Study of a Scheme of Multiple Access in OFDM-based Next Generation Optical Access Networks

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Abstract—Multiple access based on orthogonal frequency division multiplexing (OFDM) signals has been proposed to be used in the next generation of optical access networks (NG-OANs). The objective of this dissertation is to select and study a scheme of orthogonal frequency division multiple access (OFDMA) and evaluate its performance and assess the capacity of the selected OFDMA-based OAN. An adaptive subcarrier allocation OFDMA passive optical network (ASA-OFDMA-PON) scheme, where the OFDM symbols subcarriers are preprocessed at the optical line termination (OLT) to carry specific data to each user, is selected and studied. Furthermore, data reception security is ensured at the transmission, since the ONUs can only demodulate the information which was assigned to them. The particularity of this scheme is that each optical network unit (ONU) is able to recover its assigned information, with lower sampling rates and computation cost, since the received signal is sampled at a lower rate than the transmitter of the OLT. The performance of the ASA-OFDMA-PON, when transmitting OFDM signals at 10 Gb/s, is assessed for different M-QAM mappings, number of users, capacities assigned to each user, PON reaches, electrical noise power spectral density (PSD) levels and type of equalization at the receiver. The results show that, with the studied ASA-OFDMA-PON, it is possible to assign the system capacity and transmit specific data to the different users of the PON. For an electrical noise PSD level of $10^{-24}$ A$^2$/Hz, network reaches of 60, 50 and 35 km are achieved for PONs serving 16, 32 and 64 clients, respectively. The increase of the electrical noise PSD levels causes a steep degradation of the ASA-OFDMA-PON performance.

Index Terms—Passive optical network, orthogonal frequency division multiplexing, multiple access, next generation of optical access networks, subcarrier allocation

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been the center of several studies regarding high-speed optical communications for some years to this part. Previously implemented in radio frequency (RF) systems, OFDM has become of interest in the optical domain due to the multi-media driven growth of internet traffic.

The growing demand for the capacity of access networks as well as the increase of the fiber-to-the-home (FTTH) subscribers, which is expected to reach 100 million by 2013 [2], justify the necessity for an improvement of the optical access network (OAN) capacity.

Multiple access networks for fiber-optic networks arrived as a response to the need to increase the potential transport capacity offered by passive optical networks (PONs) [3]. PONs are characterised by the connection of nodes through passive optical components so that no opto-electric (or vice versa) conversion between the transmitter and the receivers end of the connection, is required.

Multiple access networks operate at much lower rates than the aggregate throughput of metro or core networks and offer a very high capacity [4]. Nevertheless, these networks require multiple access techniques, and in this work, OFDM-based multiple access next generation networks, are investigated. Previous studies have, however, explored other multi access techniques based on wavelength, subcarrier, time and coding.

Orthogonal frequency division multiple access (OFDMA) is expected to provide dynamic bandwidth assignment dealing with huge amounts of traffic [2].

Using OFDM signals, it is possible to consider the OFDM signal subcarriers as transparent, finely granular resources to dynamically allocate the bandwidth to multiple users and services. The basic principle of OFDMA-PON consists in dynamically assigning bandwidth resources to different users and services.

A differentiating feature of OFDMA-based PON is its reliance on electronic digital signal processing (DSP) to overcome performance and cost demands [2]. Through OFDMA-PON, the trend of software defined optical communications is extended to next-generation optical access. The performance is improved due to the efficient algorithms designed to the PON environments, and the cost-efficiency is ensured by the reuse of the legacy fiber, mature optics and silicon DSP platform that can be mass produced [2]. Furthermore, OFDMA reliance in DSP conveys greater flexibility to the system since the bandwidth assignment can be redistributed without requiring changes in the network components [2].

At the present, the studies regarding OFDMA-based configurations for the next generation optical access networks are branched into two specific paths, multi-band OFDMA and adaptive subcarrier allocation [1]. The latter is preferred to the former because of its profound advantages in dynamic bandwidth allocations and low cost on optical devices.

The adaptive subcarrier allocation OFDMA scheme proposes, as the name suggests, the allocation of capacity to the users through the OFDM signal subcarriers.

Several subcarrier allocation algorithms have been proposed [3]. Since the subcarrier allocation is software defined, the subcarrier distribution can be adapted according to the desired requirements for the system whether it is to maximize the spectral efficiency, to ensure data security or cost efficiency. The fine granularity of the subcarriers, combined with efficient distribution algorithms, enable a highly flexible resources assignment which can be implemented in the existing networks.
A subcarrier allocation scheme using signal preprocessing was firstly proposed in [1]. In that article, it is indicated that the preprocessing is performed based on channel characteristics division. The proposed scheme is experimentally demonstrated using optical single side band (OSSB) signals transmitted over 25 km of optical fiber where 128 OFDM subcarriers, mapped using a 32-quadrature amplitude modulation (QAM) format, transmitted over a PON with 32 ONUs.

