Adaptive Forward Error Correction for Power Savings in Optical Access Network

Zeng, Jiang
Graduate School of Information Science and Electrical Engineering, Kyushu University

Kubo, Kaito
Graduate School of Information Science and Electrical Engineering, Kyushu University

Kariyawasam, Amila
Graduate School of Information Science and Electrical Engineering, Kyushu University

Kimura, Shunji
Graduate School of Information Science and Electrical Engineering, Kyushu University

https://hdl.handle.net/2324/7183371

出版情報：信学技報. 123 (OCS-330), pp.49-54, 2024-01-04. The Institute of Electronic, Information and Communication Engineers
バージョン：

一般社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
IEICE Technical Report
OCS2023-66(2024-01)

光アクセスネットワークにおける適用誤り訂正による省電力化に関する一検討

ゼン ジャン　久保 海音　カーリヤワサム アミラ　木村 俊二

九州大学大学院システム情報科学学府　〒819-0388　福岡県福岡市西区元岡 744

E-mail:　zeng.jiang.563@s.kyushu-u.ac.jp

あらまし　本研究では、光アクセスネットワークにおける消費電力の増大に対処するため、前方誤り訂正符号(FEC)の符号化復号化処理に係る消費電力の削減について検討する。光アクセスネットワークでは、伝送距離がユーザごとに異なる。短距離のユーザは光受信感度に余裕があるにもかかわらず、各加入者装置（ONU）では同仕様の FEC が使われている。本検討では，ONU の消費電力に大きな割合を占める FEC 処理に着目した。短距離ユーザの光受信感度余力を有効的に活用し，FEC 処理への負担を軽減することで消費電力の削減を目指す。本稿では、PON システムで用いられているリードソロモン（RS）誤り訂正符号の冗長度とその消費電力の関係について検討した。伝送距離に対し適切な冗長度を選択することができれば，　短距離のユーザの場合従来の RS（255,223）に比べて 1 ビットあたりの FEC 処理の消費電力を最大で 87.2%削減できることが分かった。

キーワード　　PON，　リードソロモン（RS），　適応符号化

Adaptive Forward Error Correction for Power Savings in Optical Access Network

Jiang Zeng, Kaito Kubo, Amila Kariyawasam and Shunji Kimura

Graduate School of Information Science and Electrical Engineering, Kyushu University 744 Motooka, Nishi-ku, Fukuoka-shi, Fukuoka, 819-0385 Japan

E-mail:　zeng.jiang.563@s.kyushu-u.ac.jp

Abstract　This study addresses the escalating power consumption in optical access networks, focusing on minimizing power consumption of Forward Error Correction (FEC) processes. In optical access networks, transmission distances vary for each user. The surplus optical-receiver sensitivity of short-distance ONUs can reduce the burden on the redundancy levels minimizing their power consumption. This article explores the adaptive characteristics of Reed-Solomon (RS) FEC schemes in PON systems. We compare the bit error rate performance and power consumption of error correction codes with different redundancy levels under various signal-to-noise ratio conditions.　It is shown that by the adoptive FEC coding schemes, the network can tailor error correction levels to the actual requirements of each optical receiver of ONUs. In the case of short-distance users, an 87.2% saving in FEC power consumption per bit can be achieved in maximum compared to the conventional RS (255,223).

Keywords　Reed-Solomon (RS), Adaptive Coding, Passive Optical Networks (PON)

1. Introduction

To meet the increasing traffic demands in optical access networks, 50 Gbit/s passive optical network was standardized, and a further increase in transmission rate is being studied [1].　In current PONs, the peak transmission rate is limited by the worst-case optical budget, which is dominated by the optical path loss. Therefore, increasing the transmission rate of legacy intensity modulation-direct detection (IM-DD) PONs over 10 Gbit/s is only possible with sophisticated digital signal processing and advanced optical receivers [2]. However, the power consumption of telecommunication networks is being increased worldwide along with the traffic and is expected to reach 260,000 TWh by 2050 [3]. For the sustainability of the

