Paradigm shift for optical access network: from TDM to FDM

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***Abstract*—We reviewed the paradigm shift from TDM to FDM for optical access network and proposed a frequency-referenced coherent-PON system with >200Gb/s bit rate, >30dB power budget, and low latency using a single optical coherent receiver.**

Keywords—optical access, coherent PON, TDM, FDM, MP2P, latency

I. Introduction

A. Background

The digitization and cloudification of various service and applications call for data communication infrastructures that could fulfill the key performance indicators requirement on aspect of the bandwidth, per user bit rate, power, latency and so on [1,2]. Take smart manufacturing as an example, massive deployment of robotics in the factory facilitates automatic manufacturing with high efficiency. Such system is usually implemented with image/video recognition that each stage of the manufacturing is monitored, recorded and sent by cameras to a central control unit for analysis via high speed transmission links. The link between each camera and the central processing point requires a transmission rate of a few Gigabit/s and stable low latency (typically 10 micro-second end-to-end latency excluding signal propagation time for intra-factory communication [3]) since the missions are latency-sensitive. In addition, the data flow shows significantly higher uplink (multi-point-to-point: MP2P) data volume than the downlink (point-to-multi-point: P2MP). On the other hand, RF wireless communication based solutions are inevitably limited by the serious electromagnetic interference issue. The optical fiber link counterpart could not only avoid the RF interference issue but also offer guaranteed broadband access due to its high bandwidth. Such MP2P infrastructure also fits well to AR/VR applications where more than 1.6 Gb/s per user data rate and end-to-end latency of less than 2ms is required [4], as well as connected car fleet by considering 'AI drivers' user cases [5], and more.

B. Challenges of TDM PON

Optical fiber infrastructure is becoming ubiquitous. Passive optical network (PON) is a promising technology with a MP2P physical topology and has been standardized for many generations based on direct detection (DD) and time division multiplexing (TDM) for scheduling the upstream data traffic from various users. At low speed, DD and TDM are natural technical choices due to the low cost. Currently the 50Gbps TDM PON represents the highest speed that has been standardized, beyond which there are significant challenges of TDM PON on both technical and cost aspects. Firstly, the burst nature of the upstream data requires a high speed burst-mode receiver, which is technically challenging and expensive to develop. Second, the user signal baud rate scales proportionally with the aggregated upstream bit rate, which brings about severe fiber chromatic dispersion effect and requires costly full-rate (thus high bandwidth) user devices. Finally, the unpredictable high latency with jitter due to the dynamic bandwidth allocation protocol applied in the MAC layer, precluding latency-sensitive services.

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C. Evolution from TDM to FDM

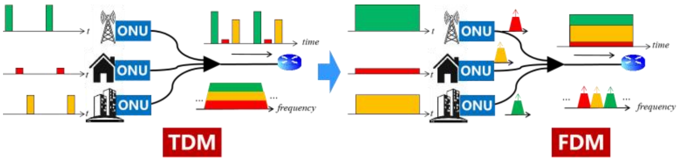

Fig. 1. Illustration of TDM to FDM evolution.

As indicated in Fig. 1, a paradigm shift from TDM to FDM could efficiently address the challenges a TDM PON faces. In this case, a FDM PON is supposed to be compatible with the power-split optical distributed network (ODN) of a TDM PON to guarantee a smooth and low-cost evolution, namely there is no need of an arrayed-waveguide router (AWG) to replace the power splitter at the remote node of the ODN. This is the core concept difference between a FDM PON and a wavelength division multiplexing (WDM) PON [6], where either an AWG at remote node or a tunable optical filter [7] at each user is required. In a FDM PON, as all users can send data simultaneously, each user operates at much lower signal baud rate meaning largely reduced fiber dispersion effect and low cost user device. In addition, due to the same reason, all users can operate at a continuous mode rather than burst mode, eliminating the need of an expensive burst mode upstream receiver. Finally, each user has guaranteed bandwidth ensuring very low latency in communication.