In this work, a multiple access scheme referred to as adaptive subcarrier allocation OFDMA PON (ASA-OFDMA-PON), with signal preprocessing and channel estimation for downstream transmission, is investigated for OFDM-based NG-OANs. The ASA-OFDMA-PON scheme studied in this work differs from the one presented in [1], since the preprocessing is developed for optical double side band (ODSB) OFDM signals. The maximum reach of the ASA-OFDMA-PON is assessed for a different number of clients being served, different $M$-QAM symbol mappings and different subcarrier distribution schemes to the ONUs.

This paper is structured as follows. In section II, the studied ASA-OFDMA-PON architecture and mathematical formulation supporting the ASA-OFDMA-PON operation are described. In section III, the characteristics of the preprocessing operation are detailed. In section IV, the results of the studied ASA-OFDMA-PON performance analyses, are presented. In section V, the final conclusions are drawn.

II. Adaptive subcarrier allocation OFDMA-PON

Low building cost, high operation efficiency, friendly structure and adaptability to fast growing service demands are expected from the next-generation optical access networks [2].

The ASA-OFDMA-PON scheme studied in this work, uses the OFDM signal subcarriers to distribute the bandwidth resources to the users according to their requests. Since each user is assigned part of the total bandwidth, analog-to-digital converters (ADCs) with lower rates and fast Fourier transforms (FFTs) with lesser points can be used at the receivers, decreasing the implementation costs at the ONUs and increasing the signal processing efficiency. To achieve this goal, the signal must be rearranged before the transmission so that the complexity of the process is centered at the optical line terminator (OLT), thus reducing the costs at the receiver side. The processing of the transmitted OFDM signal at the OLT, so it acquires the characteristics that enable that each ONU is able to select and process only its assigned subcarriers, will be named for the remain of this work as preprocessing. In this section, it is presented the architecture of the studied ASA-OFDMA-PON and the mathematical formulation of the ASA-OFDMA-PON.

A. Studied ASA-OFDMA-PON architecture

The downstream transmission architecture of the ASA-OFDMA-PON analysed in this work is depicted in Fig. 1.

The preprocessing module is represented by a functional block whose operation is explained in section B. The downstream transmission architecture of the ASA-OFDMA-PON analysed in this work is depicted in Fig. 1.

In this scheme, the preprocessed OFDM signal is built at the OLT transmitter as follows:

- The input data bitstream is split into $N_{sc}$ parallel bitstreams, one for each subcarrier of the transmitted OFDM symbols, using a serial-to-parallel converter.
- Each parallel bitstream is mapped using a constellation mapping technique as $M$-QAM. In this work, 4, 16 and 32-QAM constellation mapping techniques are analysed. The $N_{sc}$ mapped symbols at the mapper output are represented by $S$.
- The $N_{sc}$ parallel mapped symbols are preprocessed as described in section B.
- The $N_{sc}$ preprocessed symbols at the preprocessing module output, represented by $T$ modulate the OFDM symbol subcarriers using a $N_{sc}$-inverse fast Fourier transform (IFFT), which is followed by a parallel-to-serial converter, in order to obtain a serial stream of samples. This operation is repeated for all OFDM symbols of the OFDM signal. The signal at the IFFT output is represented by $Y$.
- The digital signal is converted into an analog waveform using a digital-to-analog converter (DAC). The rate of the samples at the DAC input is $SR_{DAC}$.
- A low-pass filter (LPF), consisting of an ideal rectangular filter with bandwidth equal to the OFDM signal bandwidth, is used to suppress the aliasing products generated by the DAC operation.
- The signal is up-converted to a real-valued bandpass signal using an oscillator which up-converts the baseband signal to a carrier frequency, $f_{RF}$. In this work, a carrier frequency of 4 GHz was used for the signal transmission.
- A MZM, biased at the quadrature bias point with a continuous wave (CW) laser diode (LD) are used to perform the E/O conversion. For the LD output power values of 4 and 2 mW, are considered. With a CW laser output power of 4 mW (6 dBm) and 2 mW (3 dBm) and a MZM biased at a quadrature bias point with low modulation index values, the MZM output power is 2 mW (3 dBm) and 1 mW (0 dBm), respectively.

For the transmission channel, the following characteristics are considered:

- Standard single mode fiber (SSMF) is used as the optical transmission medium.
- Circulators with insertion losses of 0.7 dB are considered to route the signal to the upstream link. Two circulators are considered, one to route the signal at the ONU and one at the OLT.
- A passive optical 1 : $N$ optical splitter is used to sep-
arate the signal to the different ONUs. 16, 32 and 64 ONUs are considered for the PON studied in this work.

