On the Upgrade of an Optical Code Division PON with a Code-Sense Ethernet MAC Protocol

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Abstract: We propose, for the first time, optical code-sense multiple access / collision detection to upgrade an optical code division passive optical network with minor modifications to transparently deploy Ethernet (or packet) based services.
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1. Introduction

Optical Code-Sense Multiple Access / Collision Detection (OCSMA/CD) is a novel Medium Access Control (MAC) protocol in the optical physical layer (PHY) which is presented here for the first time. OCSMA/CD has its primary and most attractive application to transparently run Ethernet (or packet) based services on fiber-optic networks which employ Optical Code Division Multiplexing (OCDM) or Optical Code Division Multiple Access (OCDMA). Previous work on Ethernet MAC protocols for a PON focused on optical carrier-sense [1-3]. For a code division network this obviously does not result in correct detection of collisions unless multiple wavelength channels are used per destination. However this leads to a significant increase in network complexity moreover to an inefficient usage of optical bandwidth. To mitigate this issue a MAC protocol based on optical code-sense is proposed.

A Passive Optical Network (PON) shared-fiber architecture is envisaged to provide optical transparency in the access network layer [4,5]. Network nodes have to be able to sense each other's activities in order for the MAC protocol to work. In [1] the cyclic properties of an Arrayed Waveguide Grating (AWG) are used. However, this imposes a fixed WDM scheme onto the PON. In [2] an isolator is placed at a star coupler which also reflects optical power onto the fiber of the source. Such a solution introduces a self-jamming effect. This effect also occurs in [3] although it is used for peer-to-peer or shared LAN networking. We upgrade the passive splitter in PON with a second coupler stage to have directional coupling. In other words the optical power is reflected to all-but-own fibers. Collision detection in such systems is straightforward [6]. Moreover the network is kept wavelength agnostic which in combination with wavelength agnostic Optical Networking Units (ONUs) results in a fully dynamic Wavelength Division Multiplexing (WDM) scheme.

Cost-efficiency and photonic integration are key in order for a code division network to be commercially attractive. We consider spectral amplitude coding of a cost-efficient incoherent optical source such as a Light Emitting Diode (LED). This type of OCDMA is therefore referred to as Spectral Amplitude Encoded OCDMA (SAE OCDMA). A low complexity integrated en/decoder based on Mach-Zehnder Interferometers (MZIs) was proposed in [7]. Such en/decoder is reciprocal thus the existing setup can be upgraded with the code-sense functionality by only adding few components rather than adding a separate circuit. Besides, having the sensing and transmission functionality in one device reduces the processing time which increases the network efficiency.

In this paper the SAE OCDMA PON concept is introduced, featuring wavelength routing, a code-sensing MAC protocol, and collision detection. Simulation results confirm the principle of operation.

2. Spectral Amplitude Encoded OCDMA Passive Optical Network with Wavelength Routing

In this section the general concept of SAE OCDMA on PON is introduced and a network scenario is given. The scenario not only considers a single PON connected to the CO but also multiple PONs connected. Wavelength routing of code labeled channels is suggested in the subnet of PONs. In code division networks an orthogonal code is usually assigned to each user but it can also be used to address the destination. In latter case, collisions are at stake and a MAC protocol is required.

Spectral amplitude encoding of incoherent optical sources was first proposed in [8]. The encoded spectrum is used in a Spectral Shift Keying (SSK) modulation format. In SSK a binary one is represented by the encoded pattern and a binary zero by the complementary (π shifted) version, or vice versa. As such, the filter pattern uniquely identifies a user but at the same time it represents the data flow. At the receiver the mixed SSK signals of different users is launched into one of the inputs of the decoder. Balanced detection is used at the receiver to maximize the auto-correlation for a code match and to minimize the cross-correlation for no code match. Only with such an SSK setup full rejection of multiple user interference is achieved. A significant improvement was made in [7] which

proposed an integrated MZI based cascade chain as encoder and decoder. Parallel processing of up and downstream encoded data is required at the CO for truly asynchronous medium access. Recently a tree structure has been demonstrated which cost-efficiently provides such functionality [9,10].

