A CDMA Secure Optical Access Network

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September 14, 2010

Abstract

We propose a CDMA network implementation that enhances security at the physical layer. By using an active star topology supporting both point-to-point and point-to-multipoint communication, 128 ONUs can transmit simultaneously at rates of at least 12 Mbps, with a reach of 20 km, thus addressing access network applications. Numerical simulations demonstrate the feasibility of the proposed scheme.

keywords: *optical fiber communication, access networks, secure communication, CDMA*

1 Introduction

Modern passive optical networks provide a method for fast and reliable voice and data communication between multiple premises. However, communication methods employed today are inherently insecure, as they do not provide privacy from a sufficiently motivated eavesdropper, as signals are broadcasted to all Optical Network Units (ONUs). Communication security must be implemented by the end-points on higher-level protocols, and is often neglected.

This paper aims to improve the immunity of optical networks to a variety of attacks. Inspired on a Passive Optical Network, we present a solution for this problem employing CDMA for the data codification, specifically a time-hopping algorithm at the bit level. Data security in optical networks has previously been addressed with schemes based on encryption via optical coding [10] and CDMA coding [13]. In this proposal we improve on the CDMA approach by extensive use of Forward Error Correction (FEC) techniques in order to minimize the Bit Error Rate (BER), allowing for both point-to-point and point-to-multipoint secure (at the physical layer) communication.

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In contrast to other optical network designs [4], we propose a star network topology, using a single laser wavelength and providing security at the physical level. This allows low-cost private networks or point-to-point channels to be set up between ONUs up to 10 km away from the optical hub. In TDMA, a medium is shared between several channels. The slots are assigned in a way predictable to all ONUs in the network. Thus an optimal medium utilization is achieved, but security and privacy are compromised since no safeguard is made against a malicious ONU accessing the network. Any endpoint has complete access to all channels in this broadcast medium.

We present a simple method to assign pseudo-randomized slots to every channel, so that only authorized ONUs can decode the channel. Each channel is assigned a pseudo-random generator algorithm (not necessarily the same). Two or more channels must share the secret key (usually the seed) of the Pseudo-Random Number Generator (PRNG) to make the slot sequence predictable and communication between them possible. The PRNG algorithm must be cryptographically secure. Several known algorithms exist that meet these criteria [8]. In our simulation, we consider RZ coded data streams in an optical fiber that behaves as a Z-channel [7] (a '0' bit can only be overwritten by a '1' bit), and we apply error-correction codes required for reliable communication in the presence of collisions, which happen in pseudo-randomly chosen time slots. Finally, as this protocol is implemented at the physical layer, any higher level protocols like Ethernet or ATM can be implemented on top with no modifications, furthermore, the enhanced confidentiality supports additional protocols such as secure Virtual Local Area Networks (VLANs).

2 Architecture

The proposed system is composed of an access layer, where CDMA and error correction are implemented, and a physical layer based on an optical network with certain similarities to PONs. The access layer is implemented using time-hopping CDMA, where each of the 128 possible ONUs sends bits in a slot chosen randomly from a frame of 356 slots; therefore collisions between different ONUs will happen and error correction must be used to guarantee error-free data transmission. Notice that the synchronization is performed at the bit slot level only because transmission of each ONU is random, in contrast to TDMA where synchronization is also performed at frame level. Moreover, each ONU can send data at any time, in contrast to TDMA where ONUs usually send data continuously; this feature resembles transport by Ethernet frames. A certain ONU X can receive messages from an ONU Y if X has the *key* of Y, and vice versa. Therefore, if a certain group of ONUs were to communicate over a VLAN, it is required that everyone in the group knows each others' *keys*. ONUs' data streams are encoded with the following error correction techniques (Fig. 1): Reed-Solomon (223/255) and LDPC (1024×512 matrix) algorithms (see [9] and references therein), and bloom-filters with $K = 4$ [3]. The choice of these correction algorithms was heavy influenced by modeling the optical fiber as a

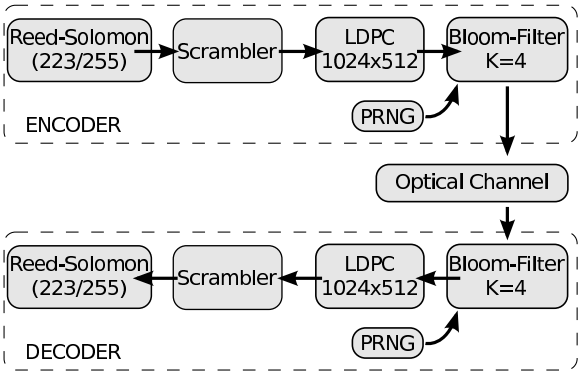

Figure 1: Proposed network design: Access Layer

Z-channel, having a Shannon limit of $C_Z = \log_2\left(1 + (1-p)p^{p/(1-p)}\right)$, where p is the probability of error. This capacity limit is larger than that of a symmetric memoryless binary channel [12].

