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# An Adaptive IEEE 802.11ad Indoor mmWave Inner-Receiver Architecture

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## Abstract

In this paper, a new design for the inner receiver of an 802.11ad WLAN system is proposed. The proposed design is a modified version of the well-known Golay Correlator (GC) based inner receiver. The GC synchronizer and channel estimator performance is degraded in the low Signal to Noise Ratio (SNR) regime due to a fixed threshold. Furthermore, higher throughput may be achieved as a result of an early SNR range indication. In our proposed scheme, an adaptive algorithm optimizes the threshold of the GC based blocks so that it becomes SNR-independent. Moreover, it gives an indication of the SNR of the received signal in an early stage. Signal path is adapted accordingly in several blocks, achiveing higher accuracy at a higher throughput rate. Our simulation results show that the proposed scheme outperforms the traditional GC based inner receivers in different indoor environments.

## 1 Introduction

The unlicensed 60 GHz radio frequency (RF) band has drawn a great attraction in the past decade due to the high bandwidth offered and the possibility of achieving multi-gigabit throughput. The IEEE 802.11ad for Wireless Personal Area Network (WLAN) [1] and IEEE 802.15.3c for Wireless Personal Area Network (WPAN) [2] standards are presented to reach data rates over 1 Gbit/s. Both use OFDM for multi-carrier transmission offering high data rates and a great immunity to multi-path fading and low Signal to Noise Ratios (SNR).In previous works [3, 4, 5] different synchronizers and channel estimators were proposed for IEEE 802.11ad compliant inner receivers. In [3], a Golay Normalized Correlator (GNC) was used to detect the Golay sequence in the preamble and to correct the estimated frequency offset. In [4] and [5] also a GC was used to calculate the estimated channel matrix depending on the auto-correlation properties of the complementary Golay bi-polar sequences. In [5], a noise cancellation window was used to remove the noise peaks added to the estimated channel matrix values. The data symbols were then equalized in frequency domain. Also, a comparison was shown against different channel estimation techniques like Least Mean Square (LMS) approximation, Minimum Mean Square Error (MMSE) approximation with and without GC; results favored the usage of the GC in both hardware resource consumption and accuracy aspects.

While the results in [3] and [5] were reliable, a problem was revealed when using the Window Based Noise Cancellation (WNC) and the Golay based Normalized auto-Correlator (NAC) that both blocks are sensitive to low SNR values. Both blocks use a fixed and a predefined threshold for estimation of the channel impulse response and frame start detection, respectively. In an earlier work [6], we proposed a novel synchronizer architecture which uses multiple thresholds to get the exact frame start. While the synchronizer proved immunity against fluctuating SNRs, it also gives information about the SNR range of the received signal. In this work we will introduce a new IEEE 802.11ad compliant inner receiver architecture which takes advantage from the adaptive synchronizer design and optimizes the signal path accordingly.

## 2 Architecture of the Adaptive Inner Receiver

Fig.1 shows the preamble structure as stated in the standard IEEE 802.11ad. It is composed of two main parts; a Short Training Field (STF) and a Channel Estimation Field (CEF). The STF consists of 17 Golay sequences each of 128 samples, with an inverted sequence at the end. The CEF is divided into three parts; two are 512 samples long Golay sequences made from smaller complementary 128 sequences and the last one is an inverted sequence.

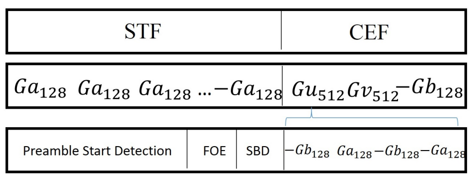


**Figure 1.** IEEE 802.11ad preamble structure.

In [6], an adaptive GC based synchronizer was proposed, it compares the NAC output with different thresholds and applies an algorithm to choose the exact start index from all triggered indices. In addition to providing the index of the estimated frame start, the synchronizer from [6] can be adapted to additionally provide all threshold triggering indices. Using a simple comparator, the ideal index coming out of the adaptive synchronizer algorithm could be compared to the indices coming from different thresholds. The nearest index to the resultant one is calculated. With this information, an early indication for the range of the received signal SNR is available. Since the different threshold trigger points are related to different SNR values. In table I, a summary for the different thresholds that trigger the exact index in different SNR ranges is given. By matching the threshold to one of the ranges in the table, we can find the SNR range for the received signal.