At the optical OFDM receiver at each ONU, the bits are retrieved from the OFDM signal by performing the following steps:

- The direct detection of the signal at the distribution fiber output is performed using a single positive-intrinsic-negative (PIN) photodiode with a responsivity of 1 A/W.
- The photo-detected signal, $I_{\text{out}}$, is down-converted using a down-converter with the same carrier frequency as the one of the up-converter, $f_{\text{RF}}$. The signal phase shift, $\Delta \phi$, caused by the channel dispersion is corrected to ensure the signal synchronization.
- After down-conversion, the baseband complex signal is filtered by a LPF to reduce the out-of-band power. An ideal rectangular filter, with the same bandwidth as the LPF present at the transmitter, is used for this purpose.
- The filtered signal is converted into discrete samples using an ADC. An ideal rectangular filter, with the same bandwidth as the LPF present at the transmitter, is used for this purpose.
- The sampled signal is split by the serial-to-parallel converter into $N_{\text{sc ONU}_x} \times N_{\text{subcarrier}}$ OFDM subcarriers. The variable $\tilde{Y}$ represents the sampled signal at the serial-to-parallel converter output.
- A $N_{\text{sc ONU}_x}$-point FFT is used to recover the data carried by the $N_{\text{sc ONU}_x}$ subcarriers assigned to $\text{ONU}_x$. Either an equalizer or a simple amplitude gain module is used to mitigate the distortion and the attenuation effects, respectively, and recover the transmitted complex-valued symbols. The resulting vector, $\hat{S}$, is composed by received complex-valued symbols carried by the $N_{\text{sc ONU}_x}$ subcarriers assigned to $\text{ONU}_x$.
- Finally, the received complex-valued symbols are demapped, and the binary data stream is recovered.

B. Mathematical formulation of the studied ASA-OFDMA-PON scheme operation

In this section, the theoretical formulation of the signal preprocessing at the OLT, is detailed. Following the ASA-OFDMA-PON architecture depicted in Fig. 1, the concept of the signal preprocessing operation is presented in Fig. 2.

Mathematically, the referred signals are represented by vectors, and matrices are used to describe the transformations between signals.

Defining $C$ as a matrix containing the frequency response at every $k$ subcarrier frequency, $f_k$, from the M-QAM mapper output to the FFT output at each ONU receiver, the signal preprocessing consists of applying a previously obtained matrix, $X$, to the mapped signal, $S$, obtaining the preprocessed signal, $T$. When the preprocessed signal is transmitted along a transmission system with the response characterized in $C$, at each transmission system output (ONU FFT output), the data carried in the assigned OFDM signal subcarriers,
\( \hat{S} \), is retrieved exactly as it was originally mapped.

\[
\hat{S} \equiv S \quad (1)
\]

meaning that, if a signal is built containing all the data carry subcarriers received by the ONUs, in the same disposition in the frequency spectrum they had when the signal was transmitted, the signal containing the data carried by all received subcarriers, \( \hat{S} \), is equivalent to the original modulated signal, \( S \).

Since each user’s optical transmission channel has different characteristics (noise, distance, dispersion, attenuation), the signal detected by the receiver at each ONU is distinct from the others, due to the impact of different optical channel responses on the signal waveform. Furthermore, the data assigned to each user is carried by subcarriers at different frequencies, \( f_k \). The signal preprocessing is only possible if the frequency response of all users’ transmission system, at the frequency of the subcarriers which carry their destined data, is obtained. For that purpose, the \( N_{sc} \times N_{sc} \) matrix \( C \) is obtained.

The data carried by each subcarrier has to be preprocessed, according to the characteristics of the user’s transmission channel, to which it is destined. As depicted in Fig. 2, the transmitted preprocessed signal is described by:

\[
T = X \oplus S \quad (2)
\]

where \( X \) is a matrix that when applied to the original subcarriers, \( S \), changes the subcarrier structure, rearranging the information carried by the original subcarriers [1].

The signal containing the set of all the \( N_{sc} \) OFDM symbol subcarriers retrieved by every ONU, \( \hat{S} \), given by:

\[
\hat{S} = C \oplus T \quad (3)
\]

results from transmitting the preprocessed subcarriers, \( T_k \), over the transmission system characterized in \( C \).

The matrix \( X \) is obtained through manipulation of the Eqs. 1, 2 and 3 using matrix algebra. Combining 2 and 3, the relation between the data carried in the original and the received \( N_{sc} \) subcarriers, is given by:

\[
\hat{S} = C \oplus X \oplus S. \quad (4)
\]

In order to obtain the equality expressed in Eq. 1, the following equation must hold:

\[
C \cdot X = I \quad (5)
\]

where \( I \) is the identity matrix. From Eq. 5, it can be concluded that \( X \) is obtained through the inversion of the matrix which describes the frequency response of the transmission system, \( C \). Therefore, the relation between the data carried by the OFDM subcarriers at the \( M \)-QAM mapper output and the preprocessed subcarriers which are transmitted, is given by:

\[
T = C^{-1} \cdot S. \quad (6)
\]

Due to its function, the matrix \( C^{-1} \) is named for the remain of this work as the preprocessing matrix (PPM).

