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Throughput enhancement of slow adaptive orthogonal frequency division multiple access based passive optical network uplink transmission in 20-km single fibre loopback link employing channel stabilisation

Sang-Min Jung, Moon-Ki Hong, Sun-Young Jung, Seung-Min Yang, Sang-Kook Han

Department of Electrical and Electronic Engineering, Yonsei University, Seoul 120-749, Korea
E-mail: skhan@yonsei.ac.kr

Abstract: The authors have proposed and experimentally demonstrated a novel slow adaptive orthogonal frequency division multiple access (OFDMA)-based passive optical network (PON) uplink transmission scheme using a 1-GHz reflective semiconductor optical amplifier operating as an optical network unit (ONU) in combination with Rayleigh backscattering (RB) mitigation in a 20-km single fibre loopback link. This RB mitigation, which can dramatically stabilise the channel state information and enhance the total throughput so that the OFDMA-PON transmitters can operate in the slow adaptive concept and provides beyond 15-Gbit/s uplink transmission, is achieved by employing 10-MHz low-frequency dithering of an optical seed carrier cooperating with a gain-saturated semiconductor optical amplifier at an optical line terminal. In doing so, the proposed scheme could guarantee a 50% total throughput enhancement with a proof-of-concept multiple access scenario for two ONUs, compared to its counterpart that does not apply the RB mitigation technique.

1 Introduction

In these days, many capacity-rich data applications such as digital video, social network and mobile entertainment services have emerged in the area of optical communications. Consequently, the optical network units (ONUs) should provide at least 10-Gbit/s to meet the explosively growing bandwidth demands in the passive optical network (PON) system [1]. As an attractive solution, advanced and spectrally efficient modulation techniques such as orthogonal frequency division multiplexing (OFDM) and discrete multitone have been widely employed on PON to satisfy these bandwidth demands and realise the next generation optical access networks. This orthogonal frequency division multiple access-based PON (OFDMA-PON) can provide various merits such as high spectral efficiency, dispersion tolerance, ease of multiple access and transparency with already-existed PON topologies [2–6]. On top of these advantages, OFDMA-PON also provides superior scalability to guarantee dynamic bandwidth allocation by employing two-dimensional bandwidth mapping like subcarrier allocation with time division multiple access (TDMA) concept [2–6] and adaptive modulation to achieve ultimate spectral efficiency by modulating multi-level signal format (quadrature or pulse amplitude modulation) in combination with bit and power loading algorithm on each subcarriers. In order to take advantage of these merits and guarantee quality of service of users, it is important to provide channel state information (CSI) perfectly to transmitters. Because subcarrier allocation and optimum bit/power loading is carried out according to estimated CSI, the deviation between the real channel state and the estimated CSI might cause severe signal deterioration.

This issue has been one of the hottest topics in wireless communications [7–9]. Since wireless channels vary rapidly, the CSI estimation and updating time should be carried on shorter than channel coherence time, if not, the loaded values are improper for current channel [7–9]. Consequently, transmitters require a large number of signal processing for faster update, thus it has been a bottleneck in applying adaptive OFDMA into practical wireless system [8, 9].

It could be indisputable that channel in fibre is more stable than wireless one. However, this condition dramatically varies because of the Rayleigh backscattering (RB) effect which is a common network topology in optical access which transmits up/down stream through a single fibre loopback link, especially in uplink transmission [10–17]. Consequently, the OFDMA-PON transmitters should estimate their CSI frequently with respect to catch up with fast-changing channel responses [18] and as a result it generates too much redundancy. Even though the OFDMA-PON can provide high spectral efficient transmission, high redundancy consumes the transmission capacity and this decreases the advantage of the system. In order to handle this issue, we proposed the new slow adaptive OFDMA-PON scheme that can stabilise the channel itself so that the transmitters do not need to update their CSI and bit/power loading profiles frequently [18]. This slow adaptive scheme can be very attractive in terms of computational complexity in estimating and updating the CSI and loading profiles [18]. It can also enhance the bandwidth efficiency by saving a large number of control signal overheads [18].

However, even though the proposed slow adaptive OFDMA-PON could stabilise the channel response dramatically, there was still the significant performance penalty in maximum achievable throughput compared to the optical back-to-back counterpart [18]. This penalty comes from the residual low-frequency noise component even though we use the low-frequency dithering technique [18]. When it comes to considering multiple access scenario which means more number of ONUs in the link, this throughput penalty is another devastating factor in realising the slow adaptive OFDMA-PON, because the line-rate for each ONU could be severely restrained by the degraded total throughput in the case of a single fibre loopback transmission.

