

Native Multicasting in a 2D-OCDMA PON

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Abstract—Optical CDMA is proposed to implement a PON that supports downstream native optical multicasting. Common wavelengths within provisioned 2D codes may uniquely represent a multicast group. We introduce a simple architecture enabling native 2D-OCDMA multicasting without resorting to code-tunability. We outline the associated code-provisioning problem and demonstrate clear SIR advantages compared to 2D-OCDMA.

Index Terms—PON, OCDMA, Native Multicasting, Code Provisioning.

I. INTRODUCTION

Many emerging applications stand to benefit from Passive Optical Network (PON) light-tree capabilities. In addition to HDTV and Optical Storage Area Networks (O-SAN), the powerful emerging trend in peer-to-peer networking, as well in as applications such as file sharing, video-conferencing, and online gaming, suggests an increase in multicast traffic at the local and access levels [1].

Few contributions address multicasting in the context of Optical Code Division Multiple Access (OCDMA). Optical Coding (OC) labels were proposed to perform multicasting in tree networks [2]. In a passive star network topology, tunable code conversion modules may also be implemented to achieve multicasting [3]. Furthermore, the switch architecture in [4] introduces the use of separate tunable decoders for multicasting. Applied in a PON context, each of these proposals requires the deployment of configurable in-field optical modules such as switches, code converters, or tunable decoders. This departs from the low-cost passive requirement of the PON topology.

Based on the deployment of fixed OCDMA wavelength/time domain (2D) codes at the Optical Network Units (ONUs), our design maintains the simplicity of the PON passive access tree and avoids the cost and complexity of tunable transceivers at the ONU. The use of individual wavelengths common to more than one ONU is introduced to achieve multicast transmissions.

Section II presents the proposed architecture and illustrates the principles of 2D-OCDMA multicast operation. In Section III, we introduce the problem of multicast-oriented code-provisioning. The advantages of the proposed multicasting method on Signal-to-Interference Ratio (SIR) is demonstrated in Section IV. We conclude with a discussion of potential research avenues in Section V.

II. NETWORK ARCHITECTURE AND OPERATION

The network topology used is a typical PON architecture based on a broadcast passive tree with the Optical Line Terminal (OLT) at its root and ONUs at its branches. A power

coupler enables broadcast transmission in the downstream direction and point-to-point upstream transmission.

In 2D-OCDMA, user k 's encoded signal may be expressed as follows:

$$s_k(t, \lambda) = b_k(t) \cdot \sum_{j=1}^W \sum_{i=1}^L C_k[i, j] \Psi(t - iT_c, \lambda - \lambda_j), \quad (1)$$

where $b_k(t)$ is user k 's transmitted bit value, indicating that this is an intensity-modulated positive system, T_c is the chip duration, W is the number of available wavelengths, and L is the number of chips per code, or code-length. C_k is a $L \times W$ matrix of binary elements representing user k 's code, with element $C_k[i, j] = 1$ indicating that the i^{th} chip uses the j^{th} wavelength. $\Psi(t, \lambda)$ is the chip signaling waveform, aligned in time and wavelength with the i^{th} chip position (iT_c) and the j^{th} wavelength (λ_j). $\Psi(t, \lambda)$ may represent the broadband pulse response of an optical component (e.g., Bragg Grating or Arrayed Wavelength Grating (AWG)). Alternatively, it may be generated by a light-emitting device (e.g., laser).

We assume 2D codes that use a unique wavelength per chip. Such codes can be expressed as a one-dimensional vector $\mathbf{c}^k = [c_0^k \dots c_{L-1}^k]$ of L indices, each representing the wavelength placement of a particular chip. Hence, for user k , $c_{i-1}^k = j \Leftrightarrow C_k[i, j] = 1$, where $i = 1, \dots, L$ and $j = 1, \dots, W$. Each ONU is equipped with an optical decoder designed to realign time-spread chip pulses of different wavelengths prior to the electrical threshold receiver. Fig. 1 shows two prior-art decoder configurations where filters are arranged in series (Fig. 1(a)) or an AWG precedes a parallel array of delay lines (Fig. 1(b)).