### III. Characteristics of the PPM operation

The first step in the preprocessing is to define the subcarrier allocation scheme. The subcarrier allocation scheme describes the distribution of the data destined to each user by the subcarriers which are to carry it.

It was verified, when studying the operation of the ASA-OFDMA-PON using numerical simulation, that certain requirements have to be met so the ADCs of the ONUs can correctly sample and demodulate the received signal. These are addressed in this section.

#### A. Requirements for the subcarrier assignment

The conditions presented next were either indicated in [1], where this technique was proposed, or identified when studying the operation of the ASA-OFDMA-PON using numerical simulation. The number of subcarriers assigned to an ONU \( x \), \( N_{s\text{ONU}_x} \), has to verify the following equation:

\[
N_{s\text{ONU}_x} = \frac{N_{sc}}{2^{n}} \cdot \{n \in \mathbb{N} \mid n \leq \log_2 (N_{sc}) \} \quad (7)
\]

where \( N_{sc} \) is the total number of subcarriers of an OFDM symbol. The capacity per subcarrier corresponds to the total system capacity (in this work it is used a fixed total system capacity of \( R_b = 10 \text{ Gb/s} \)) divided by the total number of subcarriers. Therefore, the capacity assigned to each user is:

\[
R_{b\text{ONU}_x} = \frac{R_b}{2^n} \quad (8)
\]

The subcarrier assignment to each ONU is not arbitrary. The distribution of the OFDM subcarriers on the frequency spectrum is illustrated in Fig. 3. The table presented in Fig. 4 details the correspondence between the indexes which are assigned to the subcarriers and the frequency, \( f_k \) they occupy in the spectrum.

The indexes \( k \) of the subcarriers assigned to a certain ONU \( x \), according to the capacity attributed to that user,
when simulating the ASA-OFDMA-PON operation.

carried by the subcarriers assigned to each ONU, and to obtain the necessary information to retrieve all the data ever, start at a specific time instant. This is required to be recovered. The sampling process at the ADC must, however, be filled in with the amplitudes of the training symbol received at each ONU. The matrix \( C \) is filled using a training sequence which is previously transmitted to all ONUs. The feedback signal is retrieved at the OLT through the upstream channel.

To obtain the impact of the user’s transmission channel on the assigned subcarrier, a training OFDM symbol with \( N_{sc} \) subcarriers, is transmitted. In the training symbol transmitted to obtain the frequency response of the transmission channel at the \( k^\text{th} \) subcarrier frequency, \( f_k \), all the symbol subcarriers but the \( k^\text{th} \) are transmitted with amplitude zero. The \( k^\text{th} \) subcarrier is transmitted with amplitude one. Each transmitted training symbol, \( S_T \), is given by:

\[
S_T(n) = \begin{cases} 
0, & (n \neq k) \\
1, & (n = k) 
\end{cases}, \quad 1 \leq n \leq N_{sc} \tag{11}
\]

where \( k \) is the subcarrier for which the frequency response of the transmission channel is being obtained.

The amplitude of the training symbols received at each ONU are transmitted back to the OLT. According to the subcarrier allocation scheme defined and the subcarriers’ indexing, the amplitudes of the training symbols received at the OLT, sent by each ONU, are used to complete the matrix \( C \). The \( k^\text{th} \) column of the \( N_{sc} \times N_{sc} \) matrix \( C \) is filled in with the amplitudes of the training symbol received from the ONU to which the \( k^\text{th} \) subcarrier was assigned.

After obtaining the matrix \( C \), its inverse, \( C^{-1} \), is computed in the preprocessing module at the OLT. The calculated PPM matrix, \( C^{-1} \), can be used for this transmission system for all data slots transmitted with the same subcarrier allocation schedule used to obtain this matrix.

IV. Performance analysis of the ASA-OFDMA-PON scheme

The two major causes of performance degradation of the OFDM system are noise and distortion. In this work, the error vector magnitude (EVM) as a function of the root-mean-square (RMS) voltage of the OFDM signal is adopted as a measure of the noise (whether it is electrical noise or optical noise) and distortion inflicted by the system.

The EVM performance limits are calculated for a defined bit error rate (BER) value. The BER is defined as the ratio between the number of bit errors and the number of transmitted bits.

