or 64 chips of the sequence). For the long preamble, \( a_{256}, b_{256} \) sequences shall be used each with 8 repetitions plus respective cyclic prefix and cyclic postfix. For the medium preamble, the \( a_{256}, b_{256} \) sequences shall be used each with 2 repetitions with cyclic prefix and postfix. For the short preamble an \( a_{128} \) and a \( b_{128} \) sequence shall be used with the cyclic prefix and postfix.

III. SIMULATION MODEL

A. Transmitter

At the transmitter site the preamble is sent to the pulse shaper and the baseband equivalent of the transmitted signal can be written as:

\[ s(t) = \sum_{q=1}^{Q} w(t - q' T_c) f_{cen}(t) \]  \hspace{1cm} (8)

where \( T_c \) is the chip duration, \( f_{cen} \) is the pulse center frequency, \( w(t) \) is the pulse waveform, \( q \) represents the number of chips per preamble. Here, we define the chip rate (also known as the Nyquist bandwidth) \( S_r = 1/T_c \), system bandwidth \( W = S_r(1 + \alpha) \) with \( \alpha \) representing the roll-off factor for the pulse shape. As shown in Table 1, the root-raised cosine pulse with \( \alpha=0.25 \) is employed. We assume \( f_{cen}=60.48 \) GHz. Also, \( S_r \) and \( W \) are set to 1728 Mcps and 2160 MHz.

In this work, we consider three RF impairments which degrade system performance, non-linear distortion due to power amplifier, phase noise and frequency offset.

1) Non-Linear Distortion due to Power Amplifier: For the impairment 60 GHz IBM SiGe BiCMOS power amplifier is modeled using the modified Rapp model [16]. The AM-AM effect of the amplifier can be specified as

\[ F_{AM-AM}(V_{out}) = V_{in}/(1 + (V_{in}/V_{sat})^{2p})^{1/2p} \]  \hspace{1cm} (9)

where \( V_{in} \) and \( V_{out} \) are the input and output signals voltage respectively. \( V_{sat} \) is equal to 2.09V and coefficient \( p \) is given as 1.6. The AM-PM transform function is

\[ F_{AM-PM}(\theta) = AV_{in}^{q}/(1 + (V_{in}/B)^q), \]  \hspace{1cm} (10)
where $A, B$ and $q$ are given as -10250, 0.0554 and 3.5 respectively.

2) **Phase Noise**: Phase noise in the system is modeled by below equation [16].

$$PSD(f) = PSD(0)(1 + (f/f_z)^2)/(1 + ((f/f_p)^2), \quad (11)$$

where $PSD(0) = -93$ dBc/Hz and pole frequency $f_p$ is 1 MHz. The zero frequency $f_z$ is given as 100 MHz.

3) **Frequency Offset**: Although the previous 2 RF impairments are important, effect of frequency offset can be greater. Frequency offset occurs due to different carrier frequencies at the receiver and the transmitter. Current IEEE 802.15.3c design allows ±25 ppm frequency offset for a device, therefore total frequency offset can be ±50 ppm. Assuming carrier frequency of 60.48 GHz, this generates ±1.512 MHz frequency shift. In our simulations, we will assume the worst case scenario and apply ±50 ppm frequency shift.

**B. Channel Model**

The channel models (CM) for 60GHz WPAN are based on TSV model [15] and actual propagation measurements. In this paper, we evaluate the performance in the residential environment, for NLOS CM2.3 [17] channels. These are typical environments defined in the usage models (UM) [18] for uncompressed video streaming and desktop file transferring. The detailed descriptions of the environments can be found in [18].

**C. Preamble Detection**

For the detection of the preambles, two methods are used. First incoming signal is sampled and passed through a 1 bit A/D converter. Assuming $N_{SYNC}$ repetitions are used in detection, resulting vector can be written as $\bar{r} = [r_0 \cdots r_{N_{SYNC} - 1}]$. The decision statistic for the first method of detection can be written as

$$z = |\sum_{l=0}^{N_{SYNC} - 1} r_la_T|, \quad (12)$$

where $a$ and $T$ denotes the vector of $a_{128}$ and transpose. Such a decision statistic can be obtained via a sliding correlator, which uses $a_{128}$. However, previous $N_{SYNC} \times 128$ correlation results should be kept in memory for a decision. To reduce this memory requirement, we are suggesting to use a moving average method (method 2), such that decision statistic at time instant $n$ is equal to

$$z[n] = (1 - \gamma)|r_na_T| + \gamma z[n - 1] \quad (13)$$

where $\gamma$ is the forgetting factor. This method decreases memory requirement to the Golay sequence length of 128. In the next section, we present simulation results for both detection strategies.

**D. Simulation Results**

The first simulation results are obtained for the long preamble detection and method 1 in AWGN channel, which is an acceptable approximation for a line-of-sight environment. Signal to noise ratio is set to -10 dB, which is the operating range SC-PHY beacon. Target miss detection rate is $10^{-3}$ or less. We assumed all sequences in the SYNC part are used for preamble detection.

![Fig. 3. False alarm and miss detection probabilities of long preamble with method 1 in AWGN channel.](image)

Threshold value is between 0 and 1 and corresponds to normalized value of decision statistic $z$. As can be seen in Figure 3, false alarm and miss detection curves do not cross. Therefore, very low miss detection values are possible.

In the second simulation we tested the performance of method 2, with the forgetting factor $\gamma=0.9$. In Figure 4 simulation results indicate that for a false alarm rate of $10^{-2}$, the miss detection rate is around $10^{-3}$.

Figure 5 shows the results with method 1 in CM 2.3, NLOS environment. The decrease in the miss detection performance in considerable compared to LOS case shown in Figure 3. However, it is still possible to obtain false alarm and miss detection rates less than $10^{-3}$. Although not shown here, the performance of method 2 with forgetting factor $\gamma=0.9$ is not sufficient in an NLOS environment and it is around $10^{-2}$ for miss detection and false alarm at the intersection point.

In the last performance of this work, we decreased the number of SYNC sequences to 32. In this case, miss detection is around $10^{-4}$ if the false alarm is taken around $10^{-2}$ or more as seen in Figure 6. We can conclude from our simulation results that 64 length is a good choice for preamble length in non-line-of-sight environment for SC-PHY beacons. Method 2 is a possible design alternative for inexpensive devices which will only operate in line-of-sight environments.
Fig. 4. False alarm and miss detection probabilities of long preamble with method 2 in AWGN channel.

Fig. 5. False alarm and miss detection probabilities of long preamble with method 1 in NLOS residential channel.

Fig. 6. False alarm and miss detection probabilities of medium preamble with method 1 in NLOS residential channel.

IV. CONCLUSION

In this work we have explained preamble design for a 60 GHz WPAN and compared the performance of two methods for the preamble detection. Optimum method enables the performance both in LOS and NLOS environments. Whereas low complexity method is a good design alternative, for LOS environments.

REFERENCES
