Impact of Synchronization Errors when using Ethernet as Fronthaul for Distributed MIMO in LiFi Systems

Anselm EBMEYER[1*], Kai Lennert BOBER[1], Volker JUNGNICKEL[1]
[1]Fraunhofer HHI, Einsteinufer 37, Berlin, 10587, Germany, * anselm.ebmeyer@hhi.fraunhofer.de

Abstract: In this paper, we investigate the impact of synchronization impairments when using distributed MIMO in LiFi systems. Results show that the required precision is in the order of the symbol interval. A combination of precision time protocol and synchronous Ethernet is recommended when using Ethernet as a fronthaul technology for LiFi.

Introduction

Distributed MIMO (D-MIMO) is an appealing concept for LiFi [1] because it allows spatial diversity to overcome line-of-sight blockages as well as spatial multiplexing of multiple users. D-MIMO has been recently implemented by using plastic optical fiber [2] as analogue fronthaul between a central unit (CU) and distributed units (DUs). However, the analog fronthaul approach scales poorly and the use of a mass-market technologie, such as Ethernet, is more desirable for large numbers of DUs. However, the implementation of D-MIMO based on Ethernet requires tight synchronization of DUs. To synchronize the local clocks in DUs to a master clock, the Precision Time Protocol (PTP) [4] is commonly used. However, PTP has residual timing errors [5], resulting in asynchronous clocks. The combination of PTP with Synchronous Ethernet (SyncE), allows a more precise time synchronization over Ethernet links, by providing a frequency reference to local clocks. We consider the IEEE Std 802.15.13-2023 [3] as an attractive way of implementing D-MIMO for LiFi. It is based on the Pulsed Modulation physical layer (PM PHY) with on-off-keying together with frequency-domain equalization (FDE), and the high bandwidth physical layer (HB PHY) with direct current biased optical orthogonal frequency division multiplexing. Both PHYs and the MAC layer in IEEE Std 802.15.13-2023 provide the necessary support for D-MIMO, such as orthogonal pilots and compressed feedback of channel state information from all DUs received by a mobile unit (MU). At least the PM PHY has been thoroughly investigated under ideal conditions [6], but degradation in case of residual asynchronous transmissions has not yet been investigated. In this paper, we provide a thorough study of synchronization impairments when using both PHYs described in IEEE Std 802.15.13-2023. The results enable a specification of synchronization requirements for the Ethernet fronthaul between CU and DUs.

Impact of Ethernet impairments

Simulation framework: We selected a worst-case 4x1 D-MISO scenario, where the receiver (RX) is placed at the cell edge, as shown in Fig. 1. Equal channel gains for all four channels result in maximum interference in case of an asynchronous joint transmission scheme from all DUs. Channel impulse responses (CIRs) of line-of-sight components for this setup are generated with the *OWC channel builder* developed in our group.

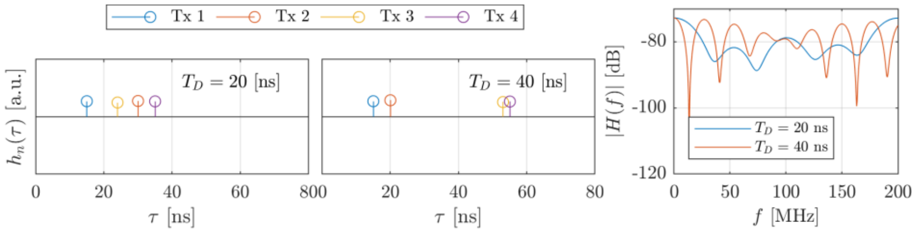

Fig. 1. CIRs of four randomly generated channels, with 20 and 40 ns maximum excess delay (left). Frequency responses of these channels (right).