**Table 1.** GC-Synchronizer threshold to SNR level mapping

| Nearest Threshold | SNR Level |
|---|---|
| 0.35 - 0.45 | SNR < 3 dB |
| 0.5 - 0.65 | SNR < 9 dB |
| 0.7 - 0.8 | SNR > 9 dB |

In Fig.2, we can see how the early indication for the SNR can propagate to the other blocks of the inner receiver. This can increase the precision and throughput of the different processes. Here, we have 2 block examples; the frequency offset estimation and the GC-WNC channel estimation. The FOE we are using is an iterative process to increase the accuracy of the estimation, the number of iterations is SNR-dependent. In higher SNRs, less iterations can be used to get the same estimation precision, increasing the overall throughput. The GC-WNC CE cancels noise using a threshold, this threshold can also be modified according to the SNR range to increase the estimation accuracy.

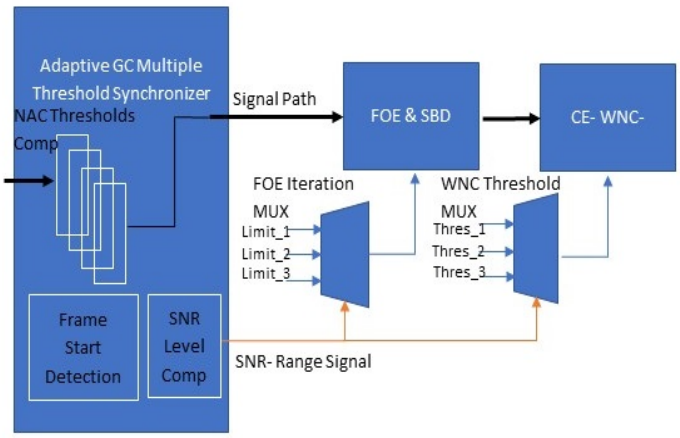


**Figure 2.** Proposed adaptive inner receiver architecture

## 3 Adaptive Frequency Offset Estimation Algorithm

After course detection of the preamble start, the frequency offset is estimated by an accumulative auto-correlation (AAC), where auto-correlation is summed for a number of Golay sequences. As mentioned in the previous section, the number of necessary iterations is SNR-dependent. First, we will revisit the equations for the FOE algorithm of [5]:

$$AC[i] = \sum_{n=0}^{N_S-1} r[i-n]r^*[i-n-N_D] \quad (1)$$

$$AC[i] = e^{N_D\theta_{CFO}} \sum_{n=0}^{N_S-1} |a^2[i-n]| + N[i] \quad (2)$$

$$\theta_{CFO} = \angle \sum_{m=i}^{i+N_W-1} [e^{N_D\theta_{CFO}} \sum_{n=0}^{N_S-1} |a^2[m-n]| + N[m]] \quad (3)$$

where a is the sent signal convoluted with the channel impulse response and r is the received signal, $N_D$ is the shifting length for the auto-correlation, $N_S$ is the length of the symbol, N is the noise factor in the signal, $\theta_{CFO}$ is the frequency offset, and $N_W$ is the number of iterations for the AAC. Since the auto-correlator of the NAC module is reused, $N_D$ is set to 128 samples, which is not enough to cancel the effect of noise and to increase the precision of the estimation. Therefore more iterations of the estimation process are used.

Since the noise factor is dependent on the SNR of the received signal, we observed that the higher the SNR, the less the number of iterations needed to get the same precision. Results are shown in Fig. 3, and also summarized in table II.

**Table 2.** Mapping of number of needed FOE iterations to SNR levels

| SNR Level | FEO Iterations |
|---|---|
| SNR < 3 dB | 9 |
| 3 dB =< SNR =< 9 dB | 5 |
| SNR > 9 dB | 3 |

Using the SNR-range signal coming from the adaptive NAC, we can now switch between different iterations. When the SNR changes, the iteration number will change accordingly, eventually this shifting will result in a higher throughput. In Fig 3, we could see that the adaptive has the lowest error rate along the SNR regime with the 10 iterations, however the average number of iterations used by the adaptive is around 5, with a distinct error rate lower than the case when using 5 iterations along the whole regime. The results in Fig. 3 show that the average percentage error of the adaptive algorithm against when using different iterations. The percentage error was calculated as follows:

$$\theta_{err} = \frac{\theta_{est} - \theta_{ideal}}{\theta_{ideal}} \quad (4)$$