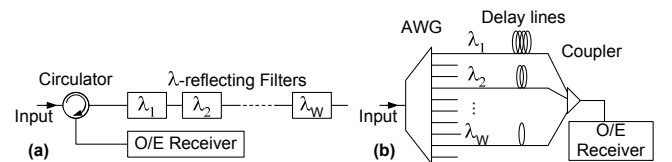


Fig. 1. ONU decoder configurations with (a) in-series band-stop filters or (b) an AWG and in-parallel delay lines

To achieve multicasting, individual user codes within the same multicast group must share one wavelength to the exclusion of all other users. In other words, users of multicast group G_g operating on wavelength λ_g , $g \in [1, W]$, verify:

$$\begin{cases} \sum_{i=1}^L C_k[i, g] = 1; & g \in \mathbf{c}^k \quad \text{if } k \in G_g \\ \sum_{i=1}^L C_k[i, g] = 0; & g \notin \mathbf{c}^k \quad \text{if } k \notin G_g \end{cases} \quad (2)$$

Note that the second condition is only possible if the codes use a subset of the available wavelengths (*i.e.*, $L < W$).

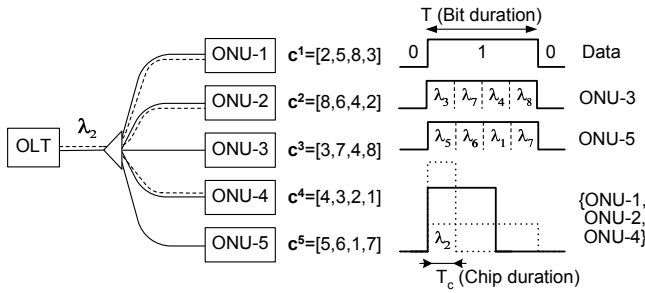


Fig. 2. A simple example of multicast operation

Fig. 2 shows an example where unicast transmissions from the OLT to ONU-3 and ONU-5 require codes $\mathbf{c}^3=[3,7,4,8]$ and $\mathbf{c}^5=[5,6,1,7]$ respectively. A multicast transmission targeting the group $\{\text{ONU-1, ONU-2, ONU-4}\}$ may operate using the common wavelength λ_2 (represented by index 2 in \mathbf{c}^1 , \mathbf{c}^2 , and \mathbf{c}^4) without generating any interference. In fact, any wavelength index $g = 1, \dots, 8$ characterizes a distinct group of ONUs satisfying (2) and eligible for multicasting.

In order to employ the same detection threshold at the ONUs, a different waveform may be required for multicast transmission at the OLT (see dashed lines in Fig. 2). To enable simultaneous transmission of different unicast and multicast bit waveforms, the OLT may be equipped with a laser array controlled by a programmable integrated circuit such as a Field-Programmable Gate Array (FPGA). Although constant OLT-ONU spans are assumed in this study, OLT-based power control is an integral part of standard PON design where the distances between OLT and ONUs vary. Note that using this architecture, no setup process is necessary to activate a light-tree.

III. CODE PROVISIONING FOR MULTICASTING

A. Code Provisioning Problem

Native multicast groups in 2D-OCDMA are formed by the provisioning of codes satisfying (2) for a number of multicast groups $\{G_1, \dots, G_M\}$. Any two provisioned groups overlap if they contain one or more common ONUs. Note that to avoid receiver collisions, only non-overlapping multicast groups may be active simultaneously.

In a PON with N ONUs, the total number of multicast groups is a sum of binomial coefficients in the order of 2^N . Providing one wavelength per group is therefore not realistic. Instead, the proposed architecture may be implemented with a prior code-assignment that maximizes single-wavelength (multicast) transmission so as to reduce Multiple Access Interference (MAI). Such provisioning requires the study of the multicast characteristics of codes. In this study, we assume Extended Hyperbolic Congruence (EHC) codes [5] satisfying the cross-correlation constraint (3) with coefficient $\lambda_c = 1$, where k and p denote any two distinct users.

$$\sum_{j=1}^W \sum_{i=1}^L \mathbf{C}_k(i, j) \mathbf{C}_p(i - s, j) \leq \lambda_c ; \quad \forall s \quad (3)$$

In our architecture, each wavelength characterizes a single light-tree, hence the number of potential multicast groups (M) corresponds to the available wavelengths (W). For a range