---

1 Sub-Nyquist sampling rate: smallest integer sub-multiple of bandpass frequency \( f_{RF} \) that meets the baseband Nyquist criterion \( f_s > 2B \).
Assuming the error of the constellation symbols at the QAM demapper as Gaussian distributed, the BER of each OFDM subcarrier, \( k \), can be evaluated from the EVM of each subcarrier resorting to the expressions used to evaluate the performance of a \( M \)-QAM modulation format. Considering \( 10^{-3} \) and \( 10^{-12} \) as the BER limits before forward error correction (FEC) and after FEC, respectively, the EVM values required from each constellation to achieve this performance are presented in Tab. I.

<table>
<thead>
<tr>
<th>Modulation Index</th>
<th>EVM [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-QAM</td>
<td>BER=(10^{-3}) -9.8</td>
</tr>
<tr>
<td></td>
<td>BER=(10^{-12}) -16.9</td>
</tr>
<tr>
<td>4-QAM</td>
<td>-16.5</td>
</tr>
<tr>
<td>16-QAM</td>
<td>-23.9</td>
</tr>
<tr>
<td>32-QAM</td>
<td>-26.9</td>
</tr>
</tbody>
</table>

The performance of the proposed ASA-OFDMA-PON scheme, when a transmission capacity of \( R_b = 10 \) Gb/s is required, is evaluated.

### A. Optimal modulation index

In this work, a MZM is used to modulate the optical signal. The MZM modulation index is a parameter which describes the measure of the amplitude variation surrounding an unmodulated carrier.

The MZM modulation index, \( m_i \), is expressed as:

\[
m_i = \frac{V_{RMS}}{V_x}
\]

where \( V_{RMS} \) represents the RMS voltage of the OFDM signal applied to the MZM and \( V_x \) is the half-wave switching voltage of the MZM.

The performance of the system varies according to the MZM’s modulation index values. It is important to find the optimal modulation index for each PON configuration considered, for which the system performance is the best.

The value of the optimal modulation index varies with the optical modulator bias point, the fiber length and the O/E converter considered (such as PIN, APD).

In this work, a study of different modulation indexes was performed for different configurations. These have their parameters presented in Table II, where \( N \) is the number of ONUs of the PON, \( N_{ONU} \) is the number of subcarriers per ONU, \( S_c(f) \) is the electrical circuit noise PSD, \( d \) is the distance of the ONUs to the OLT and \( N_{TS} \) is the number of training symbols.

The results obtained for the setups presented in Tab. II are summarized in Tab. III.

The results of Tab. III correspond to the modulation index for which the EVM value is minimum. It was seen a similar behaviour for the results of all setups. However, the minimum EVM results are obtained for different modulation indexes in each setup. For lower modulation index, electrical noise is responsible for the EVM degradation (since, for lower values of \( V_{RMS} \), the MZM still operates linearly). For higher modulation index values, the modulator and PIN nonlinearities are responsible for the performance degradation observed (since the MZM+PIN are no longer operating in the linear zone due to high values of \( V_{RMS} \)).

It was seen that, for the PONs with 32 and 64 ONUs, when \( P_{out}=3 \) dBm, the system performance is below the -16.5 dB EVM performance limit level for 16-QAM. Therefore, for the remaining performance evaluations, only the laser output power of 6 dBm, is considered.

### B. ASA-OFDMA-PON performance with all ONUs at the same distance from the OLT

In this section, the performance of the ASA-OFDMA-PON scheme, when all the ONUs are at the same distance from the OLT, is analysed. In section B.1, the maximum reach of the network, when all the ONUs are assigned the same number of subcarriers, is presented. The impact of the \( M \)-QAM mapping format used to modulate the OFDM subcarriers on the system performance, is also analysed in this section.

In section B.2, the performance of the studied ASA-OFDMA-PON, when different ONUs are assigned a different number of subcarriers, is analysed. The consequences of assigning a different number of subcarriers to each user on the system performance, when opposed to having the system capacity equally distributed among the users, is assessed.

#### B.1 Performance results when the system capacity is uniformly distributed by ONUs

As it can be seen in Fig. 5, the maximum reach of the 16-ONU PON decreases around 20 km when the electrical noise PSD value increases by one order of magnitude. This degradation is more accentuated for PONs with more

### Table I: EVM limits when BER is \( 10^{-3} \) and \( 10^{-12} \).

<table>
<thead>
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<th>Modulation Index</th>
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<tbody>
<tr>
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</tr>
</tbody>
</table>

### Table II: Parameters used to obtain the optimal modulation indexes for the different ASA-OFDMA-PON setups.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>( P_{out}=3 ) dBm</td>
<td>7</td>
</tr>
<tr>
<td>SII</td>
<td>( P_{out}=6 ) dBm</td>
<td>8</td>
</tr>
<tr>
<td>SIII</td>
<td>( P_{out}=3 ) dBm</td>
<td>20 km</td>
</tr>
<tr>
<td>SIV</td>
<td>( P_{out}=6 ) dBm</td>
<td>20 km</td>
</tr>
</tbody>
</table>

