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LETTER

Power Saving Control Method with Adaptive FEC Decoder in Optical Access Network

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Abstract With the increasing demand for network services, the power consumption of equipment has been steadily rising each year, especially in the access network domain. Passive Optical Networks (PON) traditionally operate on the principle of ensuring service provision to the farthest user. Consequently, performance tends to be excessive for short to medium distances, leading to surplus power consumption. In this study, we address the issue of reducing power consumption in access networks by tackling surplus power. Our approach involves utilizing three different types of Reed-Solomon (RS) decoders to apply appropriate forward error correction (FEC) redundancy based on transmission distance, aiming to lower power consumption of RS decoders in optical network units (ONUs). Subsequently, we evaluated the power saving of FEC decoding in a 10G-class PON and report over 48% average power saving compared to the conventional homogeneous FEC-based network.

Keywords: FEC, Reed-Solomon code, Passive Optical Network
Classification: Fiber-optic transmission for communications

1. Introduction

In Japan, the increase in internet traffic has returned to its steady upward trend after experiencing a surge during the COVID-19 pandemic [1]. This trend is expected to continue as internet-based services that were introduced during the pandemic become normalized parts of daily life. Consequently, increasing capacity is actively being studied in access networks and intra-and inter-data center networks [2], [3]. However, capacity increase of access network is accompanied by the issue of increase in network power consumption [4]. The overall power consumption of networks has been on the rise annually due to the burden on equipment caused by the expansion of users and increasing capacity. In access network, while individual equipment consumes relatively low power, the large number of users utilizing those results in significantly high overall power consumption.

Passive optical network (PON) has a history of generation upgrade while maintain backward compatibility between generations. The legacy PON were designed guaranteeing the uninterrupted service to the farthest optical network unit (ONU). That design rule has been followed when deploying newer generations of PON. However, this has been led to excess in performance of short-distance ONUs. Adaptive control of PON has been studied to overcome the drawbacks of the legacy design rule [5]. The basic idea is to use excessive performance in meaningful ways to increase the performance of PON. However, most of those studies targeted increasing total capacity of PON [6] while only a few studies focused on reduction of power consumption of the network [7].

In this work, to address the increasing power consumption in PON, we study utilizing of the surplus optical power of short-distance ONUs to reduce the power consumption of electronic circuits, namely forward error correction (FEC) encoders and decoders of PON. Compared to the decoder, power consumption of FEC encoder is relatively low because of the less computational complexity of the encoder [8]. Moreover, generally, the upstream transmission has less communication volume compared to downstream transmission, resulting in less occupancy of the encoder in ONU. Therefore, in this study, we focused only on the power consumption of the ONU decoder for downstream transmission. We experimentally measured the power consumption of Reed-Solomon (RS) FEC decoders for three different FEC redundancy levels using field programmable gate arrays (FPGAs). Subsequently, we calculated power consumption of FEC decoders in 32-ONU PON where one of the three FEC redundancy was chosen based on optical path losses of each ONU. Our calculation results predict over 48% power saving in PON when the proposed adaptive FEC is employed.

2. Power consumption of RS (Reed-Solomon) decoders

With increasing transmission rate, transmitted signal is highly susceptible to fiber dispersion and optical path loss. In 10G-EPON, hard-decision FEC with RS code is standardly adopted to compensate transmission penalties [9]. RS (n, k) code consists of k information bytes and (n-k) of parity bytes. In RS code, coding gain increases with redundancy (parity bytes) at the cost of reduced effective rate. Here, effective rate is given by the product of bit rate and code rate, where code rate is k/n.

In this study, following the standardized parameters, the frame length of FEC frames were set to be 255 bytes. In addition to the standard code type, two code types, RS (255,247) and RS (255,239), were considered, and the power consumption for each decoding was studied.

Measuring power consumption of RS decoders involved

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constructing decoders in MATLAB/Simulink, followed by Verilog Hardware Description Language (VHDL) code conversion. The code was then implemented on an FPGA (Xilinx VC709) to measure the power consumption during decoding. The FPGA was connected to a personal computer (PC) and was used in "FPGA in the Loop" configuration. To evaluate the performance of RS decoders, FEC frames were generated in the PC by encoding random data. Then output frames of FEC encoder were modified randomly to generate errors before they were sent to FPGA for decoding. Error correction was validated by comparing the encoder input and decoder output data.