Along with the evolution from TDM to FDM, the upstream receiver could replace the DD scheme with coherent detection where all FDM user signals can be detected by a single high bandwidth coherent receiver. The benefits are two-fold: one is the high optical power sensitivity due to optical amplification enabled by the local oscillator (LO) laser of a coherent receiver, meaning relaxed optical launch power requirement on user transmitter as well as an increased number of users can be supported. The other one is the avoidance of beating between user frequency bands that a DD receiver inevitably encounters, which causes serious interference between user signals.

Coherent FDM PON has been typically implemented and demonstrated based on subcarrier modulation (SCM) in digital domain [8] and user laser frequency multiplexing [9]. Laser frequency multiplexing minimizes transceiver bandwidth requirement of each user.

The prominent issue of FDM PON is the frequency synchronization among users, namely the accurate control of user transmitter laser frequency. Ideally, user frequency bands without a gap between neighboring challenges for high spectral efficiency. Unfortunately, today's mature commercial temperature controlled laser that is economically viable in access networks can only guarantee a +/-2.5GHz frequency deviation. This means that a band gap of at least 5GHz is required between two adjacent wavelength users. Considering the large amount of cameras in intra-factory scenario, it introduces a very high spectral overhead which in turn needs a very high bandwidth single coherent receiver or multiple moderate bandwidth coherent receivers to detect all user signals. Previous approaches, including optical injection locking in the user side to synchronize user laser wavelength with the downlink reference wavelength [10] and an integrated reflective semiconductor optical amplifier (RSOA) to directly reflect downlink seed wavelength as uplink carrier [11]. These approaches have drawbacks of either being incompatible with power-split ODN or be impractical caused by low tolerance to uplink reflections and Rayleigh backscattering.

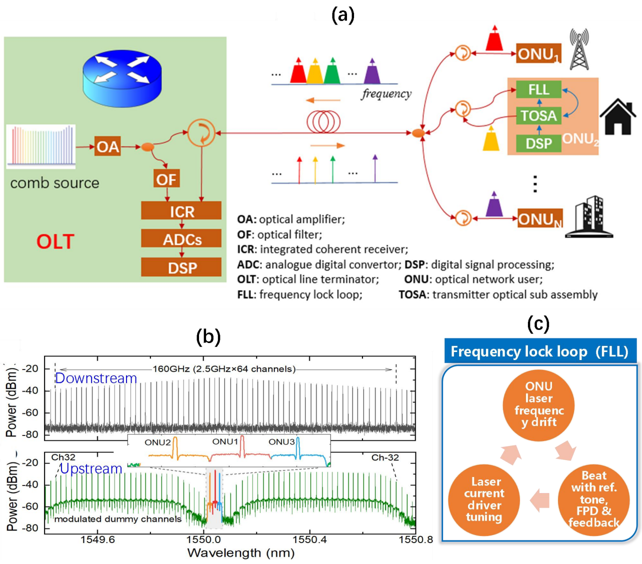

Fig. 2. (a) proposed frequency referenced MP2P access architecture where each user uses a FLL to lock its laser frequency to an assigned frequency tone. (b) the dynamics of a FLL. (c) experimentally demonstrated reference comb laser frequency tones without and with data modulation.

In this paper, we review our recently demonstrated frequency referenced MP2P coherent FDM PON system with guaranteed bandwidth and reliable low latency [9]. Each user uses a low-cost intensity modulator. The upstream communication could be de-coupled and independent from the downstream one, since very low rate control information from central site can be broadcasted to all users by modulating the reference frequency tones. This could largely increase the system flexibility and robustness. Proof-of-concept upstream system experimental demonstrations are presented to show the technical feasibility of the frequency referenced system with a >200 Gb/s aggregated bit rate and better than -30 dBm optical power sensitivity using a single polarization 16-QAM modulation and a single optical coherent receiver.