### Table III: Optimal modulation indexes obtained for the different setups of the studied ASA-OFDMA-PON.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Optimal modulation index [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>7</td>
</tr>
<tr>
<td>SII</td>
<td>20</td>
</tr>
<tr>
<td>SIII</td>
<td>26</td>
</tr>
<tr>
<td>SIV</td>
<td>44</td>
</tr>
</tbody>
</table>
ONUs, where the reduction per electrical noise PSD value order of magnitude increase, is about 25 km. The maximum network length decreases between 10 and 15 km, for PONs serving twice the number of ONUs. The link attenuation increases considerably with the number of ONUs. The difference of performance between PONs with more and less ONUs is greater when higher electrical noise PSD values are considered. When the noise levels are very high, the signal gain amplification, performed in the receiver to retrieve the severely attenuated signal, amplifies not only the signal amplitude level, but also the noise amplitude level, causing the signal to become unrecoverable. This difference is also attributed to the increase of the system complexity with the number of ONUs, resulting in additional numerical errors when processing and inverting the PPM.

The maximum network length achieved by the studied ASA-OFDMA-PON in the described conditions is 60 km. This is achieved for the lowest electrical noise PSD value considered and for the PON serving less clients.

TABLE IV: Maximum network reach of the studied ASA-OFDMA-PON when all the ONUs are at the same distance from the OLT and all the ONUs are assigned the same capacity.

<table>
<thead>
<tr>
<th>$S_c$ [$A^2/Hz$]</th>
<th>Number of ONUs</th>
<th>Network reach [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-24}$</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>35</td>
</tr>
<tr>
<td>$10^{-23}$</td>
<td>16</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>10</td>
</tr>
<tr>
<td>$10^{-22}$</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>-</td>
</tr>
</tbody>
</table>

In Tab. IV, the values of the maximum network reach seen in Figs. 5 are summarised.

When the PON serves 16 ONUs, the system performance is under the accepted EVM limits for all electric noise levels considered for up to 20 km. For PONs with 32 and 64 ONUs, this does not occur. For a 32 ONUs PON, only 5 km are achievable when $S_c = 10^{-22} A^2/Hz$. For a 64 ONUs PON, the signal is not received under the acceptable EVM limits when the highest electrical noise PSD value is considered.

Despite the number of ONUs, the behaviour of the curves is quite similar for all subcarrier modulation format. While there is not a significant variation in the performance of the system when different constellation modulation formats are used, the acceptance levels of EVM for each one vary remarkably. This results in network reaches much higher for lower $M$-QAM modulation formats. The subcarrier modulation format which allows longer network reaches, regardless the number of ONUs in the system, is 4-QAM. However, it has to be taken into account that choosing this modulation format compromises the signal spectral efficiency.

In Tab. IV, the values of the maximum network reach seen in Figs. 5 are summarised.

B.2 Performance results when the capacity is non-uniformly distributed by ONUs

The EVM results as a function of the distance of the ONU to the OLT, for a 16-ONU ASA-OFDMA-PON when a 16-QAM OFDM signal is transmitted, are depicted in Fig. 6. Tab. V summarizes the maximum network reaches observed for the ASA-OFDMA-PON, when an EVM limit of -16.5 dB is considered.

For the 16-ONU ASA-OFDMA-PON, network reaches between 20 and 60 km are achieved, depending on the electrical noise PSD level. For the 32-ONU ASA-OFDMA-PON, maximum reaches of 5 and 50 km are achievable for the highest and the lowest electrical noise PSD values, respectively. For the 64-ONU ASA-OFDMA-PON, maxi-
the MZM, resulting from being working with the optimal
modulation index, may have an impact on some subcarriers.

The ONUs assigned more subcarriers should show a
bigger impact of the MZM non-linearities in their perfor-
ance since more subcarriers are exposed to the effects of
the non-linearities.

When comparing the results presented in Tab.V, with
the ones presented in Tab.IV, related to the situation when
all the ONUs are assigned the same number of subcarriers,
it can be concluded that no substantial difference is seen
in the maximum reach of the studied ASA-OFDMA-PON
when the users are assigned a different number of sub-
carriers. This means that the scheme of allocation of the
subcarriers to different ONUs does not affect the system
performance.