In this paper, we propose a new slow adaptive OFDMA-PON uplink transmission scheme which can significantly mitigate the total throughput penalty compared to the case of optical back to back by employing a low-frequency dithering technique of the optical seed carrier and the gain-saturated semiconductor optical amplifier (SOA) as an optical preamplifier at an optical line terminal (OLT). By the high pass filtering effect of the SOA in the gain-saturation region, we almost mitigate the residual low-frequency noise component and enhance the total transmission throughput in the 20-km single fibre loopback link.

2 Proposed slow adaptive OFDMA-PON

Fig. 1 briefly represents our previous slow adaptive OFDMA-PON scheme [18]. In this scheme, it was able to establish the slow adaptive OFDMA-PON uplink transmission that could provide the total throughput of 12 Gbit/s by employing the channel stabilisation technique in our previous report. When the low-frequency driving tone directly modulates the optical seed carrier, its optical spectrum broadens because of multiple low-frequency components that are generated next to the wavelength of the optical seed carrier λ_c. This spectral broadening contributes to break a coherence relationship between the modulated OFDMA signal and the reflected seed carrier. It leads to the RB effect mitigation and as a result, the channel variation in a single fibre loopback link can also be suppressed. This RB effect mitigation stabilises the transmitted upstream OFDMA signal in a carrier distributed PON topology. Compared to the OFDMA-PON without the channel stabilisation (i.e. this was not under a slow adaptive concept), our proposed scheme provided 2 Gbit/s total throughput enhancement and this could be valuable in the perspective of system upgradability.

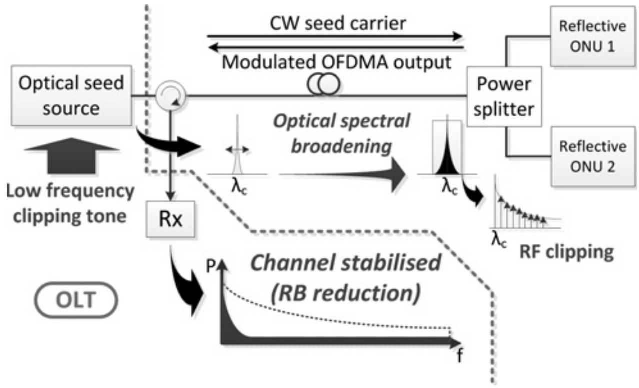

Fig. 1 *Previously proposed slow adaptive OFDMA-PON scheme*

However, as the number of ONU increases (more than 2 in the practical scenario), this 2-Gbit/s throughput enhancement could be trivial. Even though the RB effect was able to be mitigated in the proposed slow adaptive OFDMA-PON, and as a result, it was possible to realise the stable slow adaptive OFDMA-PON without any updation for the CSI and subcarrier allocation, there was a limitation to maximise the total throughput of the system. Indeed, this performance constraint was attributed to the residual RB components, which were mostly located in the low-frequency region, as