II. Frequency Referenced MP2P Optical Access

A. Proposed access network architecture

The architecture of the frequency referenced coherent FDM PON is illustrated in Fig. 2(a). The reference frequencies are generated by an optical frequency comb generator at the centre office [12] , then amplified by an integrated SOA before being split into two branches. One branch, as indicated by the measured optical spectrum shown in Fig. 2(b) [the upper spectrum] with channel space of 2.5GHz, is sent to each user (may optionally be modulated by a low rate control data) via a power-split ODN and the other filtered by an optical filter to provide a LO to the upstream integrated coherent receiver (ICR). At each user side, the reference frequency tones are fed into a frequency lock loop (FLL), where the user laser output of the transmitter optical sub assembly (TOSA) is combined with the reference tones and passes through a photo-detector. The resulting beat note carrier is fed into a frequency and phase detector (FPD) and measures the deviation relative to a specified carrier, which determines how to tune the current driver of the user laser so as to tune and lock the laser wavelength. The dynamics of the FLL is explained by Fig. 2(c), which converges and locks the laser frequency to one of the reference tones that is assigned to the user. The frequency-locked laser, as a carrier source of the TOSA integrated electro-absorption modulated laser (EML), is modulated by a 1.0725 GBd SCM QAM data in the proof-of-concept experiment. To study the full band transmission in the experiment, one of the comb's output is tapped and shaped using waveshaper to remove the three live channels and modulated to generate dummy signals with 1.0725-GBd SCM QAM signal [see Fig. 2(b) the lower spectrum with green curve]. Finally, the user output signals are combined with the dummy channels at the remote node and multiplexed in the frequency domain [see Fig. 2(b)].

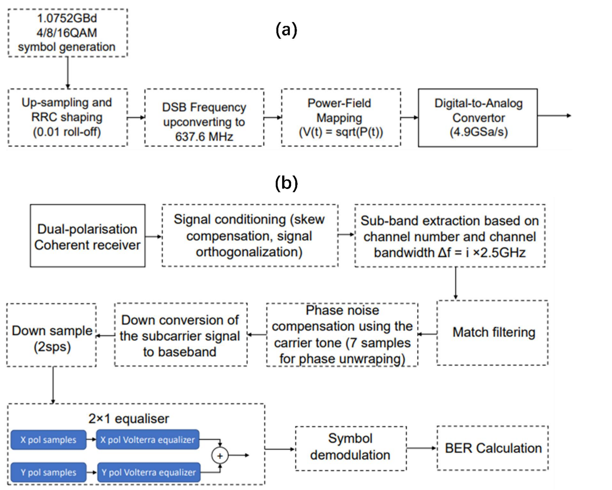

Fig. 3. DSP of (a) transmitter and (b) receiver.

The upstream FDM signal is then sent to the center office and, together with the LO, fed to a high bandwidth ICR. After being converted into digital signals via an array of analogue to digital converters (ADCs), the signals go through an offline digital signal processing (DSP) for data recovery.

B. DSP architecture

The proposed transceiver DSP is shown in Fig. 3. The transmitter DSP consists of a bits-to-QAM symbols mapping, a root raised cosine (RRC) shaper, a digital up-conversion and a pre-distortion before being converted into analogue signal. The received signal goes through coherent DSP steps including signal conditioning, sub-band extraction, match filtering, phase noise compensation using only 7 samples to unwrap the phase, digital down-conversion as well as a 2 samples per symbol 2×1 multiple input single output (MISO) equalizer which takes into account nonlinear terms [13]. Due to the strong carrier and the relatively low baud rate per user, the residual carrier frequency offset (CFO) and optical phase can be effectively tracked without needing a separate CFO DSP block as conventional coherent receiver DSP. The experiment shows that the residual CFO varies within ±10 MHz. The MISO equalization is based on very short memory length to guarantee low latency and complexity.

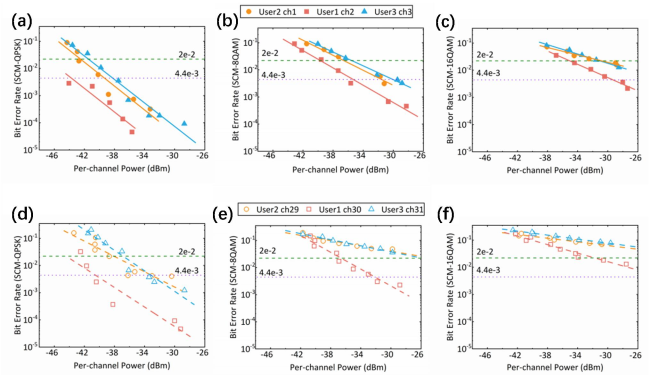

Fig. 4. BER sensitivities of the Users locked at the receiver bandwidth centre (solid markers, channel1-3) using SCM formats (a) 4 QAM; (b) 8 QAM; (c) 16 QAM and locked at receiver bandwidth edge (open markers, channel 29-31) using formats (d) 4 QAM; (e) 8 QAM; (f) 16 QAM.