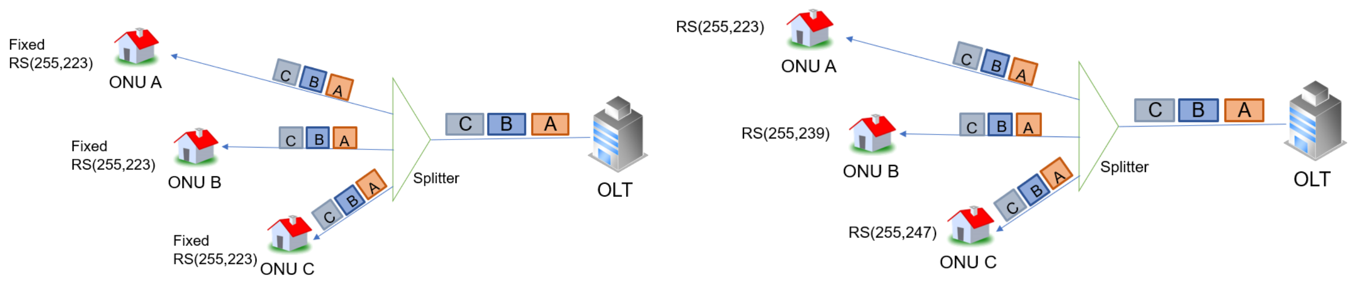

Fig. 1. Conventional PON and adaptive FEC-based PON

telecommunication networks, stringent power reduction is demanded in access networks, which contribute to 80% of network power consumption.

In current PONs, only a few ONUs experience the worst-case optical budget, while the majority are located low optical path losses. Flexible rate PON was proposed considering variations in optical path losses and channel conditions of ONUs. The increasing flexibility of PONs is being studied to increase throughput across the network using technologies such as orthogonal frequency division multiplexing (OFDM) [4],bit interleaving [5], adaptive coding and modulation[6], [7]etc. Recently, rate adaption was reported using probabilistic shaping in combination with low-density parity check (LDPC) forward error correction [8]. However, few studies have been reported on the application of network flexibility to reduce power consumption [9], [10], [11], [12], [13].

In this study, we focus on the excess optical power of the majority of ONUs, and we study reducing power consumption of forward error correction using this excess optical power of ONUs (see Fig.1). Since forward error correction (FEC) contributes considerable percentage of ONU power consumption, then we studied achievable power savings by employing appropriate FEC redundancy level of Reed-Solomon (RS) coding decided by the optical path loss of the ONU.

The rest of this paper is organized as follows: In section 2, we discuss the theory of RS code, and describe the relationship between RS coding gain and power consumption. In section 3, we quantify the power saving by utilization of adaptive RS codes in a PON system. Conclusions are drawn in section 4.

2. Reed-Solomon Coding

The structure of the RS coded frame is shown in Fig. 2. RS codes, as defined by parameters (n, k, t) [14], [15], involve the quantities k and n, representing the number of symbols before and after encoding, respectively. The parameter t is determined as $(n-k)/2$, signifying the count of symbols within n that can be corrected. The code rate is denoted by $R = k/n$. Symbols take their values in a Galois Field GF(2^m), and are thus represented with m bits.

Table 1. Meaning of Galois Field operators

$GFinv$	Inverse of a GF element
$GFmul$	Multiplication of two unspecified GF elements
$GFmul\alpha^i$	Multiplication by a specific GF element α^i
$GFadd$	GF addition
$GFreg$	Register storage
$GFmem$	Memory storage

The architecture of RS encoder is presented in Fig. 3. The number of Galois Field (GF) computational operations required during the encoding process depends on the circuit encoding architecture. Meanings of Galois field operators are given in Table1 where G_i represents the coefficients of the Galois Field (GF) generator polynomial, m_i denotes the coefficients of the original message polynomial, and P_i