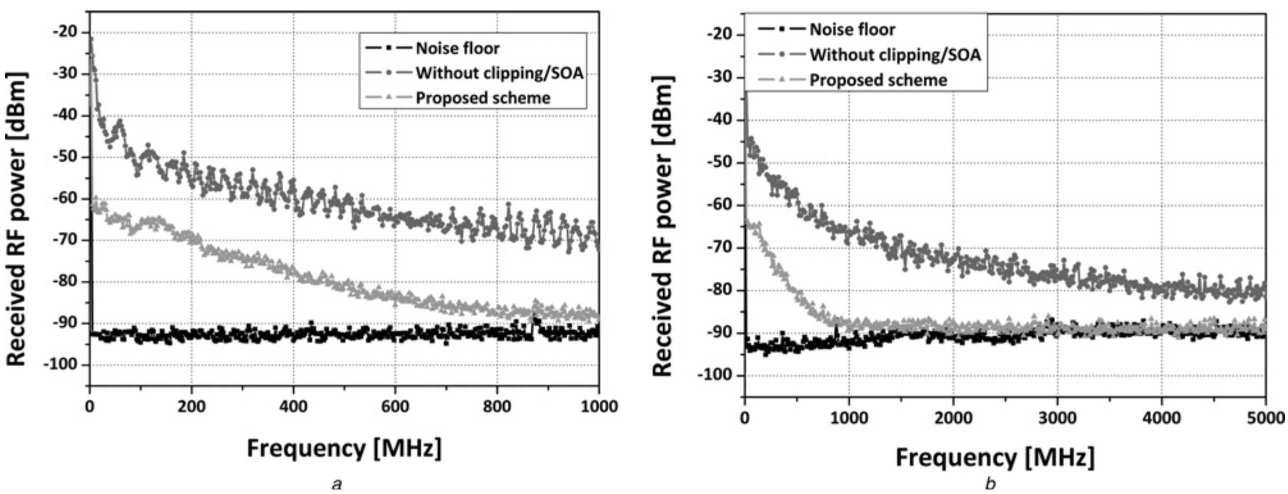

Fig. 2 *Residual RB components in RF spectrum analysis in the previous slow adaptive OFDMA-PON scheme for the frequency range*

a From DC to 5 GHz
b From DC to 1 GHz

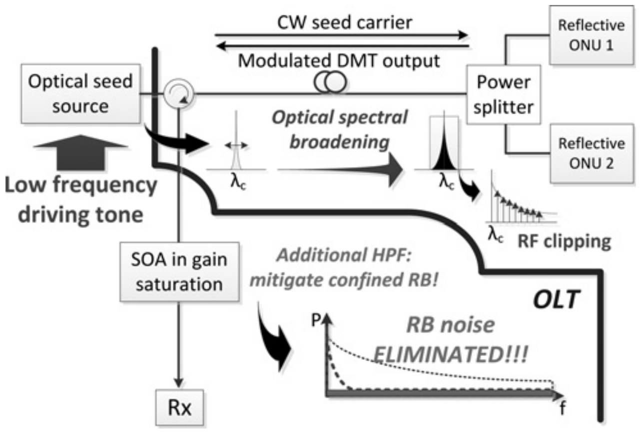

Fig. 3 *Proposed slow adaptive OFDMA-PON (especially for uplink) to mitigate the residual RB components in the low-frequency domain*

represented in Fig. 2. Especially in the spectrum analysis for the frequency region from DC to 1 GHz in this figure, the signal-to-noise ratio (SNR) of the channel was almost the same even when the proposed channel stabilisation technique was applied to the system. In this situation, the number of bits, which could be allocated into each OFDMA subcarrier based on the loading algorithm, was severely decreased in this low-frequency region because the SNR of the corresponding low-frequency subcarriers was too low to assign the large number of bits. Accordingly, the total throughput improvement was limited to the trivial achievement of 2 Gbit/s in the previous proposed scheme.

The residual RB component in the low-frequency region could be additionally suppressed by employing the gain-saturated SOA which operates as an optical preamplifier at an OLT. Fig. 3 illustrates the proposed scheme to suppress the residual RB effect completely on the transmitted uplink OFDMA signal in the carrier distributed PON topology. As shown in this figure, in first, the channel stabilisation is accomplished by using the same clipping modulation technique of the distributed optical seed carrier at the OLT using the slow frequency driving tone. After the uplink OFDMA transmission, the modulated OFDMA signal is passed through an optical preamplifier. In the proposed scheme for the additional RB suppression, this preamplifier is realised by an SOA that is operated at a gain-saturated region. It has been well known and analysed mathematically that an SOA is operated in the gain-saturated region then it has a high pass filter characteristic [17, 19–21]. Consequently, the residual RB components in the low-frequency band are able to be additionally suppressed in the proposed scheme. Since these low-frequency noise components could be further mitigated, the provided SNR for corresponding OFDMA subcarriers are better than the previous counterpart. When the bit and power loading algorithm is applied to the system, it can provide not only much higher total throughput but also provide the computationally efficient slow adaptive OFDMA-PON by employing the same channel stabilisation technique.

3 Experimental setup

The experimental setup for the proposed slow adaptive OFDMA-PON uplink transmission is represented in Fig. 4. A continuous wave (CW) optical source, which worked as the CW optical seed source for the upstream OFDMA transmission, was realised by a distributed feedback laser diode (DFB-LD) at 1554.348 nm with 5-dBm launch power. A 10-MHz RF driving tone with 12.5 dBm directly modulated this DFB-LD. The CW optical seed carrier launched into a 20-km single mode fibre (SMF) link. For the upstream transmission, OC 2 was used to separate and monitor the input optical power of the 1-GHz reflective SOA (RSOA) (as the OFDMA transmitter) without affecting the RSOA output. A polarisation controller was used to optimise its input polarisation state. The RSOA was biased at 65 mA.

