PON Downstream Scheme Supporting Simultaneously Different ONU Categories

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PON Downstream Scheme Supporting Simultaneously Different ONU Categories

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***Abstract*—We propose a PON downstream scheme simultaneously supporting different categories of ONUs (e.g. different generations), whereby lower-category ONUs employ components with limited bandwidth. Our solution relies upon CDM utilizing Hadamard codes and the spectral properties of its code words. We propose a novel code allocation scheme and provide two optimization approaches by employing an optimized secondary spreading code and a power allocation scheme to improve the system performance.**

***Index Terms*—CDMA, PON, Hadamard Transformation, Power Allocation, Receiver Bandwidth.**

I. INTRODUCTION

The passive optical network (PON) market is rapidly growing and increasingly demanding flexibility [1]. Whereas transmission rates are steadily growing, in most cases not all individual users (ONUs) need to support the peak data rate of the network. Therefore, we consider the introduction of multiple device categories, defined by the employed optical components and corresponding to different hardware costs.

It is desirable that central unit (OLT) upgrades driven by technology advancement may be deployed without impacting the backward compatibility with legacy ONUs and without using new optical bands at any generation. Time division multiple access (TDMA) does not address the two issues described above since all users need to detect the full signal and therefore, require the maximum bandwidth [2]. We want to address these challenges with a novel code division multiple access (CDMA) scheme. CDMA was proposed for PON systems [3] and provides flexible information rate assignment to users [4], [5]. However, previous schemes assume that all receivers have the same physical bandwidth.

In this work, we consider specifically the coexistence of receivers with inhomogeneous bandwidth. When the OLT and some of the ONUs of an existing PON DS-CDMA network are upgraded to a new generation, we aim to enable backward compatibility with the remaining legacy ONUs. We start by formally introducing the considered system with full- and narrowband receivers and present the proposed code allocation scheme. We propose two optimization approaches to improve the system performance and present simulation results.

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II. CDMA-DS FOR RECEIVERS WITH INHOMOGENEOUS BANDWIDTH

In CDMA, the transmitter encodes a symbol with a fixed user-specific sequence called the spreading code word $\mathbf{c}$. For a symbol sequence $\mathbf{s}$, this operation corresponds to the Kronecker product $\mathbf{s} \otimes \mathbf{c}$. Thus, each symbol is spread over n_s chips, where n_s is the spreading code length. For upstream, often Gold codes are used because of missing synchronization between users [6], [7]. Achieving symbol-wise synchronization in a distributed upstream scenario, which would allow for the utilization of synchronous codes, has been addressed in [8], but is generally not employed in practice. For downstream, orthogonal codes like Hadamard codes may be used, because all codes propagate synchronously from the OLT to each ONU [9]. Thus, no synchronization problem between different user signals exists at the individual ONUs. Hadamard codes for PON systems are proposed in [10], in order to achieve multiple access in the presence of optical-beat and go-channel interference.

We introduce users with different component bandwidth. This situation arises in an upgrade scenario where the OLT and some ONUs are upgraded while an old device generation is still employed. Legacy ONUs with a component bandwidth smaller than the upgraded system bandwidth

- cannot observe the full signal spectrum,
- do not collect the whole signal energy,
- suffer from interference caused by other users since code orthogonality may not hold on a partial spectrum.

We model such a system with full band users (FBUs) and narrow band users (NBUs). FBUs have a receiver bandwidth W_f and sampling rate R_f. NBUs have a receiver bandwidth $W_n = \alpha W_f$ with $0 < \alpha < 1$ operating at possibly lower sampling rate $R_n = \beta R_f$ $(0 < \beta \leq 1)$. The OLT operates at full bandwidth W_f. The proposed approach tries to preserve enough orthogonality and collect energy within the receiver bandwidth, such that both FBUs and NBUs can successfully be supported in one combined system.

III. SPECTRAL PROPERTIES OF HADAMARD CODES

The proposed CDMA system uses Hadamard codes. Hadamard codes are defined recursively by

$$\mathbf{C}_0 = \begin{bmatrix}1\end{bmatrix} \quad , \quad \mathbf{C}_i = \mathbf{C}_{i-1} \otimes \begin{bmatrix}1 & 1 \\ 1 & -1\end{bmatrix} \quad , \quad i > 0, \qquad (1)$$

where we call $\mathbf{C}_i$ a code, each row of $\mathbf{C}_i$ is a code word and we call i the level of the code. A Hadamard code of level i

consists of $c = 2^i$ spreading code words of length $n_s = 2^i$. Note that all code words are real valued.