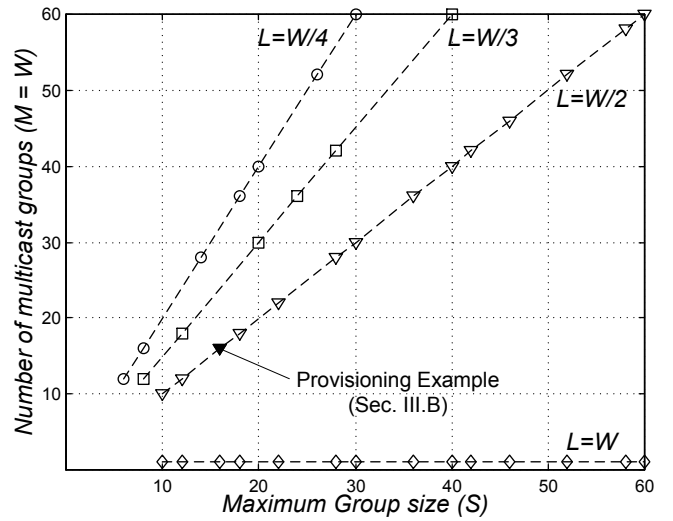


Fig. 3. Multicast Groups (M) vs. Group Size (S) for EHC codes with various W/L ratios

of values of W and L , Fig. 3 plots the number of multicast groups ($M = W$) that can be formed by EHC codes against the maximum group size (S), where S is the maximum number of codes satisfying (2) over all $g = 1, \dots, W$.

We see that when $L = W$, all codes use all wavelengths, hence transmission on any single wavelength reaches the full set of codes, yielding a single broadcast set ($M = 1$). This configuration is not useful for multicasting. However, when $L < W$, $M = W$ distinct groups appear. For a given value of W , the maximum group size S decreases for smaller code-lengths L . Clearly, the choice of L , usually linked to the receiver sensitivity, limits the maximum size of multicast groups.

B. Example

In this section we assume a sample multicasting scenario where a total number of 24 ONUs ($k = 1, \dots, 24$) must contain two non-overlapping multicasting groups, G_1 and G_2 , each including 8 users. Given the network's architectural requirements, in order to operate G_1 and G_2 on two particular wavelengths, say λ_1 and λ_2 , three distinct groups of codes must be provisioned satisfying respectively:

$$\begin{aligned} k \in G_1 & : 1 \in \mathbf{c}^k; 2 \notin \mathbf{c}^k \\ k \in G_2 & : 2 \in \mathbf{c}^k; 1 \notin \mathbf{c}^k \\ k \in G_3 & : \{1, 2\} \not\subset \mathbf{c}^k \end{aligned} \quad (4)$$

Let the system operate on $W = 16$ wavelengths. Choosing code-length $L = 8$ yields 32 EHC sequences satisfying (3) with $\lambda_c = 1$. Fig. 3 shows that the maximum multicast group size is $S = 16 > 8$. The no-overlap conditions expressed in (4) place additional constraints on the codes. Indeed, it can be shown that for any pair of wavelengths, each of the three relationships is satisfied by a distinct set of 8 codes, solving our multicasting requirement.

IV. SIR ADVANTAGES OF NATIVE MULTICASTING

A. SIR Model

In [6], Inaty *et al.* derive an expression for optical SIR in a multirate chip-synchronous 2D-OCDMA system. We reduce it

to the single-rate case and expand it, obtaining the following SIR formulation for a system with K active users. The SIR seen by the reference ONU (k) is given by:

$$SIR_k = L^2 \left/ \sum_{\substack{i=1 \\ i \neq k}}^K \sigma_i^2 + \sigma_n^2 \right. \quad (5)$$

where $\sigma_n^2 = N_o T/4$ is the white Gaussian noise term, T is the bit duration, and σ_i^2 is the SIR contribution of ONU- i :

$$\sigma_i^2 = \frac{1}{2L} \left(\sum_{q=0}^{L-1} [H_1^2(q) + H_2^2(q) + H_1(q)H_2(q)] \right) - \frac{1}{4L^2} \left(\sum_{q=0}^{L-1} H_3(q) \right)^2. \quad (6)$$