When transmitters (TXs) transmit jointly, fronthaul induced random timing errors add up on the path delay in the CIR, as exemplarily shown in Fig. 2 (left). This leads to fading which creates notches in the frequency response which can be tens of decibel deep, as shown in Fig. 2 (right). The severity of fading depends on the maximum excess delay of the CIRs. In the following, random timing errors are are drawn from a uniform distribution for each TX. The *OWC channel builder*, the fronthaul model and our IEEE Std 802.15.13-2023 reference implementations are used. Both are included in the *LiFi Software Suite* and used here to perform link level simulations. A reliability analysis of the preamble-based frame synchronization, frequency-domain equalization (FDE) and forward error correction (FEC) is performed by sweeping the maximum timing error at a fixed SNR. Metrics are a synchronization rate as ratio between the numbers of detected and transmitted frames and the block error rate (BLER) as ratio between FEC blocks, that contain at least one bit error, to the number of transmitted blocks. An SNR with a synchronization rate of 100 % and a BLER below 10^{-3} for the synchronous case is selected for each analysis.

Simulation Results: *As a* sensitivity analysis of the frame synchronization, a maximum timing error up to 500 ns and an SNR of 15 dB is used. Results are shown in Fig. 2.

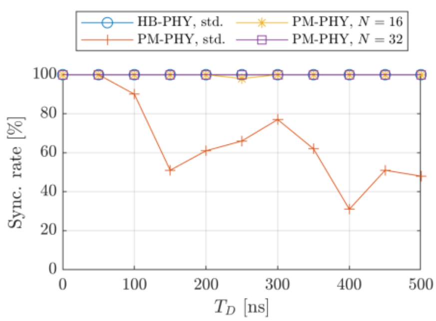

Fig. 2. Frame synchronization rate for PM-PHY and HB-PHY

Synchronization rate with the HB-PHY is 100 %, using the standard preamble and the auto-correlation metric. The PM-PHY uses OOK so that a cross-correlation metric is used. Frame synchronization becomes unreliable above 50 ns delay for preambles with subsequence lengths N=8 and N=16. Reliable synchronization is achieved at N=32. Sensitivity analysis of FDE and FEC in the PM-PHY is performed with SNRs of 6, 9, 12, 15 and 18 dB for all symbol rates in increasing order. Results are shown in Fig. 3. Maximum timing errors with zero BLER are typically a few symbol intervals, i.e., below 20 ns for a symbol interval of 5 ns at 200 MHz and less than 60 ns for 20 ns symbol interval at 50 MHz. For the HB-PHY, uniform 4-bitloading per subcarrier and a code rate of 5/6 for the LDPC code is used at SNRs of 18, 21 and 24 dB. Maximum timing errors with a zero BLER are below the inverse signal bandwidth, i.e., below 5 ns and 15 ns for a bandwidth of 200 MHz and 50 MHz, respectively.

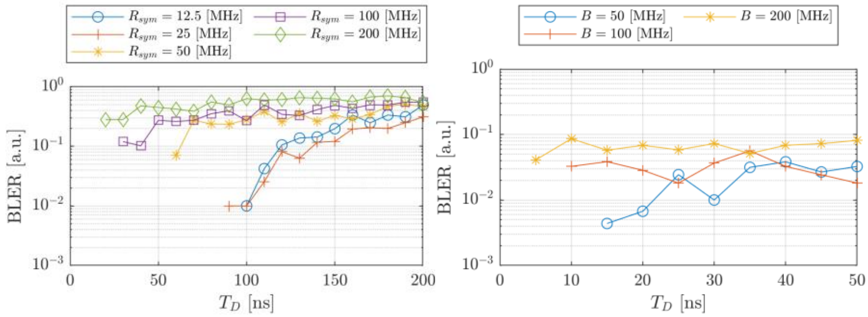

Fig. 3. BLERs for PM-PHY (left) and HB-PHY (right)

Our results show that, when used together with distributed MIMO, both PHYs in the IEEE Std 802.15.13-2023 require timing errors in the order of the symbol intervall. This is attributed to the frequency-selective channel. According to [5], PTP synchronization enables maximum timing errors in the range of 2 to several ten nanoseconds. Synchronous Ethernet (SyncE) is known to increase accuracy, since it eliminates timing error variation. Thus, PTP alone does not provide the full performance of D-MIMO LiFi system, and the use of SyncE is recommended to minimize the impact of timing errors between DUs.

References

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