The adaptively loaded OFDMA signals for ONU 1 and 2 were generated by MATLAB® and extracted by an arbitrary waveform generator (AWG: Tektronix 7122C) sampling at 8.4 Gsample/s. In every OFDMA symbol, data from two ONUs were scheduled employing a TDMA concept and each OFDMA signal was alternatively delivered from one physical RSOA to the point-to-point connected OLT as a proof-of-concept scenario, in the case of the upstream OFDMA transmission. The number of OFDMA subcarriers was 1024 with Hermitian symmetry, ranging from DC to

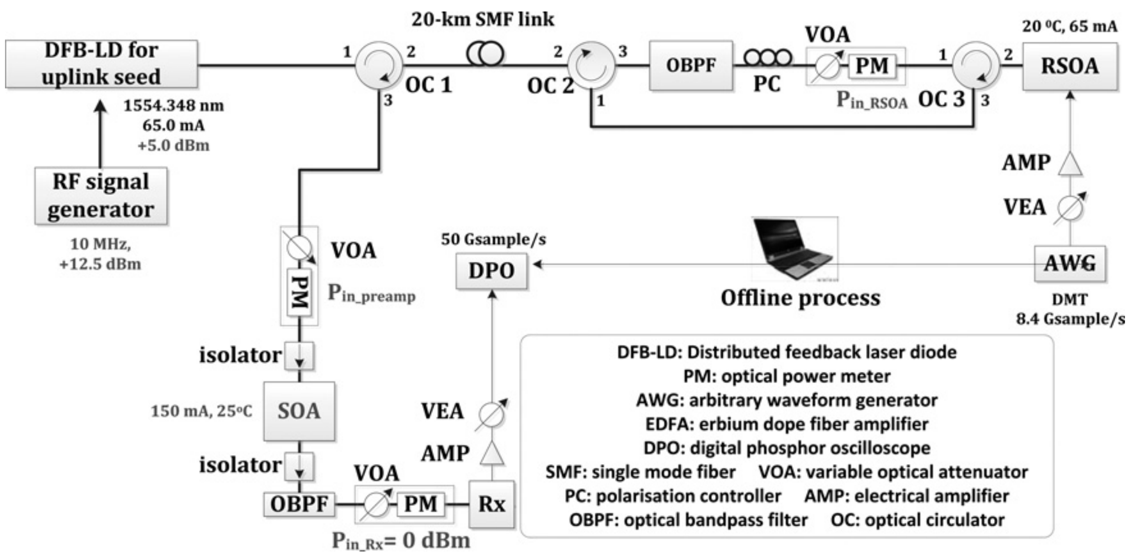

Fig. 4 *Experimental setup of the proposed slow adaptive PON*

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4.2 GHz. The modulated upstream OFDMA signals were retransmitted to the same 20-km SMF link through OC 2. In the case of OFDMA signal recovery, the transmitted carriers were delivered to a preamplifier that consisted of a gain-saturated SOA which had the threshold input power of −20 dBm for the gain-saturation operation with optical isolators. This gain-saturated SOA was biased at 150 mA with its operation temperature of 25°C. The input optical power of the preamplifier was monitored by an optical power meter. In order to minimise amplified spontaneous emission noise, an OBPF with the centre wavelength of upstream OFDMA signals was used after the preamplifier. The input power of a 12-GHz optical receiver was maintained at 0 dBm for experimental consistency. The received OFDMA signals were captured by a digital phosphor oscilloscope (Tektronix 72004C) sampling at 50 Gsample/s and evaluated by offline processing for a given ONU.