From the recursive definition follows that if $[x, y, ..., z]$ is a code word of the Hadamard code $\mathbf{C}_{m-1}$, then $[x, x, y, y, ..., ..., z, z]$ and $[x, -x, y, -y, ..., ..., z, -z]$ are code words of $\mathbf{C}_m$ which we call *type A* and *type B* respectively. Thus, for half of the code words in $\mathbf{C}_m$ every second symbol is repeated and for the other half each second symbol is followed by its opposite.

All code words on the same level are orthogonal to each other. Additionally, the signal corresponding to a *type A* code word of $\mathbf{C}_m$ can be associated also to a word in $\mathbf{C}_{m-1}$. The repetition pattern in *type A* code words implies narrower spectral bands compared to *type B* code words. For *type A* code words more power is allocated to low frequencies. We obtain a *type B* code word when multiplying a *type A* code word with an alternating sequence $[1, -1, \ldots, 1, -1]$. This corresponds to a shift in frequency domain by π and therefore a pair of *type A* and *type B* code words have mirrored spectra around $\pi/2$.

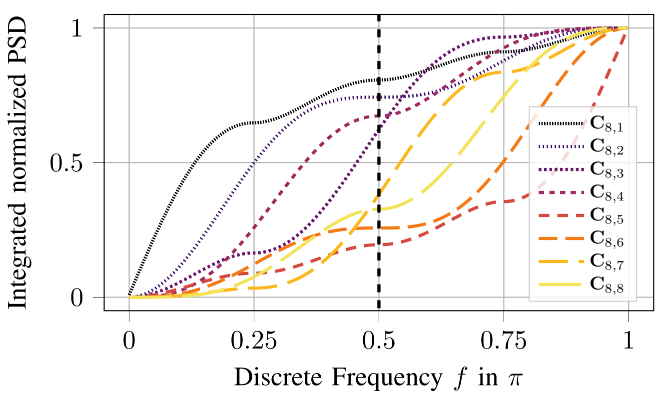

Fig. 1. Integrated normalized PSD of $\mathbf{C}_{8,1}$ to $\mathbf{C}_{8,8}$ for $n_s = 8$. $\mathbf{C}_{8,1}$ to $\mathbf{C}_{8,4}$ (*type A*) allocate more energy to low frequencies.

Consequently, a *type A* code word with energy concentrated on lower frequencies implies a corresponding *type B* code word with energy concentration on higher frequencies. The relative power of the codes that is allocated within the reduced receiver bandwidth $W_n = \alpha W_f$ of a NBU corresponds to the value at $f = \alpha$ of the corresponding graph in Fig. 1, where the integrated normalized power spectral density (PSD) of all user codes for $n_s = 8$ is plotted. We see that the first 4 code words (*type A*) allocate significantly more power within the first half of the spectrum.

For FBUs, the CDMA system operates in a fully orthogonal fashion, however, due to the band limitation, the orthogonality of the code words within the received signal is impaired for NBUs. The receiver band limitation causes inter-symbol interference (ISI) of the users own code word as well as interference from other code words, i.e., inter channel interference (ICI) from current as well as previous symbols of other users. We assume that all users are NBUs. The interference profile for $n_s = 8$ and $\alpha = 0.5$ between the code words and the respective receiver least square (LS) filters of each NBU is illustrated in Fig. 2. Each entry (x, y) in the plot corresponds to the interference level (ISI or ICI) measured after correlating the received code word $\mathbf{C}_{8,x}$ with the receive filter LS_y. The last column corresponds to the sum along each row and thus to the combined interference each user experiences. Each row y of the figure is normalized to the power of the main sample of the correlation between $\mathbf{C}_{8,y}$ and LS_y. All values are then normalized with respect to the largest combined interference value, the inverse of each value is taken and they are expressed in dB's. Thus, the plot displays the relative signal-to-interference ratio (SIR). Bright values correspond to low interference and thus high SIR values, whereas dark values indicate large interference and thus low SIR. On the main diagonal the ISI of each code word after correlation with the receive filter is displayed. Off-diagonal values display the amount of interference caused by other code words (ICI) after correlation with the NBUs receive filter. The different quadrants display the SIR

1) within the *type A* code word group,
2) between the *type A* LS filters and the *type B* codes,
3) between the *type B* LS filters and the *type A* codes,
4) within the *type B* code word group.

The last column shows the combined SIR (CSIR) after correlating the complete receive signal of a NBU with its LS filter.