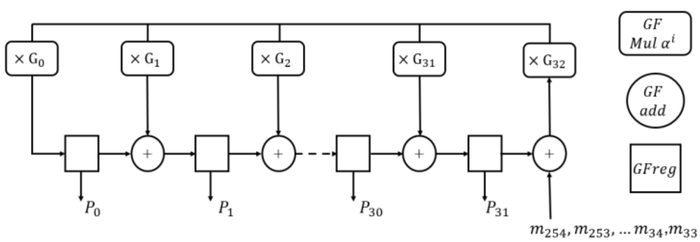

Fig. 3. Architecture for Reed-Solomon Encoder

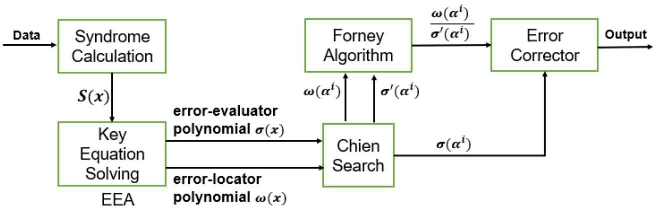

Fig. 4. RS decoders using Extended Euclidean Algorithm

signifies the coefficients of the output parity polynomial. In the encoding process, there is a requirement for $2nt$ $GFmul\alpha^i$ operations, as well as $GFadd$ and $GFreg$ operations.

A variety of decoding methods can be used to decode RS codes [14], among which the Extended Euclidean Algorithm (EEA) [16] demands the least computations for $t > 3$. Initially, the syndrome polynomial $S(x)$ is computed based on the received signal. The Extended Euclidean Algorithm (EEA) is then applied to solve the key equation, yielding the error-evaluator polynomial $\sigma(x)$ and the error-locator polynomial $\omega(x)$. The Chien Search algorithm is used to find the roots of the error locator polynomial. These roots correspond to the locations of errors in the received codeword. Once the error locations are determined using Chien Search, the Forney algorithm is employed to calculate the error values associated with these locations. The error magnitudes can be represented as $\frac{\omega(\alpha^i)}{\sigma'(\alpha^i)}$. Finally, the received codeword is corrected based on the identified error locations and corresponding error magnitudes.

The computational complexity per information bit (CCIB) can be utilized to compute digital power consumption for different set of code parameters. It can be expressed as a function of t, R and m as follows [17]:

$$CCIB = \frac{1}{m}\left[\frac{1-R}{2R}(4t+1)GFmul + \frac{1}{R}(6t-1)GFmul\ \alpha i\right] +$$
$$\frac{1}{m}\left[\left(\frac{1}{R}(6t-1) + \frac{1-R}{2R}(4t+1)\right)GFadd + \frac{1-R}{R}GFinv\right] +$$
$$\frac{1}{m}\left[\left(\frac{1}{R}(6t-1) + \frac{1-R}{2R}(6t+1)\right)GFreg + GFmem\right] + \quad (1)$$

The power consumption of the GF operations depends on the specific circuit implementation. The formula for calculating power consumption, determined by variables t, m and R.

Table 2. Computational Cost of GF operators [18]

GF operator	Computational complexity	Power consumption (pJ)
$GFinv$	m XOR	$0.4\,m$
$GFmul$	$m(m-2)/2$ XOR	$0.4\,m(m-2)/2$
$GFmul\alpha i$	m^2 AND $3(m-1)^2/2$ XOR	$0.4\,(m^2 +$ $3(m-1)^2/2)$
$GFadd$	m ROM read	$8\,m$
$GFreg$	m REG write	$2\,m$
$GFmem$	m RAM read & write	$10\,m$

2.1. Error correction performance

We calculated the error correction performances of RS codes for PAM2 signal in an AWGN channel [19][20]. The results are shown in Fig. 5. Here, Eb and N0 denote the energy per bit at receiver and the power spectral density of noise, respectively. Eb/N0 represents the ratio of energy per bit to noise power spectral density, expressed decibels(dB). From the bit error rate (BER) performance graph, we can extract the coding gain of different Reed-Solomon (RS) codes across various error rate levels. Coding gains of 4.5, 5.6, and 6.6 dB are noticed for RS (255, 247), RS (255, 239), RS (255, 223), respectively.

