A Multi-Mode Error-Correction Solution Based on Split-Concatenation for Wireless Sensor Nodes

Duc Phuc Nguyen, Thi Hong Tran, and Yasuhiko Nakashima
Graduated School of Information Science, Nara Institute of Science and Technology (NAIST), 8916-5 Takayama-cho, Ikoma-shi, Nara-ken, Japan
Email: {nguyen.phuc.ni6, hong, nakashim}@is.naist.jp

Abstract —Forward Error Correction (FEC) now plays an important role in many wireless transceivers because it helps increase link reliability and lower required transmit power. Expected features of a FEC solution are scalability, high coding-gain, low-complexity and transmit power efficiency. In this paper, we proposed a multi-mode error-correction solution which is based on split-concatenation of low-constraint convolutional code and Truncated-Iteration Layered-Decoding LDPC (TILD-LDPC) block code. The proposed FEC solution can offer many operation modes with different levels of error-correction performance and transmit power. Moreover, besides guaranteeing good BER performances, the proposed FEC approach is also a low-complexity error-correction solution by implementing low-complexity version of convolutional code and LDPC. From experimental results and theoretic arguments, we found that the proposed FEC solution is suitable to apply for Wireless Sensor Nodes.

Index Terms—Forward error correction, multi-mode, split-concatenation, wireless sensor nodes

I. Introduction

Providing a reliable communication channel with lowest power consumption of devices seems to be a critical problem in most wireless communication applications, especially in Wireless Sensor Networks (WSNs). Forward Error Correction (FEC) algorithms can detect and correct to a level of errors appearing in received bit stream due to bad channel. The basic idea of such FEC algorithms is to add redundant bits or symbols to the original data together with constraint equations, then original data will be rediscovered at receiver side [1]. Because of error-correction property, FEC algorithms helps to increase channel reliability and lower required transmitter power. Some popular FEC algorithms are Hamming Codes, Reed Solomon, BCH, Turbo, Convolutional Code, LDPC etc., each method has typical characters in error correction and they are selected considerately to apply in various applications. Besides, robust codes can provide better error-correction performance with lower transmit power requirements [2]. Therefore, preeminent BER and coding-gain performance is selected as an important target in many FEC solutions.

Moreover, it seems that flexibility and scalability are current trends for researches related to FEC [3], [4]. For creating a powerful error-correction solution, a super coder/decoder may be created by using concatenation technique. This technique is the combination of inner code and outer code in both transmitter and receiver side to take advantages of component FEC algorithms (Fig. 1). Recently, many researches have introduced several concatenated FEC solutions for WSN applications [2], [5]-[7]. They can be the combination of LDPC, Turbo code, Reed-Solomon, BCH or other FEC algorithms at various code rates, with serial or parallel architecture. Current works on concatenation-based FEC focuses on architecture optimization, scalability, or BER performance race [3], [4]. In this paper, our split-concatenation FEC solution focuses on: scalability, low complexity, transmit-power efficiency, and adaption for many diversified requirements of wireless sensor nodes.

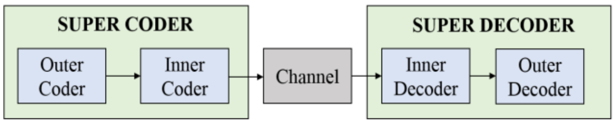

Fig. 1. Concept of concatenated FEC.

WSN consists of a set of small devices with limited energy resources, limited processing capabilities and radio frequency front-ends with limited transmit power [7]. Applying FEC for WSN transceivers needs to take care about required transmit power, and power dissipation of FEC decoder circuits. Many researchers have proposed various methods to apply FEC in WSN applications. Specifically, Moataz *et al.* [2] combined LDPC with Turbo code for WSN, their approach could remove error floor of Turbo code by concatenating with LDPC; but their BER performance decreases remarkably in concatenation mode, and high-complexity of their FEC solution was unavoidable due to iterative decoding of LDPC and Turbo code. Quassim *et al.* introduced a modification version of Reed Solomon (RS) code [1] which reduces power consumption, and it can be applied in WSN applications; but the BER/PER performance of this solution was not so good even in AWGN channel. Nashat *et al.* [7] proposed an adaptive parallel-concatenation Turbo code with various interleave sizes