The proposed physical layer topology is that of a star (see Fig. 2) where optical splitters redistribute traffic coming from each ONU to all the rest allowing point-to-multipoint as well as point-to-point communications between 128 ONUs. An Erbium-Doped Fiber Amplifier (EDFA) located in between splitters at the optical hub increases optical power to overcome network losses. RZ modulated optical signals generated at each ONU, of up to 10 Gbps by a 2-dBm 1550-nm DFB-laser, are transmitted up to 10 km upstream by a standard single-mode optical fiber (ITU-T G.652) to the optical hub.

In this hub a 128×1 splitter merges traffic from all ONUs that is then redistributed by a 1×128 splitter channeling back merged traffic to each ONU through a downstream fiber identical and parallel to the upstream fiber. Splitters' attenuation ($\simeq$ 25 dB each) contribute, as well as fiber attenuation and insertion losses ($\simeq$ 2 dB and $\simeq$ 1 dB per stretch), to high total losses ($\simeq$ 28 dB at both upstream and downstream paths). In order to provide signal amplification an EDFA ($\geq$ 27 dB gain) is placed between both splitters. This EDFA increases merged traffic power at the first splitter output ($\simeq -26$ dBm '1' active Tx) delivering an adequate power level (1 dBm, '1' active Tx) at the second splitter input to provide ONU's receiver a power level for proper reception (-27 dBm, '1' active Tx) with a high sensitivity (-28 dBm) photodetector (PD). The PD maximum optical power is not a concern as our simulations show that only up to ten '1' bits collide in any given single bit slot. Even considering a constant EDFA gain, the PD input optical power would be lower (-17 dBm) than that commercial PDs withstand unharmed (~ -5 dBm). The bit '0' level at PD is given by the addition of the '0' bit transmitted by all 128 ONUs. The receiver decision threshold should be able to separate between this state and that of a single ONU transmitting a '1' bit. As the bit '0' transmission power should be very low, imposing restrictions on the DFB-laser extinction ratio. The minimal

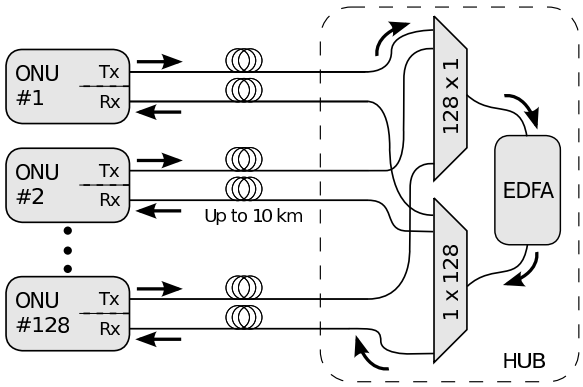

Figure 2: Proposed network design: Optical Layer

required extinction ratio ('1'/'0' peak power ratio) is addressed in the numerical simulations explained next.

3 Numerical simulations

We developed a modular simulator platform, where each block performs a single operation and blocks are totally interchangeable. For performance, each block including bloom-filter, error correction algorithms, and the physical optical channel simulation were implemented in C++ and were released under the GNU license [11].

The physical optical channel simulation block provides an estimate of the BER performance of the optical channel. Simulation steps are as follows: RZ upstream traffic coming from all ONUs is assumed to arrive at the 128×1 splitter with perfect time synchronization, i.e., there is no timing jitter. The '0'-bit slots contain a small CW optical intensity given by the Tx extinction ratio. Each on-line ONU adds its '0'-bit optical intensity yielding a base power level. Each '1'-bit adds a super-Gaussian ($m = 4$) pulse, duty cycle 1/3, to the base power level.

Upstream and downstream merged traffic suffers from attenuation due to splitter, fiber, and splice losses. The power budget is balanced by an EDFA with 27-dB constant gain. Amplified spontaneous emission from the EDFA is modeled by white Gaussian noise, with intensity proportional to the amplifier noise figure, and is added after the EDFA.

The input optical signal at the receiver is filtered (2nd order low-pass Butterworth filter, 25 GHz bandwidth) and photodetected assuming a standard PD responsivity (see section 4.4.3 of [1]). White Gaussian noise accounting for thermal and shot noise is then added to the photocurrent, and electrical filtering is applied (2nd order low-pass Butterworth filter, 14 GHz bandwidth).