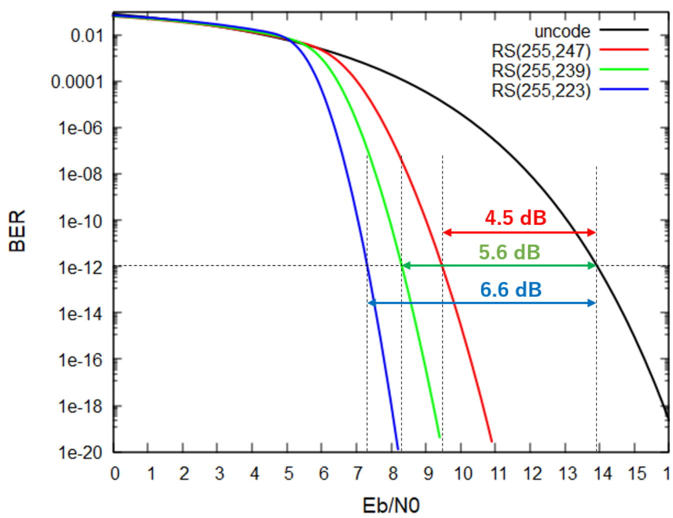

Fig. 5. Bit error rate performances of RS coded PAM2 signal in an AWGN channel

2.2. Power consumption

Based on the power consumption formula, we established the relationship between RS code power consumption and redundancy. Subsequently, we determined the coding gain at a decoded BER of 10^{-12} for different redundancy RS code based on the BER vs. E_b/N_0 curve. With the increase in t, the error-correction capability of RS codes strengthens, leading to an improvement in coding gain. Concurrently, the power consumption also increases rapidly. It is noteworthy that after certain level of redundancy, coding gain starts to saturate though power consumption increases linearly with t.

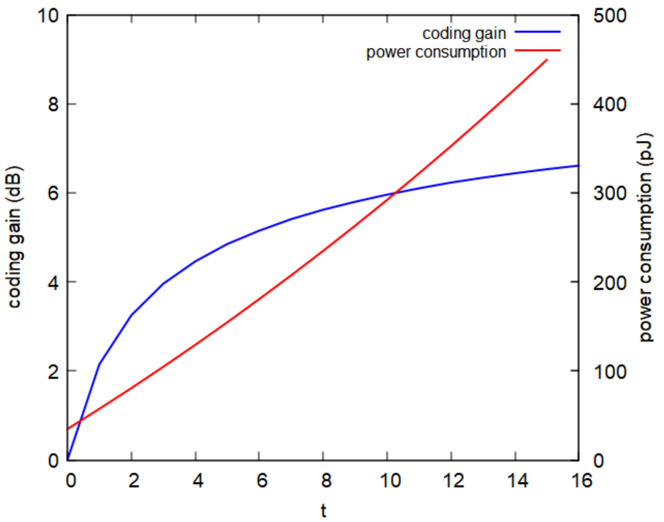

Fig. 6. Power consumption and coding gain of RS

3. Power saving by RS coding based variable FEC

In PON systems, the distance between ONU and OLT leading to varying requirements for the coding gain to meet the reception sensitivity. However, the currently deployed PON system employ RS(255, 223) coding for error correction. RS(255, 223) code scheme is satisfying the maximum reception distance of 20 km.

The surplus optical sensitivity of short-distance ONUs can be used to reduce the power consumption related to RS encoding and decoding. In this study we selects distinct RS coding schemes based on the distance of the ONU. Close-proximity ONUs necessitate only a modest coding gain to fulfill the sensitivity requirements of received optical signals; thus, employing RS codes with reduced redundancy is feasible. Because the power consumption of low-redundancy error correction codes is markedly lower than that of their high-redundancy counterparts, substantial power saving can be expected by selecting the appropriate redundancy to fulfil the requirements of each ONU.

We calculated the achievable power saving of FEC encoders and decoder in a 10G-EPON system. Power saving results are depicted in Fig.7. For this calculation, we assumed a PON of 32 ONUs. Network parameters are given in Table 3.