The central office is not limited to just a single PON but it may have multiple PONs connected. If each PON operates on its own (dynamically) assigned wavelength, all-optical Wavelength Routing (WR) maximizes the throughput in the CO's subnet of PONs. We aim at no wavelength conversion at the CO to increase the end-to-end optical transparency. It also simplifies the network scenario. As a result the SSK signal is transmitted on the wavelength of the destination PON (lambda_out) by using the optical orthogonal code of the addressee. If the code labeled wavelength channel is routed correctly, the broadcast-and-select properties of PON and OCDMA ensure that the addressee receives its data. It is clear that a collision may occur at an aggregation point when multiple ONUs simultaneously transmit data to a similar destination. Data not intended for nodes outside the "home" PON is sent on the assigned wavelength (lambda_home) with the ONU's own optical orthogonal code. Collisions may also occur if direct or peer-to-peer communication is enabled between two ONUs in the same PON.

3. Spectral Amplitude Encoded OCDMA Passive Optical Network with WR and Collision Detection

Fig. 1 shows the architecture of the SAE OCDMA PON. The necessary upgrades for code sensing abilities are denoted with a grey background and dotted outline. Code sensing is implemented in the optical PHY to lower the complexity in the protocol stack. The autocorrelation peak of any transmission on a set code is detected. The presence of optical power is sufficient to establish that a collision has taken place.
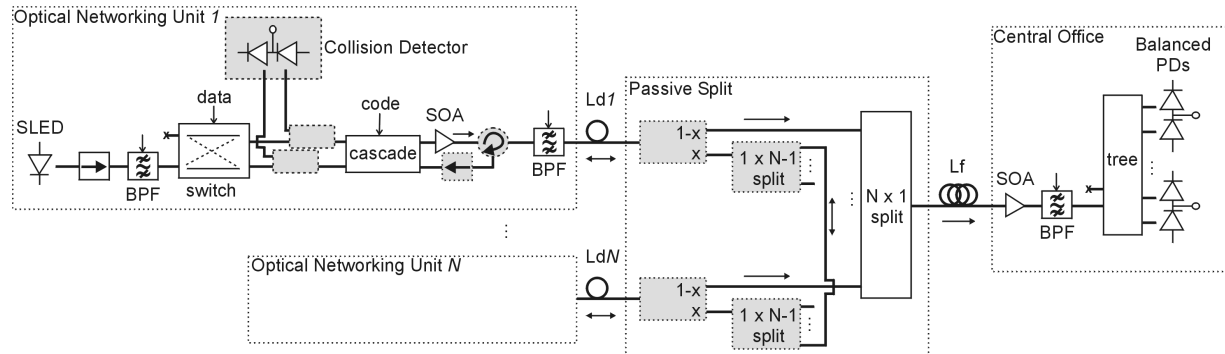

Fig. 1: Spectral Amplitude Encoded OCDMA Passive Optical Network with Wavelength Routing and Collision Detection

A tunable Band-Pass Filter (BPF) is used in combination with a Superluminescent LED (SLED) to select a transmission wavelength band at the ONU. An isolator between the BPF and SLED prevents reflections that degrade performance and blocks downstream signals used by the collision detector. A switch is used for SSK modulation by switching the optical signal either to the upper or the lower input of the cascade. One of the outputs of the cascade is then amplified by a Semiconductor Optical Amplifier (SOA). A second tunable BPF is set to a similar band as the first filter and suppresses out-of-band downstream wavelength channels and ASE noise added by the SOA. To upgrade the ONU node design with collision detection only few extra components are required. Firstly, two couplers couple part of the received optical field to a (balanced) collision detection unit. Secondly, a circulator is added to split upstream and downstream traffic before the SOA. The downstream reflected optical field might saturate the SOA such that the required gain for the upstream traffic can not be provided. An extra isolator makes sure secondary upstream traffic is not passed through the SOA. The design of the ONU allows cost-efficient photonic integration which is of key importance. Many efforts are made towards the integration of the circulator and isolator [11,12].