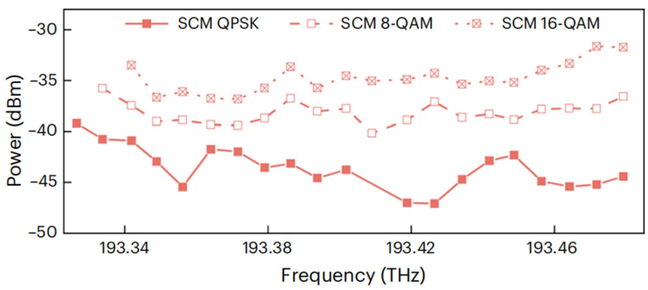

Fig. 5. Upstream receiver sensitivity at SD-FEC threshold (BER of 2 × 10^{-2}) for user 1.

III. Results

Three live user upstream signals using 4/8/16 QAM formats were measured on bit error ratio (BER) vs. optical power performance, as indicated in Fig. 4 (supplementary of [9]). The power per user channel was measured using an optical spectrum analyser of 0.01nm resolution before an optical pre-amplifier in receiver. Each BER value was calculated using a PRBS of 2^{15} length. User 1 located at the centre of the spectrum and user 2 and 3 are locked to 2.5 GHz spacing apart. Two cases are shown here: three users were locked to neighboring channels at the center (channel 1-3 @193.412 – 193.417 THz, closed markers) and the edge (channel 29-31 @193.482 – 193.487 THz, open markers) of the optical bandwidth. Their frequency offset to center wavelength (i.e., the LO wavelength) is $\Delta f = k \times 2.5$GHz, where k is the channel ID. User 1 exhibited about 4 dB higher sensitivity than user 2 and user 3, irrespective of modulation format. This is mainly due to the EAMs used in the user transceivers. The EAM in user 1 is optimized for 1550 nm, while the EAMs for user 2 and user 3 is optimized for 1535 nm. Compared to center channels, edge channels exhibit worse BER performance due to the frequency roll-off of the coherent receivers. Considering user 1 with 2.5 GHz offset from the LO, the average sensitivities for the formats of 4, 8 and 16 QAM at the hard-decision forward error correction (HD-FEC) threshold of 4.4×10^{-3} (6.7% overhead) were -40, -34 and –30 dBm, respectively. The sensitivities at the soft-decision (SD) threshold of 2×10^{-2} (15.3% overhead) were –44, -38 and –35 dBm, respectively, for the 4, 8 and 16 QAM.

Figure 5 presented the measured receiver sensitivities using live user 1. At the SD-FEC BER threshold, the required lowest power values are approximately -47, -40 and -35 dBm, respectively, for 4/8/16 QAM formats. The variation of the sensitivity for different FDM channels is due to the high frequency roll-off and imperfect impedance matching of the coherent receiver. Since the user transceivers output about -4 dBm, these results indicate a power budget of 43, 36 and 31 dB for an upstream per-use data rate of 2.14, 3.22 and 4.3 Gbit/s using 4/8/16 QAM signals, respectively.

IV. Results

We discussed the motivations and driving forces of paradigm shift from TDM to FMD for MP2P optical access networks, and proposed a frequency referenced a frequency referenced coherent FDM PON system with guaranteed bandwidth and reliable low latency. A proof-of-concept experimental demonstration with 3 users and dummy channels transmission were performed and results show that a >200 Gb/s aggregated bit rate and better than -30 dBm (30 dB) optical power sensitivity (optical power budget) are feasible using a single commercial optical coherent receiver.

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