Table I Resource utilization of RS decoders

Resources	Utilization in Decoder		
	RS (255,247)	RS (255,239)	RS (255,223)
Look-up tables (LUT)	2504	4798	9352
Flip-flops (FF)	1195	2258	4402
Block RAM (BRAM)	8	16	32
Input and output resources (IO)	27	27	27
Global clock buffer (BUFG)	1	1	1

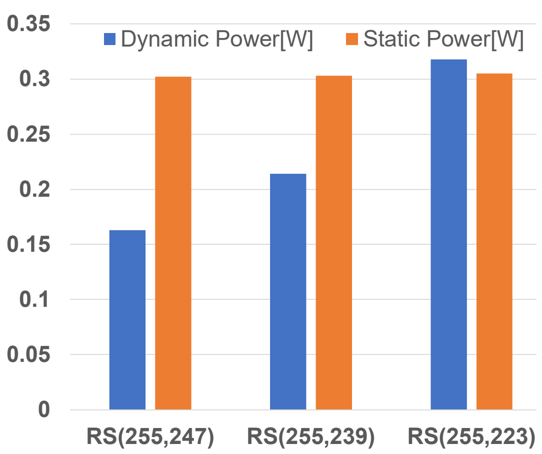

Fig. 1 The power consumption of each RS decoder

Resource utilization of RS decoders are presented in Table I. While IOs (input and output) and BUFG (global clock buffer) remained constant due to circuit configuration constraints, it was observed that LUTs (look-up table), FFs (flip-flop), and BRAMs (block random access memory) decreased as the FEC redundancy shortened. In our experiment we noticed the power consumption of resources are in the order of LUT(+FF) > BRAM > IO > BUFG. Accordingly, reducing the FEC redundancy resulted in a reduction in circuit size, thus decreasing overall circuit power consumption.

The measured power consumption of three RS decoders is depicted in Fig. 1. The values of power consumption were obtained from the power report in Vivado FPGA design software. Static Power represents standby power, while dynamic power represents power consumption during decoding one code word (255 bytes) of data. It was observed that variations in static power is negligible. However, as expected from the resource utilization, dynamic power decreased as the FEC redundancy decreased. It was found that dynamic power decreased by approximately 49% at maximum.

3. Achievable power saving in ONU FEC Decoders in Standard PON Configurations

To analyze achievable power saving in standard PON configurations using the proposed adaptive FEC decoders, we built a transmission simulator using MATLAB/Simulink. The structure of the transmission simulator is depicted in Fig. 2. Using the simulator, we analyzed FEC decoder power consumption for downstream transmission in a PON with 32 ONUs. Transmission parameters referenced from standard 10G - EPON are given in Table II.

For the sake of simplicity, we neglected all signal distortions, all optical and electrical noise of the system. In our simulator, we assumed sufficient compensation of optical path loss by FEC gain. FEC gain of each RS code for electrical signals is given in Table III. For optical fiber transmission, coding gains become approximately 0.7 to 0.9 times of that of electrical signal [10]. This value may reach 1 when there are sufficient photons. However, in our simulator we assumed 0.7 times gain of electrical signal considering the worst scenario.

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{\left(-\frac{x^2}{2\sigma^2}\right)} \qquad (1)$$

Distance distribution of ONU in PON can be approximated to a Rayleigh distribution $f(x;\sigma)$ based on statistical data [11]. In this study we assume the distance between optical line terminal (OLT) and ONU as the transmission distance. By varying the value of the standard deviation σ of the Rayleigh distribution of Eq. 1, the ONU distance distribution can be changed (Fig. 3). In this study, σ values of 1, 3, and 5

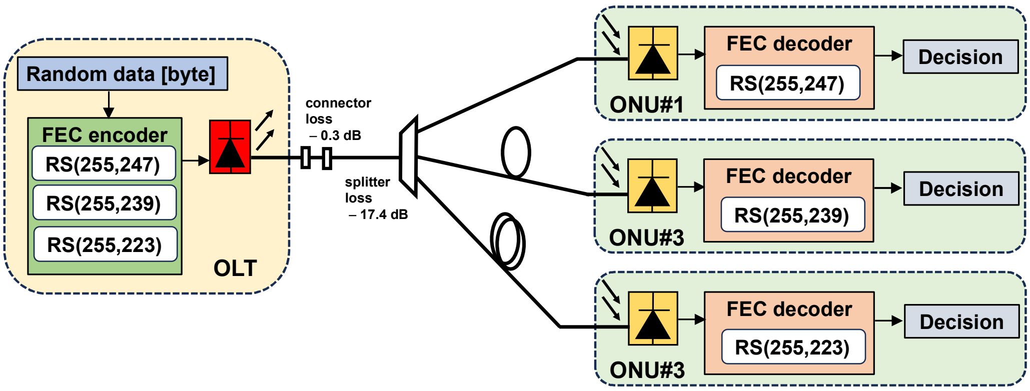

Fig. 2 The transmission model of the PON under investigation

Table II Transmission parameters

Parameters	Value
wavelength loss	−0.25 dB/km (λ =1577nm)
optical transmission power	+2 dBm
connector loss	−0.3 dB
branching attenuation (32 branches)	−17.4 dB
minimum received power	−28 dBm

