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Comparison and analysis of codes for remodulation WDM-PON with adaptive code selection

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ABSTRACT

In a remodulation PON, the upstream signal quality can be improved when the downstream signal is coded. But low code efficiency may result in network congestion in downlink. Based on the downlink traffic, a self-adapting PON can select the proper downstream modulation codes to achieve the optimal network performance. With adaptive code selection, network congestion can be avoided and the remodulated upstream signal suffers minimal performance degradation. Some codes of various coding efficiency are required to be selected in this self-adapting PON. These codes should induce as little crosstalk to the upstream signal as possible. Several candidate codes with coding efficiencies from 50% to 80%, such as Manchester code, 3b5b code, 4b5b code, 4b6b code and 6b8b code are tested through simulation and experiment in this paper, and their performances are compared. The results show that the optimum code for downstream modulation depends on the downlink traffic and the upstream bit rate. The results will help the self-adapting remodulation WDM-PON to select the proper downstream modulation codes in different traffic situations.

1. Introduction

WDM-PON is an attractive solution for fiber-to-the-home (FTTH) access networks due its potential to support the high capacity traffic [1]. As each optical network user (ONU) is assigned a dedicated wavelength channel, wavelength-specific or tunable light sources for every user are generally required, which results in high network costs.

Centralized light source and remodulation of the downstream signal for upstream traffic are attractive approaches toward cost-effective solutions for WDM-PONs. However, the performance of optical upstream signal generated through the remodulation of optical downstream signal can be limited due to the crosstalk from the downstream signal. In order to mitigate the issue of remodulation crosstalk, various modulation and coding schemes have been proposed for WDM-PON optical downstream signal generation and for support of remodulation for optical upstream signal transmissions [2–7]. Considering the cost sensitivity of optical access networks, it is generally preferable to use intensity modulation and direct detection schemes for both downstream and upstream transmissions. In [5], it is shown that the upstream signal remodulated on a Manchester coded downstream signal gives better performance than that on an inverted return-to-zero (IRZ) coded downstream signal since the Manchester coded downstream signal induces less crosstalk to the remodulated upstream signal. Previously, we have shown that IRZ-Manchester coded modulation can be used for remodulation WDM-PON for much reduced crosstalk, and that differential phase shift keying (DPSK) modulation can be overlaid on the downstream optical ASK signal for broadcasting services [6].

The code efficiency (which is defined as the line rate ratio of input signal to output signal after the coding) of Manchester code and IRZ-Manchester code is only 50% and 25%, respectively. The effective downstream bit rate will be much lower than the line rate at low code efficiency. As the network traffic throughput requirement changes from time to time, the desired downlink throughput may go beyond the effective downstream bit rate, resulting in congestion. During congestion, the downlink data suffers from delays and even has to be discarded if the buffer in OLT is full. To avoid the congestion, codes with higher code efficiency become preferable under high downlink traffic. In [7], the line code of high efficiency is applied in the remodulation PON, but the upstream signals suffer obvious crosstalk and forward error correction (FEC) code is required. The codes with high code efficiency but inducing little crosstalk are the ideal candidates. However, in practice, there is a compromise between the code efficiency and the induced crosstalk between upstream and downstream signals.

To achieve good upstream signal quality while avoiding network congestion, a self-adapting remodulation PON, as shown in Fig. 1, should select through software the proper modulation code for downstream depending on the bandwidth requirement of downlink traffic and uplink traffic. When the transmission data buffer in the

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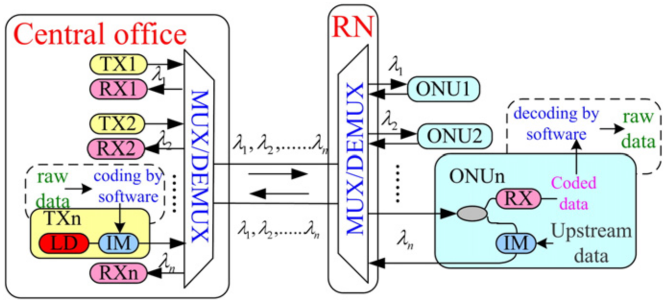

Fig. 1. The remodulation PON with self-adapting function. IM: intensity modulator, LD: laser diode, TX: transmitter, RX: receiver.

optical line terminal (OLT) becomes full with downlink data while the buffer in ONU turns almost empty, the PON will change the downstream modulation code to a different code with higher coding efficiency. When there is no downlink data waiting in the OLT, the PON will select a proper downstream modulation code inducing reduced crosstalk to the upstream remodulation. The selection should be accomplished in MAC layer.