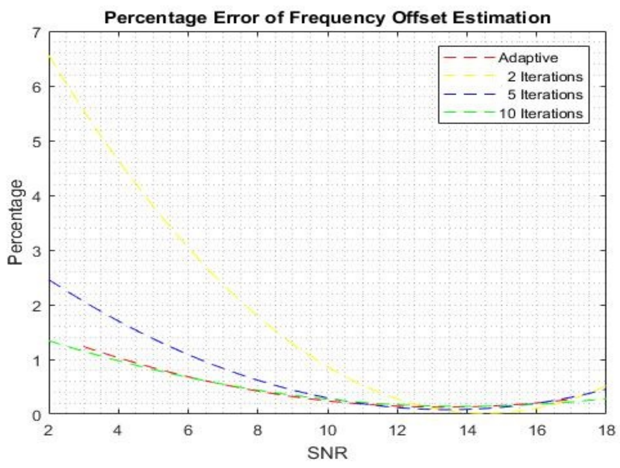


**Figure 3.** Percentage Error of Frequency Offset Estimation

## 4 Adaptive Golay Correlator-Window Noise Cancellation Channel Estimation

The channel estimation part in the preamble comes after the inverted Golay sequence in the STF. The CE method we are using is Golay sequence dependent, where the Golay sequences in the CE part of the received signal are cross-correlated with pre-saved ideal Golay sequences. Due to the correlation properties of the complementary Golay sequences, when their correlation results are added, the result is a delta function. Consequently, when adding the cross-correlation of the CEF of the received signal with a pre-saved ideal sequence, the channel parameter matrix is found assuming a noise-free channel.

Starting from (2), we cross-correlate the CE part in the preamble with the pre-saved Golay sequences:

$$AC_a = \frac{1}{256}\sum_{n=0}^{256-1}((x_k * h + N_k)(Ga_k - n)); x_k = G_a \quad (5)$$

$$AC_b = \frac{1}{256}\sum_{n=0}^{256-1}((x_k * h + N_k)(Gb_k - n)); x_k = G_b \quad (6)$$

Adding the two correlator results gives:

$$AC_a + AC_b = (R_a * h) + (R_b * h) + (\frac{1}{256}\sum_{n=0}^{256-1}((Ga_k - n + N_k)) + (\frac{1}{256}\sum_{n=0}^{256-1}((Gb_k - n + N_k)) \quad (7)$$

$$AC_a + AC_b = \delta(k)h + N_{cor} \quad (8)$$

where $N_{cor}$ is the correlation of the noise component in the received signal with the pre-saved Golay sequence. While the resulting AWGN peaks could be relatively small; ranging from 0.01 in the high SNR till 0.06 in the low SNR, the AWGN peaks could give a whole mistaken equalization output when added to the estimated channel frequency response. In [4], a window based noise cancellation technique was used to cancel these peaks. The window depends on a pre-defined threshold to cancel the AWGN peaks. From Fig 4, we see that a higher threshold reduces the peaks. The less the SNR value, the higher the peak and therefore, with low SNR a higher threshold should be used. The problem with the higher threshold is the risk of losing some of the channel impulses.

To avoid that, we propose a technique that uses a higher threshold when the received signal has a low SNR. Based on the estimated SNR level from the proposed extension of the synchronizer block, a threshold is selected according to table III.

**Table 3.** SNR level to AWNC-Threshold mapping

| SNR Level | AWNC Threshold |
|---|---|
| SNR < 5 dB | 0.06 |
| SNR < 15 dB | 0.03 |
| SNR > 15 dB | 0.01 |

## 5 Performance Results

The proposed synchronization and channel estimation algorithm was integrated in an IEEE 802.11ad compliant 60 GHz high data rate OFDM system. The transmitted signal is first 5/8 Low Density Parity Check (LPDC) coded, then the signal is QPSK modulated. The preamble is $\pi/2$ BPSK modulated. Both data and preamble are mapped to sub-carriers in a 512 FFT OFDM modulator. To simulate the system performance, the TGad conference room channel model with the NLOS scenario from [7] was applied. Both stations are on the same horizontal level and are 2 meters apart. Furthermore the transmitted signal was exposed to phase and frequency offsets, in addition to phase noise.