It was concluded that, for low electrical noise PSD levels,
the influence of the electrical noise on the system constel-
lation is not noticeable, since it behaves as if there was no
electrical noise contribution. As the electrical noise con-
tribution gets more relevant, by increasing the distance or by
imposing higher electrical noise PSD values, the degrada-
tion of the signal quality is more noticeable. When distor-
tion has a greater impact than electrical noise, the network
reach increase does not contribute for the signal degrada-
tion. Thus, for distances from 0 to 20 km, the system
performance is similar. This explains the behaviour of
the curves presented in Fig. 6 a), which present an al-
most constant EVM between 0 and 20 km. As the dis-
tance increases, the signal level decreases, the noise con-
tribution gets more noticeable and the degradation of the
signal quality is steeper. When higher electrical noise PSD
values are imposed to the system, regardless of the net-
work length, the SNR values are lower, leading to a faster
degradation of the signal.

C. Performance evaluation of the PPM with ONUs at
different distances from the OLT

In a real multiple access transmission system, the ONUs
are not all at the same distance from the OLT. In this sec-
tion, the performance of the studied ASA-OFDMA-PON,
when its ONUs are not all at the same distance from the
OLT, is evaluated. Different scenarios, representing differ-
ent spatial distributions of the PON are defined to perform
this analysis. In scenario D1 the network length ranges

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![Graph](image)

Table V: Maximum network reach of the studied ASA-OFDMA-
PON when all the ONUs are at the same distance from the OLT for
PONs with 16, 32 and 64 ONUs, and the capacity of the system is
not uniformly assigned to the different users.

<table>
<thead>
<tr>
<th>$S_c \text{ A}^2/\text{Hz}$</th>
<th>Number of subcarriers per ONU</th>
<th>Network reach [	ext{km}]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>16 ONUs</td>
<td>32 ONUs</td>
</tr>
<tr>
<td>$10^{-24}$</td>
<td>16</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>$10^{-23}$</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>22</td>
</tr>
</tbody>
</table>

---

In Fig. 6 a), it can be seen, for shorter network reaches
(0-20 km), a difference of 1-2 dBs in the EVM between
the ONUs which are assigned more and less subcarriers.

For short distances and low PSD electrical noise values,
the distortion is the greatest contributor for the signal
degradation. This difference becomes less noticeable either
when the network reaches increase, increasing the attenua-
tion as well, or when the electrical noise PSD level increases (Fig.
6 b) and c)). This difference of 1-2 dB on the EVM can be
explained by the fact that the same modulation index is
used to modulate the signal at the OLT, which is trans-
mitted to all the ONUs. This means that the non-linearities of
the MZM, resulting from being working with the optimal

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![Graph](image)
from 10 to 50 km for different ONUs. In scenario D2 the ONUs are close to each other and in short reach to the OLT. In scenario D3, the ONUs are close to each other, but farther from the OLT.

C.1 Performance results when the capacity is uniformly distributed by ONUs

The results obtained for each one of the ONU distances distribution plans, for a 16-ONU ASA-OFDMA-PON when transmitting a 16-QAM OFDM signal are depicted in Figs. 7. For each electrical noise PSD level considered, the ONUs located at the distances presented in the referred figures, represent the ONUs of the ASA-OFDMA-PON. For this analysis it is considered that all ONUs are assigned the same number of subcarriers.

In Fig. 7 b), the curves present an almost constant behaviour for the lowest electrical noise PSD levels, and the degradation becomes evident when the electrical noise PSD values increase. In Fig. 7 c), where every ONU has a network length above 30 km, the increase of the EVM results is visible even for \(S_c = 10^{-24} \text{ A}^2/\text{Hz}\).

In Fig. 7 a), the performance degradation is observable for the ONUs located at more than 20 km (for the lowest electrical noise PSD level considered) from the OLT. This conclusion is in agreement with what had been seen in section B.1, for the case where all the ONUs were at the same distance from the OLT.

Similar maximum network reaches are achieved for the ASA-OFDMA-PON when its ONUs are all at the same distance from the OLT. In conclusion, similar performance will be obtained for an ONU located at a certain distance from the OLT, regardless of the network length of the other ONUs in the PON. The same conclusion holds for the ASA-OFDMA-PON with 32 and 64 ONUs.

It was also seen that the behaviour of each ONU, in the proposed ASA-OFDMA-PON, is independent of the spectral position of its assigned subcarriers. This conclusion holds independently of the number of subcarriers assigned to it. This analysis is performed in the next section.

C.2 Performance results when the capacity is non-uniformly distributed by ONUs

In this section the study on the achievable network reach of the studied ASA-OFDMA-PON when 16 ONUs, located at different distances from the OLT, are not all assigned the same number of subcarriers of the transmitted OFDM signal, is presented.

Network reaches between 20 and 50 km are achieved for the highest and the lowest electrical noise PSD levels considered.

It was concluded from the obtained results that, when the ONUs are not all assigned the same number of subcarriers, the performance of each ONU of the ASA-OFDMA-PONs is independent of the network reach of the remaining ONUs in the network. A similar conclusion had been drawn with respect to the case where all the ONUs were assigned the same system capacity.