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Corresponding author email: nguyen.phuc.ni6@is.naist.jp
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for sensor nodes, forwarding nodes and base stations. This approach can help reduce power consumption of sensor nodes but Turbo code at code rate 1/3 was quite low, together with BER performance at small sizes of interleaver memory was not good. Moreover, power efficiency was not evaluated in the paper. Ravanesh. M presented a flexible parallel-concatenated Turbo codes in [5]. Contribution of this research was that he evaluated BER performance of Turbo code in many communication hops and at different interleaver sizes. However, error floor appeared clearly even in low SNR area, this creates a big drawback to apply in WSN applications.

In this paper, we propose a multi-mode FEC solution which is based on split-concatenation of truncated-iteration layered-decoding LDPC (TILD-LDPC) and low-constraint convolutional code. Our approach shows a diversification in error-correction performance, transmit-power efficiency with reduced complexity. Potential flexibility of the proposed FEC solution is suitable for wireless sensor nodes.

II. Transmit-Power Efficiency of Forward-Error Correction on Wireless Sensor Nodes

In low-power WSNs, extending battery life of wireless nodes is the most critical problem. Wireless nodes usually do not transmit up to a maximum power limit. Transmitting with lowest power as possible while maintaining a required transmission reliability is our target. In low-power WSNs, power-constrained is considered as more important than bandwidth-constrained [8]. Therefore, in order to achieve power efficiency, sometimes we could accept transmitting more redundant data, especially in wireless sensors.

Coding gain is used as a parameter to evaluate the transmit-power efficiency of a FEC solution. The coding gain of a coding scheme at a given value of bit error rate (BER) will be defined as the difference in decibels between the E_b/N_0 required to obtain that BER with coding and without coding. We assume the minimum required transmit powers $P_{TX,U}$, $P_{TX,FEC}$ at the signal-to-noise ratio (SNR_U) required to achieve a desired BER for an uncoded system and coded system using FEC respectively. As following [8], effect of FEC's coding gain on transmit power is given as (1).

$$P_{TX,FEC}[W] = \frac{\eta_C B_C}{\eta_U B} \frac{P_{TX,U}}{10^{FEC_{gain}/10}} = \frac{P_{TX,U}}{10^{FEC_{gain}/10}} \quad (1)$$

where, η_U, η_C are the spectral efficiency of uncoded and coded system respectively. B and B_C are bandwidth of uncoded and coded system respectively. Note that $\eta_C B_C = \eta_U B = R$ which R is the transmission rate. The equation (1) demonstrates using of FEC helps lower the required minimum transmit power as a result of coding gain (FEC_{gain}). Our error-correction solution provides different options for coding gain performance, and some transmit-power reduction levels are also provided. Besides, our concatenation mode can provide a powerful error-correction ability; but in this mode, transmit power have to be considered as a more important factor than information transmission efficiency because of the incident low-code-rate feature of the concatenated FEC concept.

III. Proposed Method

A. Description of the Proposed Method

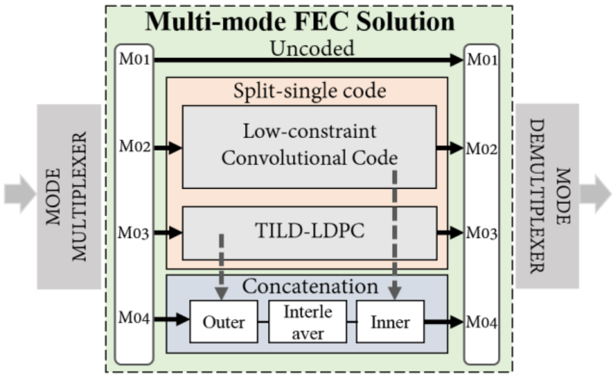


Fig. 2. Block diagram of proposed multi-mode FEC solution based on split-concatenation.