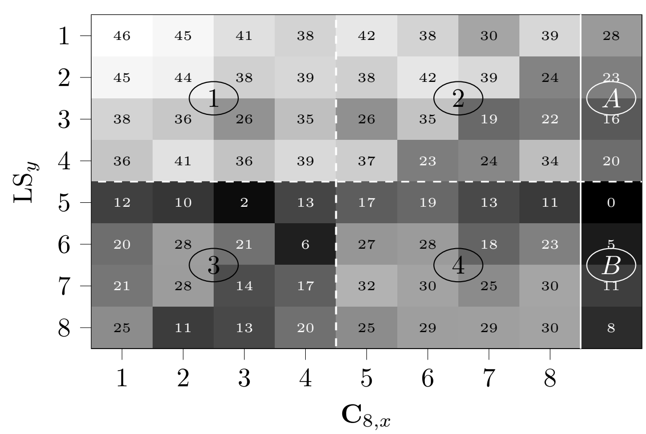

Fig. 2. Interference profile between the received code words $\mathbf{C}_{8,x}$ for $n_s = 8$ and $\alpha = 0.5$ and the receive filters LS_y. Logarithmic, values in dB. The x-axis corresponds to the indices for the received user code words, the y-axis displays the indices for the different receive filters.

The interference within the *type A* code word group (1) is lower compared to the inter-group interference between *type A* and *type B* code words (2). In the same way, the interference within the *type B* code word group (4) is also lower compared to its inter-group interference (3). The impairment of the orthogonality within the whole Hadamard code book introduced by the reduced receiver bandwidth is weaker within the two code subgroups *type A* and *type B* compared to the strong loss of orthogonality between the two code groups. The overall interference experienced for each code word is much weaker for the first 4 code words, i.e., the *type A* code group.

IV. Code Allocation Scheme

In the following, we describe the procedure to assign the code words of the level i Hadamard code book $\mathbf{C}_i$ of size

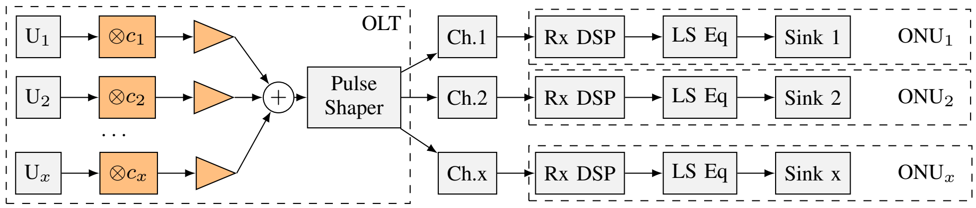

Fig. 3. Block diagram of the proposed CDMA system with optimization steps marked in orange.

$c = 2^i$ to NBUs and FBUs. Let $c_A = c_B = 2^{i-1}$ be the code book subgroup size for *type A* and *type B* code words, and let n, f be the number of actual deployed NBUs and FBUs in the system. The proposed CDMA system supports generally a maximum number of c users, equal to the number of code words in the code book, thus $n + f \leq c$. We generally assume $n \leq c_A$ NBUs in the system.

For a system with $n + f \leq c$ users, there exist $p = \binom{c}{n+f}$ possibilities (for a system at capacity, i.e., $n + f = c$ there only exists one possibility) to choose a code subgroup $\tilde{\mathbf{C}}_i^{n+f}$ of size $n + f$ from the complete code book $\mathbf{C}_i$ of size c. For each of these possibilities, we generate the interference profile according to Fig. 2 and assign the n least interfering code words, i.e., code words with largest CSIR values, to NBUs and remaining code words to FBUs. We choose the one code subgroup and NBU-FBU assignment with the lowest overall interference for the assigned NBUs (the highest sum of the CSIRs of the corresponding assigned NBUs). For $n + f = c$ and $\alpha = 0.5$, these n code words are always part of the *type A* code group. Since the number of possibilities p can grow rapidly for larger systems below capacity, generating the p interference profiles can become infeasible. A simple but suboptimal code allocation can be found by taking the interference profile plot for $n_s = c$. For the p code subgroups we neglect the respective rows and columns in the interference plot and assign lowest interference codes to NBUs. We then choose the code subgroup and code assignment that leads to lowest overall interference for the assigned NBUs, as described previously.