The passive Nx1 splitter is modularly upgraded for power reflection to all-but-own fibers. It is common to reflect at the passive splitter to avoid excessive delays in collision detection due to the long length of the feeder fiber (Lf) with respect to the distribution fibers (Ld) of the PON. The modular solution proposed for star couplers in [13] has been modified to suit a 1xN splitter. Major difference is that most optical power has to be coupled towards the CO and smaller portions have to be coupled towards the ONUs. The passive Nx1 splitter is extended with two extra couplers per distribution fiber. The coupling ratio x of the first coupler is a variable to optimize the setup. The second coupler has a 1xN-1 equally distributed splitting ratio. The tree structure is placed at the CO to simultaneously decode each individual SSK channel. An SOA is used as pre-amplifier with a tunable BPF to suppress out-of-band noise. Transmission from the CO to the ONU is not considered here.

4. Simulation results

In this section simulation results are discussed of the system that is shown in Fig. 1. Three ONUs have been simulated where one of the three is transmitting part of its data on the code of one of the other ONUs. The coupling ratio x in the novel design of the passive splitter is set to 0.8 but can be further optimized. A two-stage cascade and a two-stage tree are used to generate and process the required code set [10]. The optical distribution and feeder fibers are replaced by attenuators and optical delay modules to avoid excessive simulation time. The results are expected not to change significantly since the fiber distances are short in case of PON in the access network layer.
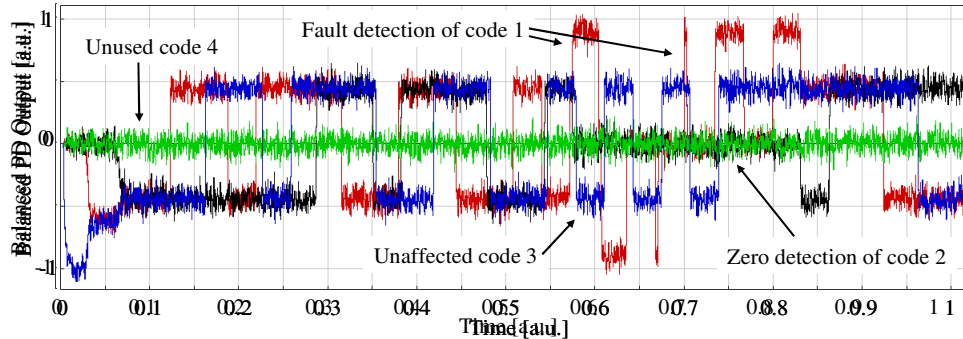

Fig. 2: Received and decoded bit streams at the Central Office

Fig. 2 shows the received bit streams at the CO. The soft capacity characteristic of OCDMA is clearly seen at the beginning of the transmissions. Adding users results in an overall reduction in Signal-to-Noise Ratio (SNR). During its data transmission, ONU 2 suddenly switches from code 2 to code 1. It is then interfering ONU 1 and vice versa. In the response at the CO this is observed by fault detection at code 1 and zero detection at code 2. This extreme case should not happen if more intelligence is added in the simulation. ONU 2 should sense the medium before actually transmitting its data. The transmission of ONU 3 on code 3 remains unaffected.
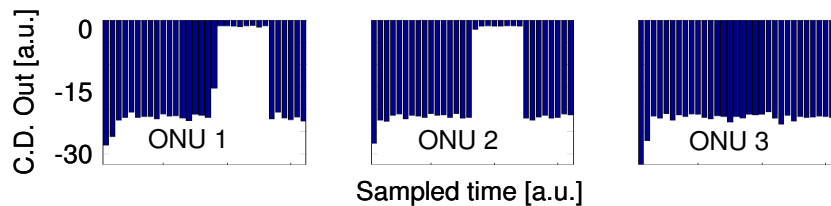

Fig. 3: Collision Detector (C.D.) output of three different ONUs

Fig. 3 shows the electrical output power of each of the three collision detection units which corresponds with Fig. 2. The high CD output of ONU 1 and ONU 2 indicate a collision is detected. The CD of ONU 3 detects no collisions.

5. Discussion and further work

The SLED and tunable BPF may be removed if remote wavelength band delivery is performed from the CO, for example, on a separate fiber. The proposed system and scenario is generally applicable to similar OCDM/OCDMA systems, for example, as in [14].

6. Conclusion

We have proposed, for the first time, optical code-sense multiple access / collision detection to implement Ethernet (or packet) based services on optical code division passive optical networks. A collision detection unit can be easily implemented by employing the reciprocal behavior of the existing en/decoder at the optical networking unit. The passive splitter is modularly upgraded with directional coupling to reflect optical power to all-but-own fibers.

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