Fig. 2 shows the block diagram of the proposed method. The proposed solution includes four modes of operation:

- Uncoded (M01): Channel coding is not implemented in this mode. In normal cases, Automatic Repeat Request (ARQ) technique may be applied in this mode to increase the reliability of channel (not covered in this paper). This mode is suitable for applications which require: near distance transmission, low-noise environment, low data rate, and errors in received bitstream are accepted. This mode is often supported in low-power sub-1Ghz RF front-ends like TI's CC1100, CC1150 which are applied in small area WSNs.
- Low-constraint convolutional code (M02): high-constraint convolutional code is applied in IEEE 802.11.a,b,g,n, and low-constraint versions of convolutional code are also applied in low-power sub-1Ghz RF transceivers [4]. We propose using low-constraint convolutional code which has low-complexity and accepted performance of error-correction. This mode is suitable for applications which require: medium distance transmission, low-noise environment, high data rate, limited performance of error-correction.
- Truncated-Iteration Layered-Decoding LDPC (TILD-LDPC) (M03): Due to iterative decoding characteristic of TILD-LDPC, this mode has good error-correction performance. Therefore, TILD-LDPC is selected as main error-correction block and it is located at "Outer" position in concatenation mode. Our M03 mode is suitable for applications which require far distance transmission, high-noise environment, medium data rate, good performance of error-correction.

- Concatenated (M04): Concatenation mode provides very high error-correction performance, low-complexity with free burst-error. However, this mode requires more redundant data in transmitting data. This mode is suitable for applications which require far distance transmission, very low data rate, very good performance of error-correction in high-noise environment. This mode is suitable for low-power large-area WSNs or satellite communication.

B. Truncated-Iteration Layered Decoding QC-LDPC (TILD-LDPC)

LDPC has shown benefits such as error-correction performance approaching the Shannon limit, low-complexity, be suitable for hardware implementation. Also, LDPC has better error-floor performance compared with Turbo code. In the proposed method, Quasi-cyclic LDPC (QC-LDPC) [9] is selected as the main error-correction block and it works as "Outer" code in concatenation mode. Moreover, layered decoding technique with Offset-Min-Sum (OMS) algorithm are also implemented to improve convergence speed and performance of the universal QC-LDPC. Also, through our simulation with different number of iterations, we found that BER performance of the layered decoding QC-LDPC improves unremarkably when iteration number is larger than 5 (Fig. 3). Therefore, we selected 5 as an iteration limit for the iterative layered decoding QC-LDPC. In common multi-processor architectures of layered decoding QC-LDPC, an iteration is represented by one processing processor. Using truncated-iteration method will reduce remarkably implementation-complexity of layered decoding QC-LDPC.

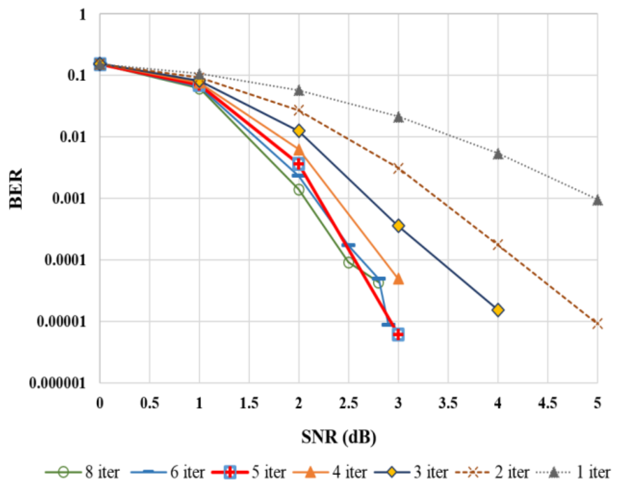


Fig. 3. BER performance of Layered Decoding QC-LDPC at different values of iteration number.