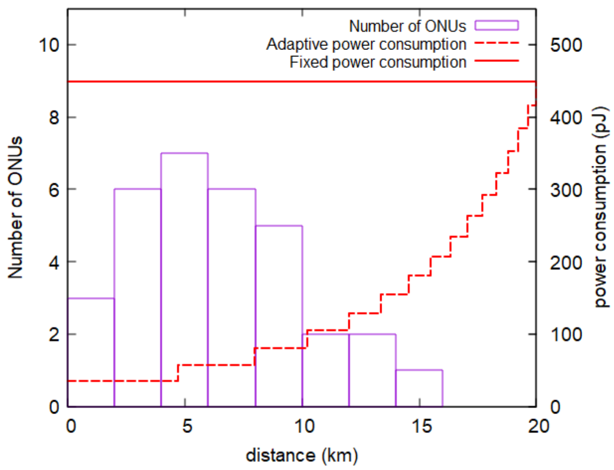

Fig. 7. Power consumption by employing distance based FEC redundancy for each ONU

In Fig.7, the red line represents the power consumption per information bit for RS encoding and decoding at different distances of ONU. Due to the current PON system employ fixed RS(255,223) code, its power consumption remains constant irrespective of the distance, as depicted by the solid line. The dashed line illustrates the power consumption when FEC redundancy is adapted according to the transmission distance of the ONU. Here, redundancy of RS code was varied from 2 to 16 bits.

When the distance < 4.73 km, RS code with 2-bit redundancy was employed. Reduction of the redundancy was possible because of the excessive optical power received by the ONUs at this distance range. In this distance range, power consumption of RS encoder and decoder is 57.5 pJ per bit. Comparing to the fixed RS (255,223) decoder with power consumption of 449.5 pJ per bit, 87.2% of power saving per ONU is achievable in maximum.

When the distance increases, the redundancy of the RS code had to be increased accordingly to compensate the optical path loss. Consequently, reduction in achievable power saving can be noticed with the distance.

In Fig.7, the distribution of ONUs at different distances, simulated using the Rayleigh function [21], is visually represented by the purple bar graph.

Table 3. Experiment parameters

Parameters Name	Values
Number of ONUs	32
Maximum Transmission Distance	20 km
Rayleigh Deviation σ	5
Fiber Loss	0.22 dB/km
Bit Rare	10 G
Wavelength	1580 nm
Output Optical Power	2 dBm
Reception Sensitivity	-28 dBm
Redundancy	t=2~16

The simulation results indicate that with the adaptive RS coding, the average power consumption of an ONU FEC encoder and decoder in the network is 88.8 pJ per bit. In contrast to the network with the fixed RS (255,223) scheme where the power consumption of ONU FEC encoder and decoder is 449.5 pJ per bit, the average power consumption of FEC decoder can be reduced by over 80.2% using adaptive FEC scheme.

4. Conclusion

In this study, we investigated the possibility of reducing DSP power consumption of ONUs in PON by selecting suitable a FEC scheme based on transmission distance. When RS coding is employed, redundancy of RS code can be selected according to transmission distance. This allows maximum power saving of 87.2% in ONU FEC decoders when the distance is less than 4.73 km. We calculated achievable power saving in a PON with 32 ONUs when the distance aware FEC redundancy was employed. Our calculation results predict the possibility of 80.2% reduction of average power consumption per ONU.

Acknowledgment

This work was partly supported by The Telecommunications Advancement Foundation.

References

[1] IEEE 802.3 ETHERNET WORKING GROUP https://www.ieee802.org/3/

[2] R. Borkowski et al., "FLCS-PON—an opportunistic 100 Gbit/s flexible PON prototype with probabilistic shaping and soft-input FEC: operator trial and ODN case studies," in Journal of Optical Communications and Networking, vol. 14, no. 6, pp. C82-C91, June 2022, doi: 10.1364/JOCN.452036.

[3] Impact of Progress of Information Society on Energy Consumption (Vol. 3): Current Status and Future Forecast of Network-Related Energy Consumption and Technical Issues, LCS-FY2020-PP-04, Social scenario research program towards a carbon neutral society, Japan Science and Technology Agency – JST

[4] N. Cvijetic, "OFDM for Next-Generation Optical Access Networks," in Journal of Lightwave Technology, vol. 30, no. 4, pp. 384-398, Feb.15, 2012, doi: 10.1109/JLT.2011.2166375

[5] D. Suvakovic et al., "A Low-Energy Rate-Adaptive Bit-Interleaved Passive Optical Network," in IEEE Journal on Selected Areas in Communications, vol. 32, no. 8, pp. 1552-1565, Aug. 2014, doi: 10.1109/JSAC.2014.2335331.