The performance for the adaptive system is compared to the Golay based correlator synchronizer and GB WNC channel estimator from [3, 4]. The threshold used for the channel estimator is set to 0.01, which is the one used in the referenced publications. The comparison with the GB synchronizer and channel estimator seems reasonable due to the pre-published results in [3, 4], indicating the favoring of the Golay based systems over the typical channel estimator performances as ZF, LS, MMSE. The results in Fig. 5 show the improvement in the FER when using the proposed adaptive inner receiver compared to fixed threshold synchronizers with pre-defined threshold channel estimators.

## 6 Conclusion

This paper presents a novel inner receiver design based on Golay complementary sequences. With little hardware

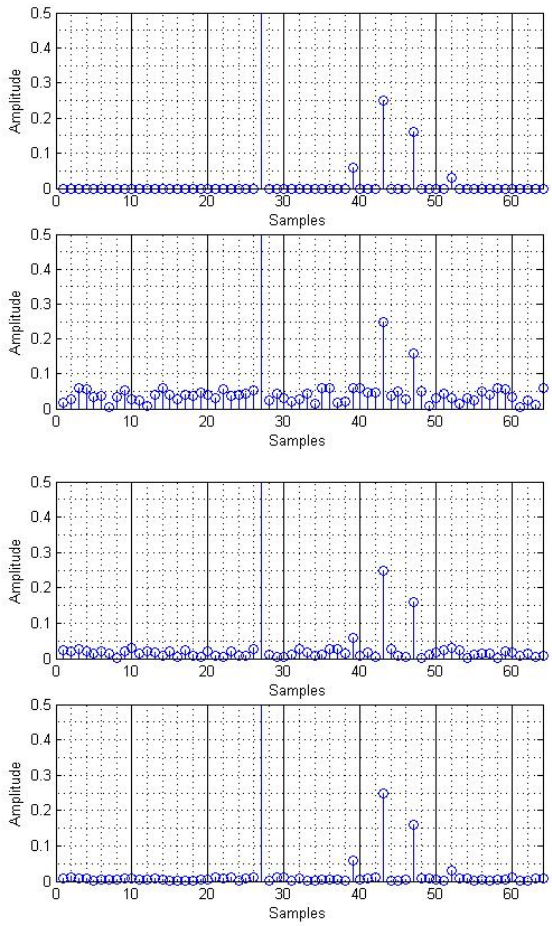


**Figure 4.** (a) Exact channel impulse response, (b) Estimated channel impulse response with a WBNC threshold = 0.06, (c) Estimated channel impulse response with a WBNC threshold = 0.03 and (d) Estimated channel impulse response with a WBNC threshold = 0.01.

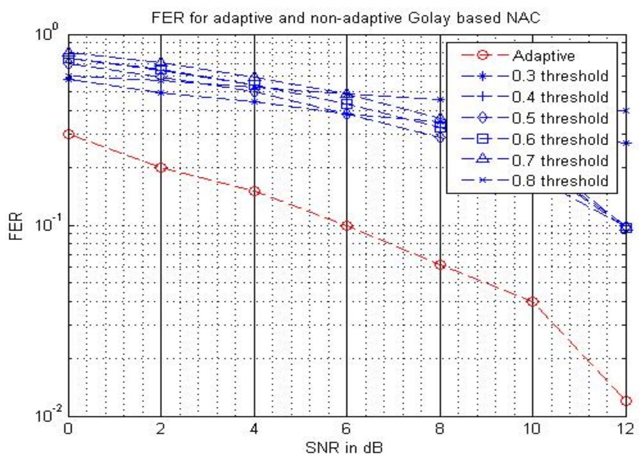


**Figure 5.** Frame Error Rate Results for 1000 Frames for both adaptive and fixed thresholds NACs

overhead, the performance of the whole system is remarkably improved. The theory presented here is not limited to the IEEE 802.11ad standard but could be adapted to several standards when applying the same concepts. Also, the block level performance improvements are not limited to the pre-mentioned blocks but to any blocks with SNR-dependent parameters. Furthermore, with such inner receiver, the whole system gains more flexibility against dynamic changes in the SNRs allowing it to be more reliable.

## References


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