In (6), the terms denoted by $H_j(\cdot)$, $j = 1, \dots, 3$, are various forms of the aperiodic Hamming cross-correlation function between the codes of ONU- i and the reference ONU (k). They are detailed in (7), where q represents a modulo- L sequence shift and $h(\cdot)$ is the hamming function.

$$H_1(q) = \sum_{j=0}^{q-1} h(c_{j-q}^i, c_j^k); H_2(q) = \sum_{j=q}^{L-1} h(c_{j-q}^i, c_j^k) \quad (7)$$

$$H_3(q) = \sum_{j=0}^{L-1} h(c_{j-q}^i, c_j^k); h(x, y) = \begin{cases} 1; & x = y \\ 0; & x \neq y \end{cases}$$

B. Numerical Results

Using the multicast scenario and provisioning of Section III-B with 24 ONUs, we evaluate the SIR as a function of the total number of active users. The three plots in Fig. 4 correspond to variations of the number of active multicasting groups (M). $M = 0$ represents a fully unicast network where multicasting is performed by replicating packets over individual ONU codes. $M = 1$ denotes that a single wavelength is used for transmissions towards one of the two multicast groups. $M = 2$ signifies that the members of the two multicasting groups use single-wavelength transmission.

The vertical arrows mark the effect of the activation of a multicasting group on the SIR of the reference ONU when no other unicast connection is present. The activation of the first and second group represent SIR increases of 8.24 dB and 12.6 dB, respectively, compared to the unicast case. For each multicasting configuration, the horizontal lines in Fig. 4 depict the worst-case SIR, evaluated when all users are active. They show a 5 dB SIR increase in the full multicasting configuration ($M = 2$) compared to the unicast case. The significant increase in SIR when more multicast groups operate reflects the fact that the ONUs in active multicast groups switch to single-wavelength transmission, effectively removing their contribution to MAI.

V. CONCLUSION

2D-OCDMA PONs are shown to have native multicasting capabilities with important SIR performance improvements. Further advantages include higher power efficiency since only one copy of each multicast packet is sent, whereas in a unicast 2D-OCDMA PON, multicasting is achieved by transmitting multiple copies of each packet simultaneously.

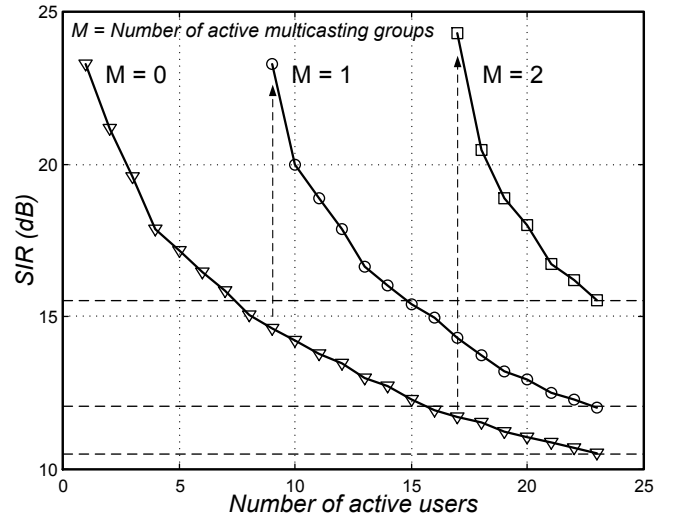


Fig. 4. SIR experienced by a reference ONU as a function of the number of active users, for different multicast configurations

Future research may address a number of extensions to single-wavelength 2D-OCDMA multicasting. For instance, code-provisioning algorithms may be designed to exploit network planning information such as the expected size and load of the most-frequent multicasting configurations.

The presented architecture exploits interference chips to implement light-trees. Code design may further take into account multicasting properties. For instance, easing the cross-correlation constraint ($\lambda_c > 1$ in (3)) enables multicast groups to use *sub-codes* rather than single wavelengths, hence increasing the number of light-trees. The use of codes with multiple pulses per chip or time-blank patterns may yield more light-trees. Direct Sequence (DS) OCDMA is expected to exhibit equivalent multicasting capabilities.

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