In this paper, some codes of various coding efficiencies are chosen for downstream modulation in the experiment. The impacts of these codes are evaluated and compared through simulation and experiment. The results will help the self-adapting remodulation PON to choose the proper downstream modulation code in different PON traffic situations.

2. Remodulation crosstalk analysis and code proposals

In the amplitude modulation scheme, the upstream signal is modulated directly on the downstream signal. The direct current (DC) component of the downstream signal is reused for upstream data remodulation. As the upstream bit rate is usually much lower than the downstream bit rate under the asymmetric PON traffic, the low speed receiver in the OLT can filter out the high-frequency component induced by downstream signal, as shown in Fig. 2.

The high-frequency component of the downstream signal is filtered out, and therefore the crosstalk on the upstream signal mainly comes from the low-frequency component of the downstream signal which is in the baseband of the upstream signal. To reduce the crosstalk, the codes with minimal low-frequency component are good candidates for remodulation WDM-PONs. Please note that long consecutive “one” or “zero” bits contribute to low-frequency components, while alternating bits reduces low-frequency components. To ensure the bit transition, the codes proposed are constructed according to such a rule: every N-bit cell always contains “1” bits and “0” bits. Five codes of different code efficiencies are used in our experiments:

Manchester code: every 2-bit cell contains 1 “one” bit. The information capacity of each code cell is 1 bit ($\binom{2}{1}=2^1=2$). The code efficiency is 50%.

3b5b code: every 5-bit cell contains 3 “one” bits. The information capacity of each 3b5b code cell is more than 3 bits ($\binom{5}{3}=10>2^3=8$). The code efficiency is 60%.

4b5b code: every 5-bit cell contains 2 or 3 “one” bits. The information capacity of each 4b5b code cell is more than 4 bits ($\binom{5}{2}+\binom{5}{3}=20>2^4=16$). The code efficiency is 80%.

4b6b code: every 6-bit cell contains 3 “one” bits. The information capacity of each 4b6b code cell is more than 4 bits ($\binom{6}{3}=20>2^4=16$). The code efficiency is 66.7%.

6b8b code: every 8-bit cell contains 4 “one” bits. The information capacity of each 6b8b code cell is more than 6 bits ($\binom{8}{4}=70>2^6=64$). The code efficiency is 75%.