V. Simulation Setup

The transmitter generates uniformly and independent distributed bit sequences which are coded and scaled before summation. The transmitter applies root-raised cosine pulse shaping with roll-off factor $\alpha_r = 0.1$. We consider AWGN channels with adjustable SNR and model the optical receiver frontends with brickwall filters. The receiver DSP includes a LS filter with $2n_s$ taps for FBUs and $3n_s$ taps for NBUs. Fig. 3 shows the complete setup. The simulations evaluate $2 \cdot 10^6$ chips per user and per SNR value. We utilize the root mean square of the error vector magnitude (EVM) as performance metric of the system. In the following we will assume for all simulation results that $\alpha = \beta = 0.5$. Fig. 4 shows a degraded system deploying *only narrow-band receivers* for length $n_s = 8$ codes. Dashed lines indicate a corresponding BER of 10^{-2} and 10^{-3} with BPSK signaling. The conversion of EVM to BER holds under the assumption that the noise and interference have AWGN statistics. Furthermore, the dotted line marks the EVM for orthogonal CDMA signaling. We observe that just one user may pass the 10^{-3} threshold, i.e., the system fails with too many legacy/low category devices at full rate and we need to utilize the proposed code assignment and carefully design the power allocation. Note that *type A* code words coincide with the four best NBUs, i.e., $\mathrm{NBU}_1 \ldots \mathrm{NBU}_4$ and the user performance ranking matches the interference profile from Fig. 2.

In the following simulations, we use the proposed code allocation scheme with code length $c = n_s = 8$ and deploy 4 NBUs with half bandwidth ($\alpha = 0.5$) and half sampling rate ($\beta = 0.5$) and 4 FBUs. Note that in all the following figures, the FBU curve represents all FBUs since they all see orthogonal codes and thus have identical performance.

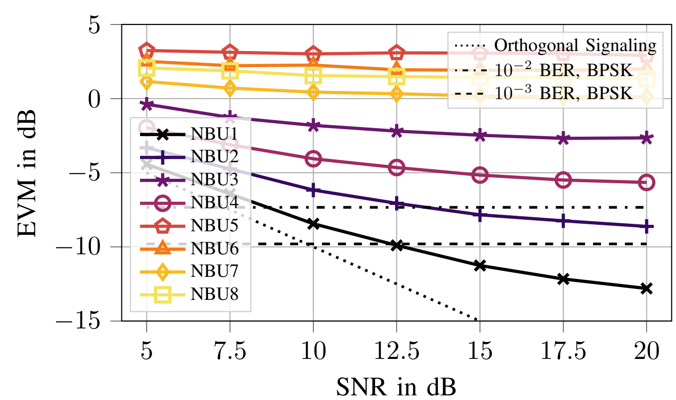

Fig. 4. EVM over SNR for narrow band receivers for $n_s = 8$ and $\alpha = 0.5$.

VI. Secondary Spreading Codes

Since NBUs correspond to legacy or lower-category devices with only a fraction of the FBUs bandwidth, their respective data rate may be lower in a real use case. If FBUs have a bit rate of $R_{b,f}$ then NBUs only support a bit rate of $R_{b,n} = \gamma R_{b,f}$ (with $0 < \gamma \leq 1$). An additional length l spreading code $\mathbf{c}_r$ applied before the Hadamard codes reduces the bit rate by a factor $\gamma = 1/l$. The combination of spreading and Hadamard code $\mathbf{c}_{cr}$ corresponds to $\mathbf{c}_{cr} = \mathbf{c}_r \otimes \mathbf{c}$. Consider, e.g., a code word $\mathbf{c} = [1, -1]$ and a repetition code of length $l = 2$ $\mathbf{c}_r = [1, 1]$, then $\mathbf{c}_{cr} = [1, -1, 1, -1]$. The respective spectral concentration of the transmit power at low frequencies induced by the code word may be improved by using a suitably designed spreading sequence $\mathbf{c}_s$ instead of a repetition code. We choose the secondary spreading code (SSC) $\mathbf{c}_s$ that results in the longest sequences of equal consecutive symbols in the combined code word. In the above toy example, an alternating spreading sequence $\mathbf{c}_s = [1, -1]$ leads to the combined code word $\mathbf{c}_{cs} = [1, -1, -1, 1]$ and the induced spectrum is narrower than in the case of the ordinary repetition code. All code words remain orthogonal.