[6] E. S. Chou and J. M. Kahn, "Adaptive Coding and Modulation for Robust Optical Access Networks," in Journal of Lightwave Technology, vol. 38, no. 8, pp. 2242-2252, 15 April15, 2020, doi: 10.1109/JLT.2019.2963276.

[7] V. E. Houtsma and D. T. van Veen, "Investigation of Modulation Schemes for Flexible Line-Rate High-Speed TDM-PON," in Journal of Lightwave Technology, vol. 38, no. 12, pp. 3261-3267, 15 June15, 2020, doi: 10.1109/JLT.2020.2976959.

[8] R. Borkowski et al., "Operator Trial of 100 Gbit/s FLCS-PON Prototype with Probabilistic Shaping and Soft-Input FEC," 2021 European Conference on Optical Communication (ECOC), Bordeaux, France, 2021, pp. 1-4, doi: 10.1109/ECOC52684.2021.9606115.

[9] H. Feng, C. -J. Chae, A. V. Tran and A. Nirmalathas, "Cost-Effective Introduction and Energy-Efficient Operation of Long-Reach WDM/TDM PON Systems," in Journal of Lightwave Technology, vol. 29, no. 21, pp. 3135-3143, Nov.1, 2011, doi: 10.1109/JLT.2011.2166109.

[10] Hideaki Kimura, Kota Asaka, Hirotaka Nakamura, Shunji Kimura, and Naoto Yoshimoto, "Energy efficient IM-DD OFDM-PON using dynamic SNR management and adaptive modulation," Opt. Express 22, 1789-1795 (2014)

[11] Xiaofeng Hu, Pan Cao, Zhiming Zhuang, Liang Zhang, Qi Yang, and Yikai Su, "Energy-efficient optical line terminal for WDM-OFDM-PON based on two-dimensional subcarrier and layer allocation," Opt. Express 20, 25284-25291 (2012)

[12] K. Kanonakis and I. Tomkos, "Energy-efficient OFDMA-PON exploiting modular OLT/ONU digital signal processing," 2013 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), Anaheim, CA, USA, 2013, pp. 1-3, doi: 10.1364/OFC.2013.OTh3A.4.

[13] H. Mukai, F. Tano, and J. Nakagawa, "Energy Efficient 10G-EPON system," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, OSA Technical Digest (online) (Optica Publishing Group, 2013), paper OW3G.1.

[14] S. B. Wicker, Error control systems for digital communication and storage, Prentice Hall, 1995.

[15] S. Lin, D. J. Costello Jr., Error Control Coding, Second Edition, Prentice Hall, 2004.

[16] H. Lee, M.-L. Yu, L. Song, "VLSI design of

ReedSolomon decoder architectures", IEEE Int. Symp. Circuits and Systems, vol.5, pp.705-708, May 2000.

[17] L. Biard, D. Noguet, "Choice and Implementation of a Reed-Solomon Code for Low Power Low Data Rate Communication Systems", IEEE Radio and Wireless Symp., pp.365-368, Jan. 2007.

[18] C. Desset, "Selection of channel coding for low-power wireless systems", Vehicular Tech. Conf., vol.3, pp.1920- 1924, Apr. 2003

[19] Ziemer, R. E., and R. L., Peterson. Introduction to Digital Communication. 2nd ed. Prentice Hall, 2001.

[20] Sklar, Bernard. Digital Communications: Fundamentals and Application. 2nd ed. Upper Saddle River, N.J: Prenruce-Hall PTR, 2001.

[21] F. Vacondio, O. Bertran-Pardo, Y. Pointurier, J. Fickers, A. Ghazisaeidi, G. de Valicourt, J.-C. Antona, P. Chanclou, and S. Bigo, "Flexible TDMA access optical networks enabled by burst-mode software defined coherent transponders," in Proceedings of ECOC 2013, paper We.1.F.2 (2013).