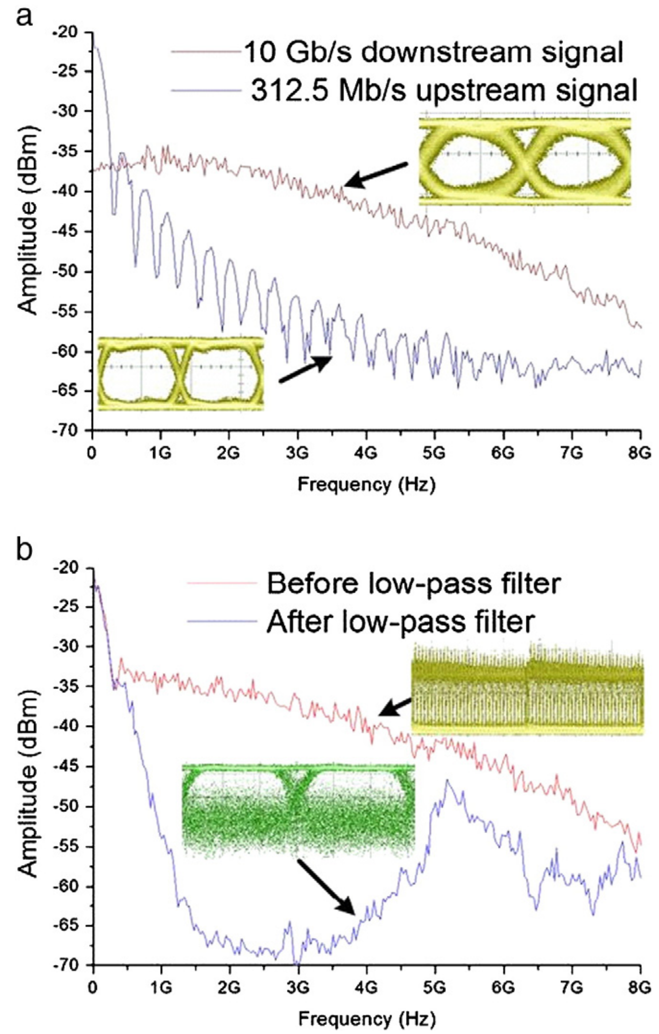

Fig. 2. Electrical spectra of (a) downstream signal and upstream signal and (b) upstream signal remodulated on downstream signal.

3. System simulations

We conduct simulations to evaluate the performance of received upstream signals remodulated on various coded downstream signals. In our simulations, the modulation index of MZMs is set to 30 dB, and the downstream line rate is set to 10 Gb/s. Upstream signals at bit rates of 312.5 Mb/s, 625 Mb/s and 1.25 Gb/s are evaluated. The upstream receiver bandwidth for upstream signal is set as 75% of the bit rate.

The eye diagrams of 625 Mb/s upstream signals remodulated on various coded downstream signals are shown in Fig. 3.

In simulations, BER can be calculated based on eye diagram analysis. Thus we show the simulation results of the bit error rate (BER) for 312.5 Mb/s, 625 Mb/s and 1.25 Gb/s upstream signals remodulated on different coded downstream signals in Fig. 4 (a)–(c). The power penalty of upstream signals remodulated on different code downstream signals versus these codes' efficiencies is shown in Fig. 4 (d).

All the coded downstream signals induce much less crosstalk than uncoded downstream signals. Performance of upstream signal is improved when downstream signal is coded. When the upstream bit rate increases, the degradation of the upstream signal becomes more serious. The codes under investigation show such a trend: higher code efficiency causes more crosstalk between the upstream and downstream signals. The only unusual example is that 4b5b coded downstream signal has higher code efficiency but induces less crosstalk than 6b8b coded downstream signal under 1.25 Gb/s upstream, as shown in Fig. 4 (c) and (d).

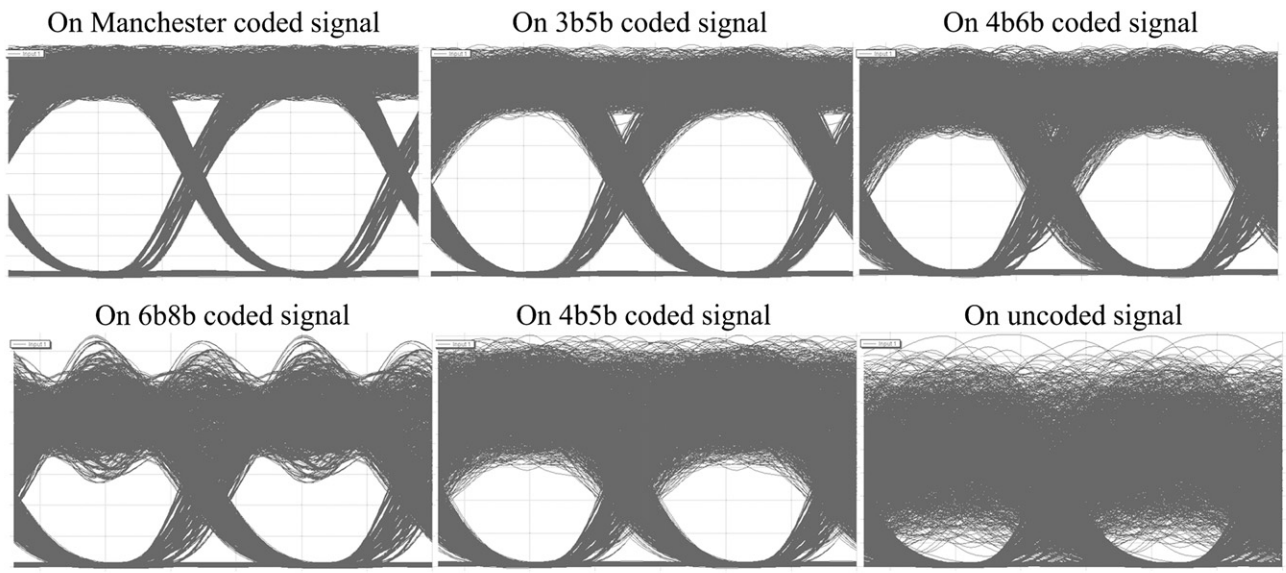

Fig. 3. Eye diagrams of 625 Mb/s upstream signals remodulated on different downstream signals.