4 Results and discussions

4.1 Total throughput enhancement with slow adaptive subcarrier allocation

The detailed transmission system performance analysis was based on the logical and qualitative explanation with experimental results only. The delicate mathematical modelling and simulations including all the optical devices physics will be an issue of another communication later. In order to verify the residual RB component suppression, the RF spectrum analysis was carried out in the proposed scheme as represented in Fig. 5. As shown in this figure, the residual RB components, which were located in the low-frequency band from DC to 1 GHz in the scheme without the gain-saturated SOA, were successfully suppressed in the proposed scheme. Especially under this condition, it was able to put more bits into the corresponding OFDMA subcarriers, because their SNR was much higher than the case of without the residual RB suppression counterpart. Of course, because of the channel stabilisation technique realised by modulating the distributed CW seed carrier with a low-frequency driving tone of 10 MHz, the stable slow adaptive OFDMA-PON was also achieved in this scheme. Fig. 6 shows the subcarrier allocation stability as a function of BER fluctuation of OFDMA windows. Without the channel stabilisation, the BER fluctuation of OFDMA windows was severe because of the RB effect which changing the CSI faster than the channel coherence time. But with the channel stabilisation, the BER fluctuation of OFDMA windows was stabilised and it can satisfy the BER criteria of 2×10^{-3} for FEC limitation in any windows. In this operation, the bit loading profile was fixed in transmitting the entire OFDMA windows of 20, which was equivalent to 100 000 OFDMA symbols.

Under this circumstance, the maximum achievable total throughput of the upstream OFDMA transmission could be dramatically improved from 12 to 15 Gbit/s, when the input optical powers of the preamplifier and the RSOA were higher than −12.5 and −7.5 dBm, respectively, as shown in Figs. 7*a* and *b*. This total throughput performance was 0.5 Gbit/s lower than the case in the locally fed scheme in which the CW seed carrier was directly injected into the RSOA without the 20-km SMF transmission. It means that the performance penalty because of the RB effect could be minimised to <0.5 Gbit/s in the proposed scheme. There was still 2-Gbit/s performance penalty in the proposed scheme compared to the optical back-to-back counterpart. This was attributed to the chromatic dispersion during the transmission. Even though the employed OFDMA was traditionally tolerant to the dispersion, since the occupied physical bandwidth was higher than 4 GHz, it also activated the dispersion effect. This dispersion effect could be mitigated by reducing the occupied signal bandwidth in combination with the optimisation of the electrical driving circuit in modulating the modulators.

4.2 Low-frequency driving tone magnitude effect on channel stabilisation and total throughput improvement

Since the proposed channel stabilisation and the residual RB mitigation technique could be activated by broadening the optical spectrum of the distributed seed carrier, the clipping magnitude of the low-frequency CW driving tone might be very critical in the proposed scheme. In order to analyse this effect, the system performance was monitored in terms of the maximum achievable total throughput and the system

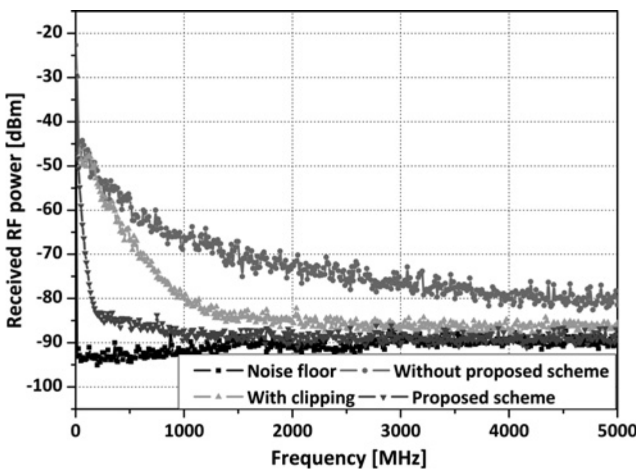

Fig. 5 *RF spectrum analysis for the frequency band from DC to 5 GHz in order to verify the residual RB suppression (inset: the same analysis from DC to 1 GHz)*

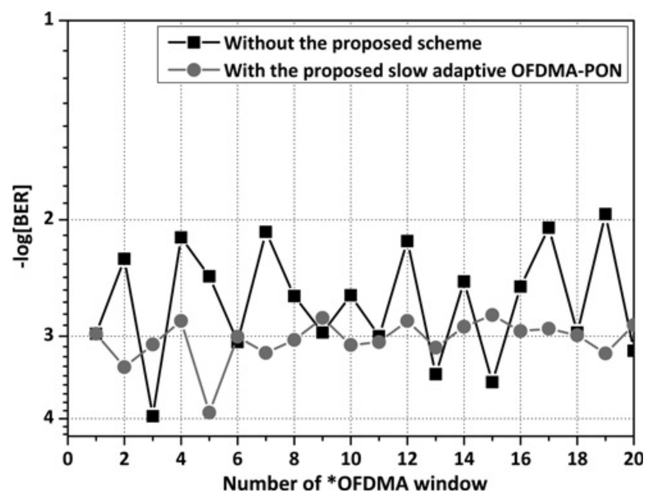

Fig. 6 *Subcarrier allocation stability with providing 7.8258 Gbit/s for each ONU in the proposed slow adaptive OFDMA-PON*