The disparity of 1-2 dB between the ONUs with more or less subcarriers, discussed in section B.2, is seen as well for the present analysis.

The ASA-OFDMA-PON performance, when different M-QAM OFDM subcarrier modulation formats are considered, is evaluated for 4-QAM and 32-QAM, respectively. These results are in accordance with the ones obtained in section B.1. The EVM values required for the acceptable performance limit, when a BER threshold of \(10^{-3}\) is considered, is higher for lower modulation M-QAM formats. Therefore, a much longer network length is achievable for lower modulation M-QAM formats. However, the EVM values as a function of the distance are lower for higher...
M-QAM modulations. The power fading which affects the signal with larger bandwidth is the reason for this to happen.

The conclusions stated above hold for PONs with 32 and 64 ONUs. However, and as described in the previous sections, the network reaches decrease when the number of ONUs increases.

Similar achievable PON network reaches to the ones observed before, were obtained for the case where the ONUs are at different distances from the OLT and the capacity of the system is not uniformly distributed to all user. For the 16-ONU ASA-OFDMA-PON, the performance was under the acceptable EVM limits for distances from 20 to 50 km, for the highest and lowest electrical noise PSD level considered, respectively. For the 32-ONU ASA-OFDMA-PON, maximum reaches of 50 km are achievable for the lowest electrical noise PSD values. Since the spatial distributions considered does not present distances lower than 10 km no EVM values for the highest electrical noise PSD levels considered were under the acceptable EVM limit of -16.5 dB. For the 64-ONU ASA-OFDMA-PON, maximum reaches between 10 and 35 km are achievable when $S_e = 10^{-23}$ $A^2$/Hz and $S_e = 10^{-24}$ $A^2$/Hz, respectively.

V. Conclusions

The studied ASA-OFDMA-PON scheme presents a flexible OFDMA-based dynamic bandwidth assignment solution for the NG-OANs. The resources allocation is defined on the digital domain and a change on the assignment schedule has no impact on the network configuration. Since each ONU has only to process its assigned subcarriers, the ADCs have lower sampling rates and the FFTs smaller sizes. Therefore, the components complexity at the ONU-side is reduced. The simplification of the elements on the user end is very advantageous from a cost-efficiency standpoint. Furthermore, since each ONU has a channel with different characteristics, different waveforms arrive at each ONU. This implies that each user is only able to recover its assigned subcarriers. As a consequence, the signal transmission security and information privacy is ensured on a physical level [1].

This scheme allows for dynamic digitally controlled system capacity allocation and it is based on a preprocessing matrix which is used to change the signal, so the users are able to select and recover their information. It was concluded that the preprocessing works as intended, meaning that the ONUs are able to recover all the information carried by the subcarriers assigned to them. However, the limitations in the subcarrier allocation scheme imposed by the sampling process, as well as the synchronization required so that each ADC starts the signal sampling at a specific time instant, compromises the applicability of the ASA-OFDMA-PON in the NG-OANs. Regarding the operation of the proposed ASA-OFDMA-PON, it was confirmed that the performance of each ONU is independent, not only of the subcarriers’ assignment, but also of the characteristics (distance to the OLT, capacity assigned) of the remaining ONUs in the PON.

One of the limitations of this scheme is the austerity of the sampling process. The ADC at each ONU has to start sampling the signal at a specific time instant. This is necessary to guarantee that the assigned subcarriers are recovered by the ONUs, and the matrix $C$ with the frequency response of the channel at the frequency of each subcarrier is not singular. This implies that the ONUs must be synchronized so that the ADC is able to start the sampling process at that instant. The resilience of the ASA-OFDMA-PON to a desynchronized sampling should be evaluated on an experimental setup where it is possible to sample continuous waveforms. It is also predictable that the signal preprocessing will not be able to mitigate any of the noise-related degradation in the signal, due to its arbitrary nature.

When the inversion process of the matrix $C$ and the application of the PPM to the signal takes place, the signals destined to the different ONUs become correlated. Therefore, any numerical errors or problems with the channel frequency response are propagated to the entire system. This makes the system vulnerable to erratic behaviours caused by the PPM calculation.

The performance and capacity of the ASA-OFDMA-PON scheme, are presented. The results showed that network reaches of 60, 50 and 35 km were achieved for PONs with 16, 32 and 64 subcarriers, respectively. These values were obtained for the lowest electrical noise PSD level considered, $10^{-24}$ $A^2$/Hz. It was concluded that the electrical noise PSD levels have a great impact on the system performance, since the network reaches achieved are considerably lower when higher electrical noise PSD values were considered. It was determined that the $M$-QAM, format for which greater network lengths are achieved, is 4-QAM.

References