Table III Coding gain

FEC redundancy	Coding gain (BER=1E−12)
RS (255,247)	5 dB
RS (255,239)	6 dB
RS (255,223)	7.2 dB

Table IV RS code usage rate in each subcarrier density

Subscriber density	Usage rate (%)		
	RS (255,247)	RS (255,239)	RS (255,223)
σ=1	100	0	0
σ=3	100	0	0
σ=5	84.375	9.375	6.250

were used, to simulate three subscriber densities, where peak subscriber densities happened at 1 km, 3 km and 5 km, respectively. The power consumption of ONU RS decoders in standard PON configurations was then determined using these distance distributions where the maximum transmission distance is 20 km.

Power consumption of RS decoders per bit was calculated using the experimentally measured dynamic power consumption value as shown in Eq. 2.

$$P = \frac{dynamic\ power(RS(255,k))}{255 \times 8}[\frac{mW}{bit}] \quad (2)$$

Next, the received power of each ONU was calculated using the transmission model of Fig.1. FEC redundancy for each ONU was selected by comparing the received power with the receiver sensitivity. Then, the power consumption per bit of RS decoders were calculated for all 32 ONUs and averaged.

Calculated RS decoder power consumption results are presented in Fig. 4 for comparison. Average power consumption of RS decoder was 0.08 mW/bit in all three subscriber densities. Compared to the conventional PON model where RS (255,223) decoding is done at each ONU, over 48% reduction in power consumption per bit was observed when distance based FEC was employed. A slight difference in power saving depends on Rayleigh distribution was noticed as follows; 48.7% for $\sigma = 1$ and $\sigma = 3$, and 44.2% for $\sigma = 5$, respectively. This slight difference is due to the variation of subscriber density, resulting in differences in RS code usage ratios in each subcarrier density. In our transmission simulator, we employed RS (255,247) up to transmission distance of 11 km, RS (255,239) in 11.1 ~ 15.5 km range, and RS (255,223) in 15.6 ~ 20 km range. The usage ratio of each RS code is given in Table IV.

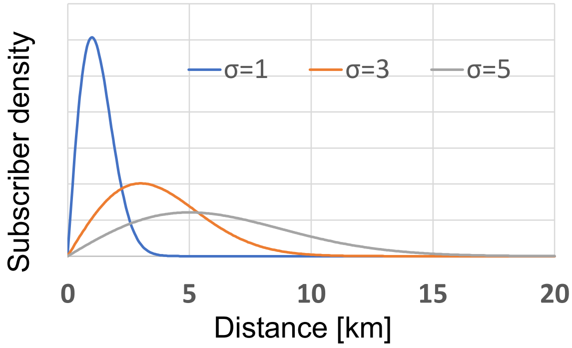

Fig. 3 Subscriber density distribution

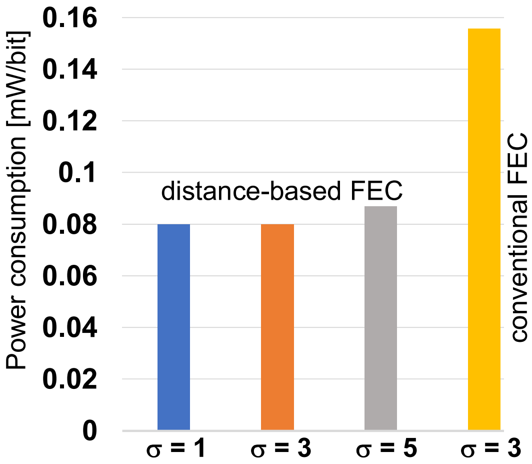

Fig. 4 Average power consumption per bit of RS decoders in ONUs

4. Conclusion

In this study, we investigated achievable power saving of PON by exchanging excess optical power of short distance ONUs to reduce FEC requirements. Because of considerable power conosumption of FEC decoders, firstly we studied RS FEC decoder power consumption in relative to redundancy of FEC code using hardware emulation. From our experimental results we found that dynamic power consumption of RS decoders highly depends on redundancy of the code.

Using measured power consumption values of three RS codes with different redundancies, we calculated achievable power savings in ONU FEC decoders when the redundancy of RS code was chosen in accordance to the transmission distance. According to our calculation reults, average power consumption of RS decoders in 32 ONU PON can be reduced by 48.7% and 44.2% in subscarrier density distributions of for $\sigma = 1$ or 3 and $\sigma = 5$, respectively.

Future efforts will focus on exploring methods for implementing these findings into practical systems, optimizing circuit size for implementation, and validating the upstream transmission model, including coordination with dynamic bandwidth allocation.

Acknowledgments

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