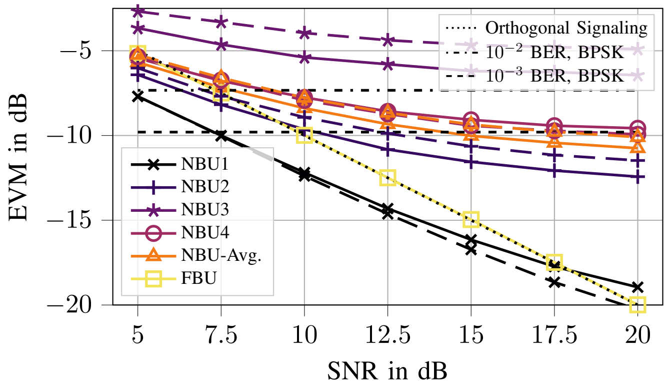

Fig. 5. EVM over SNR for SSC (solid lines) with spreading factor $l = 2$ versus ordinary repetition code (long dashed lines) for $n_s = 8$ and $\alpha = 0.5$. The average NBU EVM is additionally displayed.

The effect of the SSC with spreading factor $l = 2$ can be observed when comparing Fig. 5 and U_1 to U_4 of Fig. 4. Note that the bitrate of the NBUs is halved, thus $\gamma = 0.5$. By applying the optimized SSC (solid lines) instead of a repetition code (long dashed lines), the average EVM of all NBUs can be lowered. Still, with uniform power allocation, only two of the four NBUs pass the 10^{-3} threshold.

VII. Power Allocation

DS-CDMA with Hadamard codes operates interference-free for FBUs. However, NBUs experience interference from three different sources: ISI, interference from NBUs and interference from FBUs. The strongest source of interference are FBUs since the orthogonality of the FBU spreading codes to NBU code words is significantly impaired when subsampled and received with reduced bandwidth, as previously examined. Therefore, the EVM for NBUs is significantly higher and shows a floor due to the interference. Power allocation is crucial to balance interference from FBUs on NBUs.

We start from a uniform power allocation and update it iteratively to minimize the sum of EVM over all users. The update equations are

$$\hat{P}_i^k = P_i^{k-1}\sqrt{\frac{\mathrm{EVM}_i^{k-1}}{\sum_{l=1}^{N}\mathrm{EVM}_l^{k-1}}} \quad , \quad P_i^k = \frac{\hat{P}_i^k}{\sum_{l=1}^{N}\hat{P}_l^k} \qquad (2)$$

where P_i^k and $\hat{P}_i^k$ are the (normalized) power allocation of user i at iteration k, N is the total number of users in the system, EVM_i^{k-1} is the EVM of user i in the previous iteration $k-1$. The resulting EVMs are similar for all FBUs and NBUs. We could also bias the algorithm in favor of specific users using suitable weights.

Fig. 6 shows the user performance with optimized power allocation. All users now have uniform EVMs and do not exhibit any error floor within the relevant SNR region. All FBUs are treated equally by power allocation since all FBUs see orthogonal codes. For the optimized power allocation, more power is assigned to the NBUs. The worse their initial performance is, the higher their power allocation becomes. As the SNR increases, more power is assigned to NBUs, because in the high SNR region, the FBU interference is the main limitation for NBUs. In the proposed system, all users pass the 10^{-3} BER threshold with a penalty of 0.6 dB with respect to an orthogonal CDMA system.

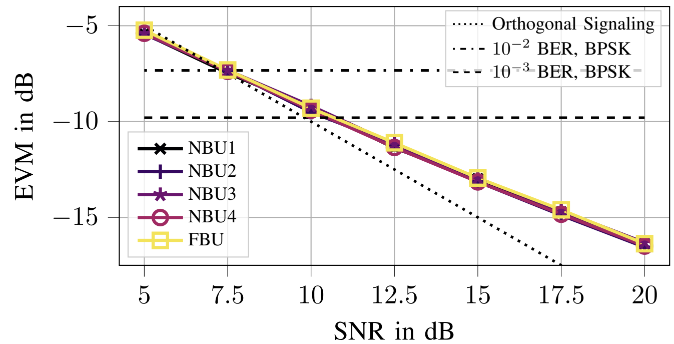

Fig. 6. EVM over SNR after Power Allocation for $n_s = 8$ and $\alpha = 0.5$.

VIII. Conclusion

We proposed a CDMA downlink scheme with a novel code allocation, code design and power allocation that enables PON supporting different ONU categories. In an exemplary network, we showed that the coexistence of full-band and half-band users induces an SNR penalty of only 0.6 dB at BER 10^{-3} compared to a network with homogeneous ONUs. Finding an asynchronous code book and adapting the proposed scheme for an uplink scenario is a topic for future work.

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