4. Experimental setup and results

After simulation, a remodulation scheme of 312.5 Mb/s upstream bit rate and 10 Gb/s downstream bit rate is demonstrated experimentally, as shown in Fig. 5.

The raw data used in our experiment is pseudo random binary sequence (PRBS) with a length of 2^{10}–1. The data is coded by software using Manchester code, 3b5b code, 4b5b code, 4b6b code or 6b8b code. The downstream line rate is 10 Gb/s. The extinction ratio (ER) after modulation is more than 13 dB for the two MZMs used in the

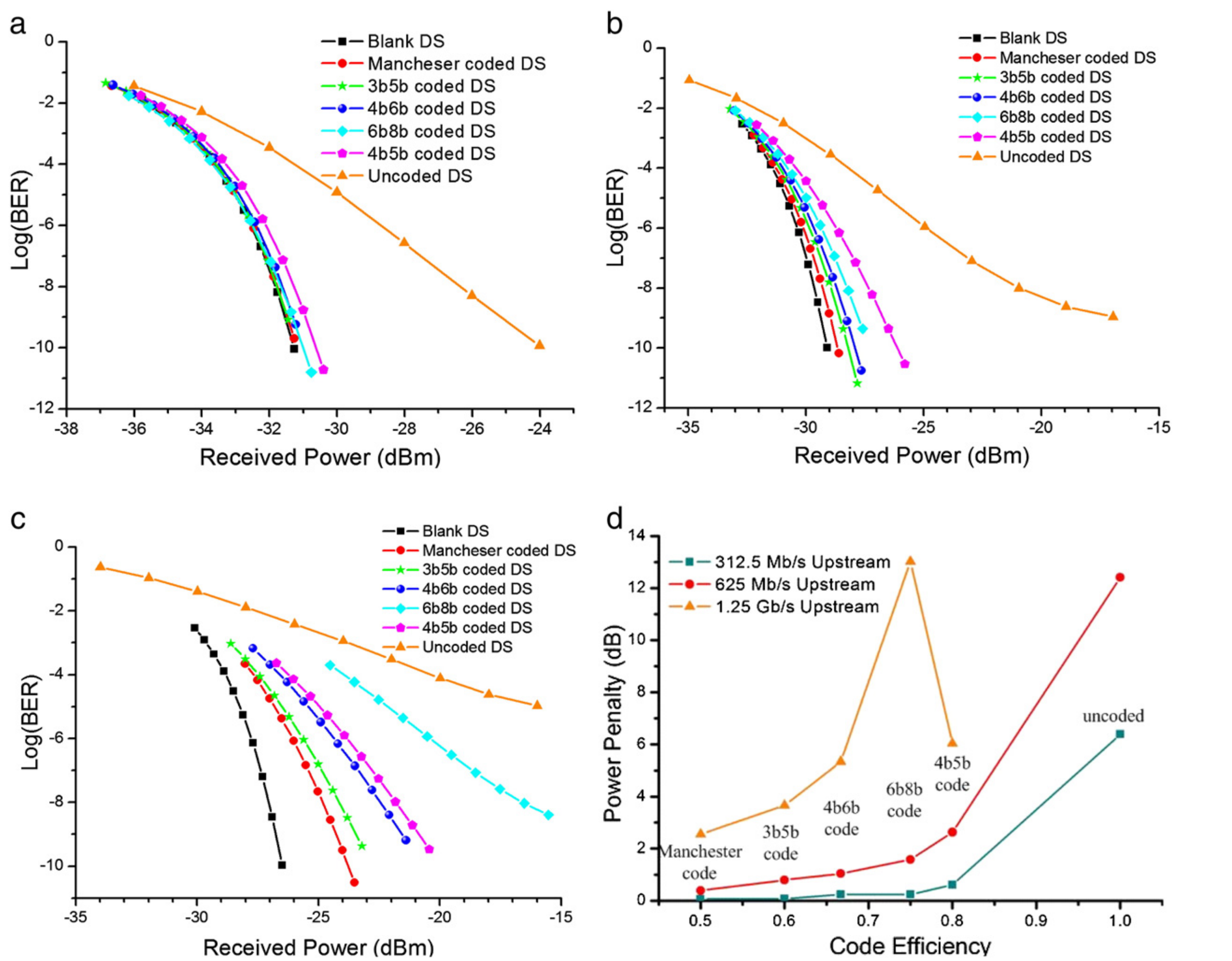

Fig. 4. BER of (a) 312.5 Mb/s, (b) 625 Mb/s and (c) 1.25 Gb/s upstream signals remodulated on different downstream (DS) signals and (d) power penalty at BER = 10e − 9.

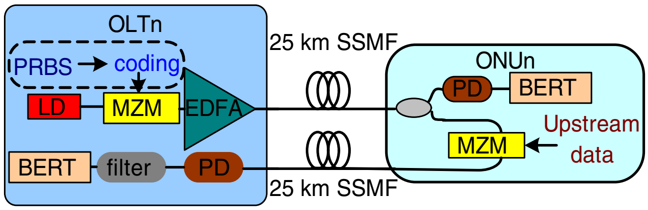

Fig. 5. Experimental setup. LD: laser diode; MZM: Mach–Zehnder modulator; EDFA: erbium-doped fiber amplifier; SSMF: standard single mode fiber; PD: photo diode; BERT: bit-error-rate tester.

OLT and the ONU. The upstream bit rate is 312.5 Mb/s. A 280 MHz low-pass filter is used after PD in the OLT.

The BER of the upstream signal remodulated on the coded data and the uncoded data are tested and shown in Fig. 6. In the figure we also show the BER of upstream signal remodulated on blank light (downstream is amplitude-constant).

In Fig. 6, the power penalty at BER = 10e − 9 when the upstream signal is remodulated on the Manchester coded signal, 3b5b coded signal, 4b6b coded, 6b8b coded signal and 4b5b coded signal are 0.8 dB, 1.63 dB, 1.3 dB, 2.3 dB and 3.6 dB, respectively. Among the coded signals, the Manchester coded downstream