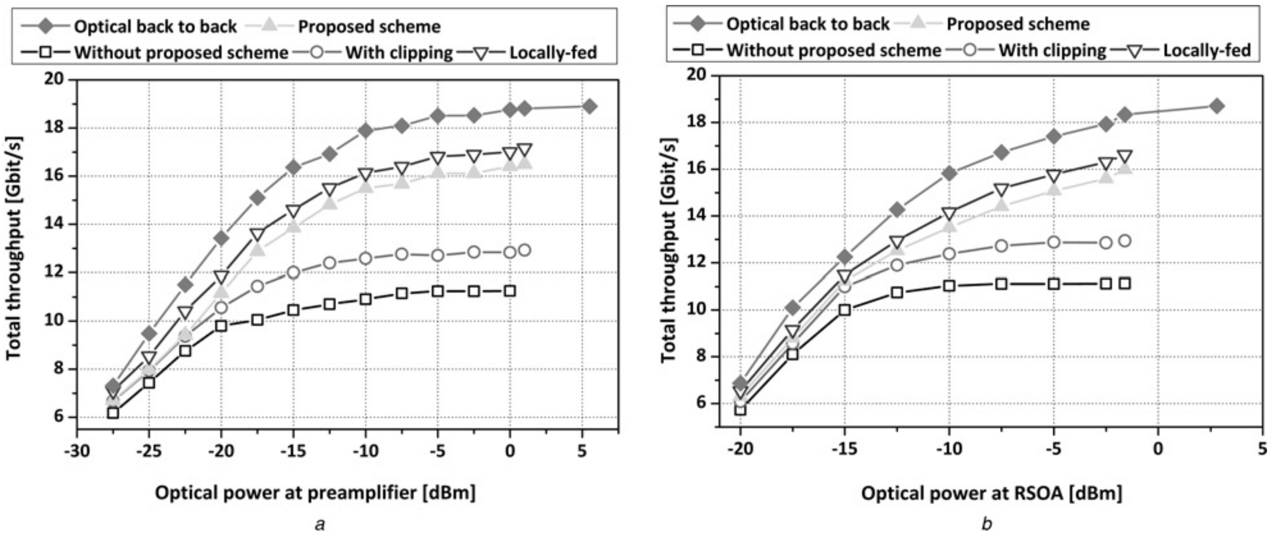

Fig. 7 *Total throughput achievement for the upstream OFDMA-PON transmission in the proposed scheme compared to various network topologies as a function of*

a Input optical power of the preamplifier
b Input optical power of the RSOA as the upstream modulator

outage probability as a function of the clipping magnitude, as shown in Fig. 8. In this analysis, the system outage probability was defined as the ratio of the number of OFDMA windows which led to the system outage to the given total number of OFDMA windows. In the slow adaptive OFDMA-PON operation, the signal performance could not satisfy the BER criterion of 2×10^{-3} for some of the OFDMA windows unless the channel was stabilised. This phenomenon was well described as a black square curve in Fig. 6 (notated as 'without the proposed scheme'). In the case of without the proposed scheme in Fig. 6, 11 OFDMA windows among the total 20 OFDMA windows could not provide QoS data transmission because of their bad BER performance. Therefore, in this case, the system outage probability was 0.55.

As indicated in Fig. 8, both performances, such as total throughput and the system outage probability, were abruptly enhanced when the modulation index of the 10-MHz driving tone was higher than 75%. Especially, the system outage probability was decreased from 0.55 to 0 (or 0.05). This means that the channel stabilisation, which was the must-have feature to offer the slow adaptive OFDMA concept in PON, was activated at this point of magnitude. The total throughput was also improved from 11 to 15 Gbit/s.

Once the magnitude of the low-frequency driving tone was higher than the threshold level of 75% modulation index, the slow adaptive OFDMA-PON could be achieved no matter how much magnitude of the driving tone the distributed CW seed carrier was modulated. However, when it comes to the total throughput achievement, the magnitude of the low-frequency driving tone should be less than the point that had the modulation index of 115%. If the magnitude was higher than this point, the total throughput started to decrease and in the end, the total throughput enhancement was not accomplished any more. This principle was able to be explained as follows.