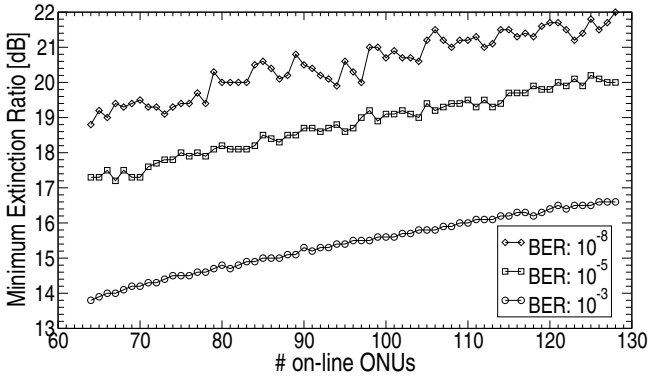

Figure 3: Physical layer simulation result: Minimal extinction ratio required to assure a given BER

4 Simulation results

Noise fluctuations at power levels near the PD sensitivity limit have an important effect on signal detection. Shot noise is of particular concern as it is proportional to the mean photocurrent. In our network proposal the later is higher than in PONs as bit '0' optical intensities from all ONUs are added. The resulting base-level optical intensity is then heavily dependent on the Tx extinction ratio. Fig. 3 shows minimal extinction ratios required to achieve an arbitrary BER in the physical layer as a function of the number of on-line ONUs. In the 128 ONUs scenario a BER$< 10^{-3}$ can be achieved using commercially available transmitters with an extinction ratio $\simeq 16.6$ dB. This BER is low enough to allow for logical-channel error-correction routines that guarantee error-free transmission, while still making use of a fair fraction of channel capacity. Fig. 4 shows simulation results for the fraction of the total capacity and the BER of one channel at the coding level (circles) and including physical layer impairments (squares). These results were obtained by sending one Gigabit of data for each ONU simultaneously. This figure shows a channel utilization of 15.7% when all of 128 ONUs are transmitting simultaneously, with a BER$< 10^{-8}$. From Fig. 2 we observe a penalty of 8 ONUs when impairments from the optical layer (mainly extinction ratio and noise from EDFA and PDs) are taken into account. Considering that the system was designed to support asynchronous communications (e.g., Ethernet), it is not likely that all the ONUs will transmit simultaneously (e.g., Internet links often operate at most at 90% load); and therefore our system has a BER $< 10^{-8}$ for each channel when 119 ONUs are transmitting at a same time ($119/128 > 0.9$). Observe that the high error rates correspond to a worst-case scenario when all ONUs are transmitting simultaneously at full capacity, and also there is a low penalty due to physical layer impairments.

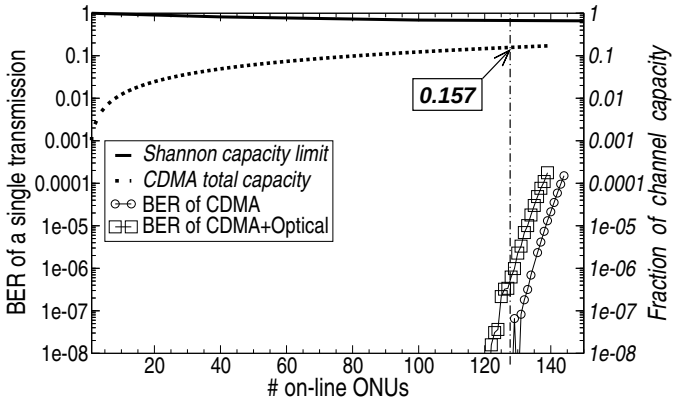

Figure 4: Simulation results: Logical channel

5 Information security

There are four basic goals related to information security: Confidentiality, integrity, availability and authenticity [6]. This system provides confidentiality and integrity in the downstream channel, leaving availability and authenticity implementations to higher-level protocols. Confidentiality and integrity are achieved using CDMA coding. We can regard this coding as a kind of symmetric cipher [2]. Attacks in this system can be classified in two types: external attacks, where the attacker neither participates in the network nor has a key, and internal attacks, where the attacker has access to at least one key and controls at least one network node. In our design, an internal attacker can only receive data from their assigned channel, under any circumstance. An external attacker, or eavesdropper, that intercepts an optical fiber cannot decipher the downstream channel; however, the proposed design does not provide protection to the upstream data channel. This is due to a physical limitation: In a man-in-the-middle attack, the outgoing signal is the only high-power signal in the upstream channel, thus making it easy to detect. The problem of safe key distribution is not part of this design. The distribution must be performed beforehand using any secure method available [5]. The key must be long enough to prevent trivial dictionary attacks.

6 Conclusions

We proposed a CDMA network architecture capable of both point-to-point and point-to-multipoint communication of up to 128 ONUs with a worst-case rate of 12 Mbps. Furthermore, the proposed scheme provides security at the physical layer and private networks between ONUs can be set up without additional higher-level protocols. We also showed that there is a low penalty due to physical layer impairments, such as transmitter extinction ratio and attenuation at fibers,

splitter, and splices. We believe that our proposal opens the door to the design of a larger CDMA network, covering longer distances and servicing more end users. Finally, the proposed scheme also allows for the eventual dynamic allocation of unused channel capacity.

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