signal induces the least crosstalk and 4b5b coded signal induces the most crosstalk. The upstream signal remodulated on any coded downstream signal shows much better performance than that on uncoded downstream signal. The trend agrees well with the simulation results, though the BER curves of upstream signals show larger interval.

The performances of these codes can be explained from the electrical spectra of 10 Gb/s downstream signals in different codes in Fig. 7. The spectra are from the received downstream signal in the ONU.

Compared with the uncoded data, the low-frequency components of coded signals are suppressed because long sequences of consecutive "one" or "zero" are avoided. As a result, the signals remodulated on the coded signals show much lower crosstalk than the uncoded signal, as shown in Figs. 3, 4 and 6. Among the coded signals, the suppression of the low frequency component in 4b5b coded signal is not as severe as that in the other coded signals. The reason is that the mark space ratio (the ratio of the number of "one" bits to the number of "zero" bits) of 4b5b coded signal is not the same for all the 5-bit cells. Some 5-bit cells contain 3 "one" bits while the others contain 2 "one" bits. The former has 50% more total power than the latter. The power fluctuation per 5-bit cell contributes to low-frequency component. That's why the 4b5b coded downstream signal induces the most crosstalk in the coded signals when the upstream bit rate is not more than 625 Mb/s, as shown in Figs. 3, 4 and 6. The size of the code cells used in the experiment is different. As shown