When the low-frequency driving tone modulated the CW seed carrier, this carrier began to have multiple harmonics of the driving tone, which were located neighbouring to the centre wavelength. Since these harmonics were generated

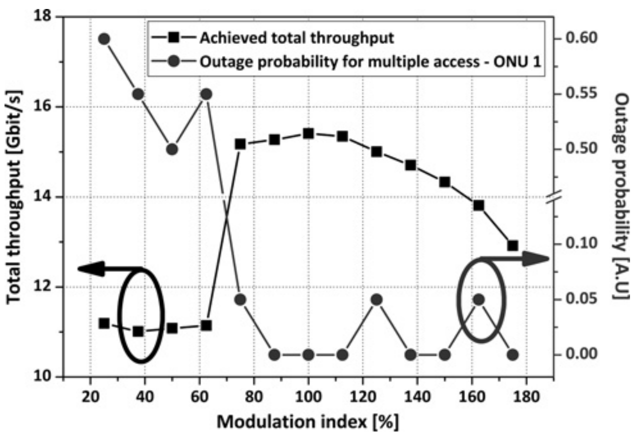

Fig. 8 *RF driving magnitude effect analysis on the proposed slow adaptive OFDMA-PON performance in terms of the total throughput and the system outage probability*

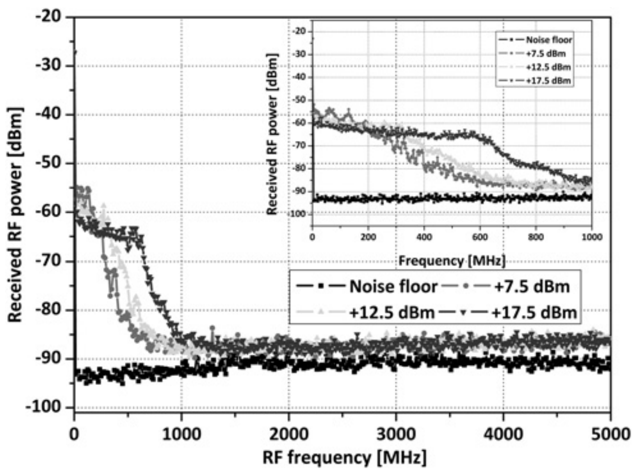

Fig. 9 *RF spectrum analysis for the magnitude effect of the low-frequency driving tone (inset: the same analysis from DC to 1 GHz)*

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from the non-linear property of the clipping modulation (i.e. the low-frequency modulation of the CW seed carrier), there would be more number of harmonics that could be generated when the magnitude of the driving tone became bigger and bigger. This tendency was able to broaden the optical spectrum of the seed carrier much further and as a result, the detected RF spectrum was broadened, as shown in Fig. 9. As represented in this figure, even though the proposed scheme was applied, the SNR of the low-frequency band became worse when the magnitude of the driving tone was higher than 12.5 dBm (equivalent to the modulation index of 115%, which was the threshold level in the proposed scheme). The loading algorithm assigned less number of bits into these OFDMA subcarriers and led to the total throughput degradation. Therefore when the proposed scheme is applied, it is very important to find the optimum magnitude for the low-frequency driving tone in order to activate the channel stabilisation effect as well as maximise the achievable maximum throughput performance.

5 Conclusion

We successfully demonstrated the reliable 15-Gbit/s OFDMA uplink transmission based on 1-GHz RSOA in the 20-km single fibre loopback with channel stabilisation. This channel stabilisation and total throughput enhancement were easily achieved by the RB interference reduction based on the clipping modulation of the optical seed carrier with the gain-saturated SOA as a preamplifier. The proposed scheme could provide the stable multiple access performance even the OFDMA-PON transmitters at ONUs with the fixed CSI estimation and the subcarrier allocation configuration. On top of this slow adaptive operation, the proposed scheme also enabled one to improve the total throughput by adopting the gain-saturated SOA as the optical preamplifier at the OLT through suppressing the residual RB components in the low-frequency band based on its HPF characteristic. In the proposed scheme, it was able to realise over 15-Gbit/s OFDMA uplink transmission through the 20-km single fibre loopback link with slow adaptive modulation.

6 Acknowledgments

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