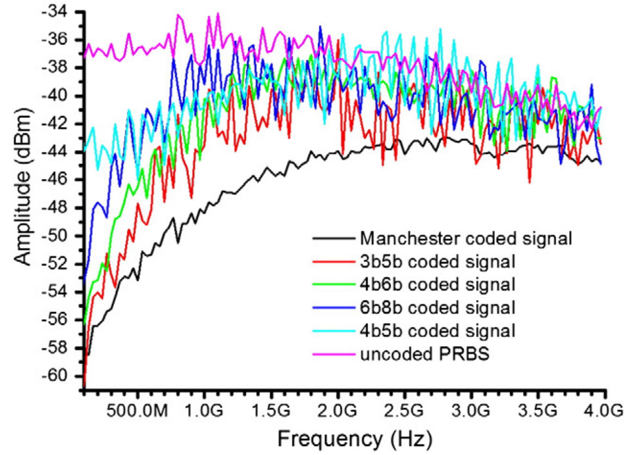

Fig. 7. Electrical spectrums of 10 Gb/s coded and uncoded signals.

in Section 2, the cell sizes of Manchester code, 3b5b code, 4b5b code, 4b6b code and 6b8b code are 2, 5, 5, 6 and 8, respectively. From Fig. 7, we can find that at larger cell size, the low frequency component increases faster with frequency. The low frequency component of 6b8b coded signal increases the most rapidly and overtakes 4b5b coded signal when the frequency is above 500 MHz. When the upstream bit rate increases, the overlap of spectral components for the 6b8b coded downstream and upstream signals becomes larger, resulting into more induced crosstalk. Therefore, the upstream signal remodulated on the 6b8b coded signal suffers more serious degradation than those remodulated on other coded signals when the upstream bit rate increases, especially from 625 Mb/s to 1.25 Gb/s, as shown in Fig. 4. From the results in Fig. 4 (c) and (d), it is concluded that the total component below 937.5 MHz (1.25 G$*$0.75 Hz) of 6b8b code is more than that of the 4b5b code. As a result, more crosstalk is induced to 1.25 Gb/s signal remodulated from the 6b8b coded signal than that from the 4b5b coded signal. In general, the code whose cells contain the same number of "one" bits (which means the cell power is uniform) will cause little crosstalk to the remodulated signal, since the low frequency component is highly suppressed. The codes of smaller cell size cause less crosstalk than that of larger cell size, especially when the upstream bit rate is close to the downstream.

5. Code comparison and selections

In general, codes of uniform cell power and small cell size, such as the Manchester code, are good candidates for remodulation PON. However, to achieve uniform cell power and a small cell size,

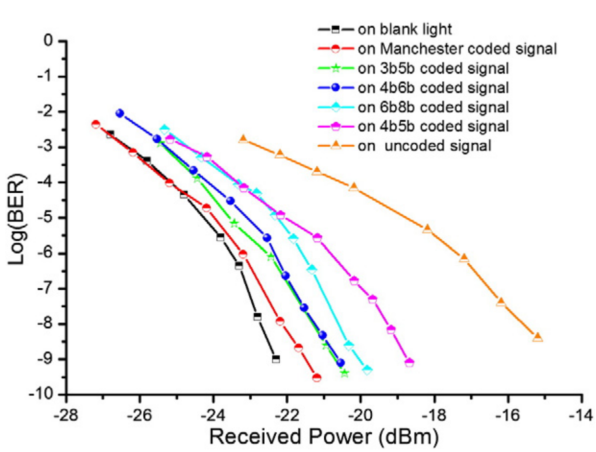

Fig. 6. BER of upstream signals remodulated on different downstream signals.

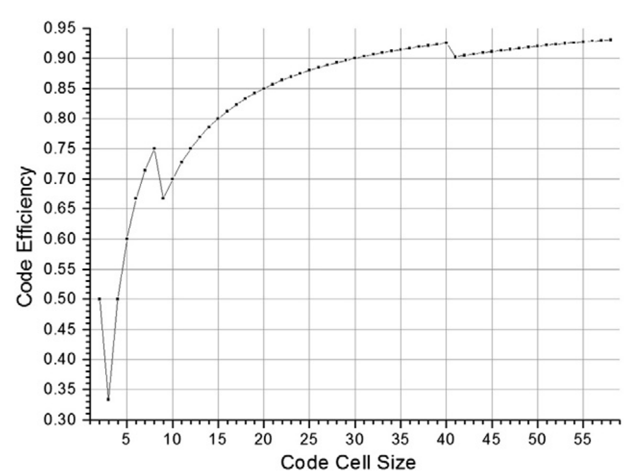

Fig. 8. Code efficiency versus different code cell sizes.

Table 1
Selection order of downstream modulation code.

Downstream bandwidth demand	312.5 Mb/s upstream	625 Mb/s upstream	1.25 Gb/s upstream
0 b/s	Blank	Blank	Blank
0–5 Gb/s	Manchester code	Manchester code	Manchester code
5–6 Gb/s	3b5b code	3b5b code	3b5b code
6–6.67 Gb/s	4b6b code	4b6b code	4b6b code
6.67–7.5 Gb/s	6b8b code	6b8b code	4b5b code
7.5–8 Gb/s	4b5b code	4b5b code	4b5b code
8–10 Gb/s	No code	No code	No code

the code efficiency has to be sacrificed. The code efficiency can be increased by relaxing the restriction of cell size (such as 6b8b) or uniform power distribution (such as 4b5b code).

To obtain uniform cell power and code efficiency as high as possible, a code should be constructed in this way: every N-bit cell contains int(N/2) (int(N/2) is the largest integer no more than N/2) “one” (or “zero”) bits. The information capacity is $\log 2\binom{\mathrm{int}(N/2)}{N}$, so each cell could carry M bits ($M=\mathrm{int}(\log 2\binom{\mathrm{int}(N/2)}{N})$), M is the largest integer no more than $\log 2\binom{\mathrm{int}(N/2)}{N}$). This code could be called MbNb code and the code efficiency is M/N. The code efficiency versus code cell size (N) is shown in Fig. 8. The code efficiency increases with code cell size. However, it increases rapidly only when code cell size is lower than 8. When the code cell size becomes larger, the increase of code efficiency is not so obvious. Compared to 6b8b code with 75% code efficiency, 12b15b has almost twice the cell size but only 10% more code efficiency. The cell size has to be enlarged to 30 (27b30b) to obtain 90% code efficiency. The larger cell size means more induced crosstalk.

There is a compromise between the code efficiency and the induced crosstalk between the downstream and upstream signals. An adaptive selection PON should choose proper code according to the bandwidth requirement: using the code of uniform cell power and small cell size when downlink traffic is light and choosing the code of high efficiency when the downlink traffic is heavy.

To be specific, for a PON with 10 Gb/s downstream line rate and 312.5 Mb/s (or 625 Mb/s) upstream line rate, when the downlink traffic increases, the choice of the downstream modulation code which can provide enough code efficiency while inducing least crosstalk to the upstream signal is in this order: the Manchester code, 3b5b code, 4b6b code, 6b8b code and 4b5b code. If the upstream line rate is 1.25 Gb/s or higher, 6b8b should be got rid of from the sequence as it shows no benefit compared with 4b5b code under this upstream line rate. Table 1 shows the selection order of the downstream modulation code for a self-adaptive remodulation PON with 10 Gb/s downstream line rate. In fact, when the downstream demand is higher than 8 Gb/s, we also can find other candidate codes whose code efficiency is more than 80%, as shown in Fig. 8.

6. Conclusion

A self-adapting remodulation PON which can adjust downstream modulation code based on the different PON traffic demand is proposed and demonstrated. Our simulation results show reduced crosstalk to the upstream signal induced by these coded downstream signals. A compromise is shown between the code efficiency and the induced crosstalk except under 1.25 Gb/s upstream bit rate, the 6b8b coded signal induce more crosstalk than the 4b5b coded signal. We further demonstrate the performance of various codes in the remodulation PON with 312.5 Mb/s upstream bit rate and analyze the spectra of these coded signals. The relation between code efficiency and cell size is discussed and the code selection order for the self-adapting PON under 10 Gb/s is proposed.

According to the results, the codes with uniform cell power distribution have a little low-frequency spectral component, inducing less crosstalk especially under low upstream bit rate, while the codes with smaller cell size have a slowly increasing low frequency component, inducing less crosstalk, especially under high upstream bit rate. However, the codes of uniform cell power and small size always have limited code efficiency. Thus there is a code selection order, which depends on the upstream bit rate.

The results will help a self-adapting PON to adaptively adopt proper downstream modulation codes under different downlink bandwidth requirements. The proposed self-adapting feature of WDM-PON will get the best upstream signal while avoiding downlink network congestion.

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