C. Low-Constraint Convolutional Code

Convolutional Code (CC) is used as FEC solution in many wireless standards [4]. Convolutional code is often characterized by code rate and constraint length *(n, k, K)*. The code rate is typical given as *n/k* where *n* is the input data, *k* is the output symbol and *K* is the constraint length (CL). We have conducted simulation in both AWGN and fading channel, as well as in hard and soft decision modes of convolutional code. Although in single FEC mode, high-constraint convolutional code shows better performance compared with low-constraint candidate.

However, we found that concatenating low-constraint (*K=3*) convolutional code (code rate 1/2) with TILD-LDPC (code rate 1/2) always gives better BER performance compared with high-constraint cases. Ioannis et al. introduced the relationship of constraint length and complexity of convolutional code [10]. He found that the complexity of convolutional code increases exponentially when the constraint length increases. Using low-constraint CL3 (CL = 3) convolutional code will reduce up to 1300 equivalent additions compared with high-constraint CL7 (CL = 7) [10]. For a low-complexity FEC solution, our proposed method has selected low-constraint convolutional code for "Inner" code.

D. Influence of Inner and Outer Coder/Decoder to Super Encoder/Decoder's Performance

We have simulated four scenarios to give conclusions about selecting FEC algorithm for Outer and Inner blocks.

- *Scenario 01*: Outer = TILD-LDPC matrix 324×648; Inner = BCC Encode/Viterbi Soft Decision Decoding.
- *Scenario 02*: Outer = BCC Encode/Viterbi Soft Decision Decoding; Inner = TILD-LDPC matrix 324×648.
- *Scenario 03*: Outer = TILD-LDPC matrix 324×648; Inner = BCC Encode/Viterbi Hard Decision Decoding.
- *Scenario 04*: Outer = TILD-LDPC matrix 324×648; Inner = 2 ×(TILD-LDPC matrix 324×648).

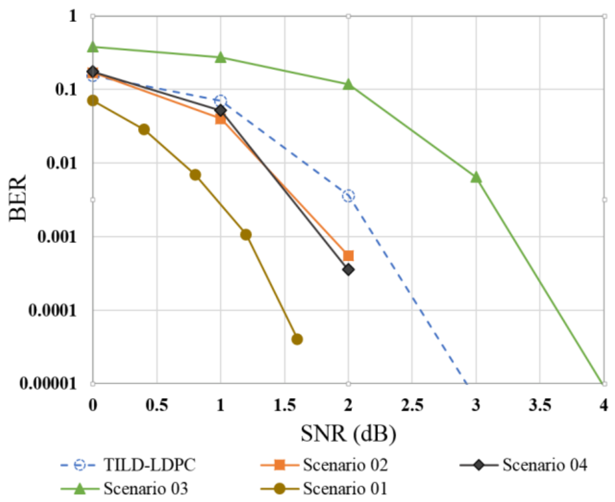
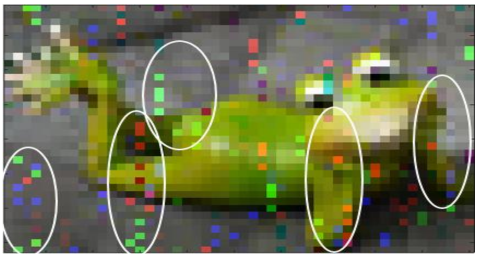


Fig. 4. Influence of Inner and Outer code to concatenated FEC performance.

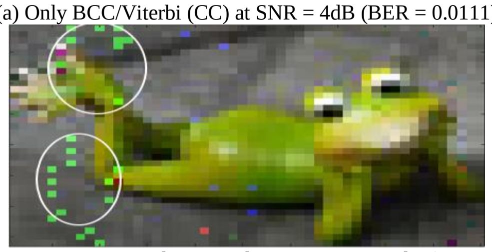
Fig. 4 shows BER simulation of four scenarios and TILD-LDPC at code rate ½ for reference. We see that scenario 01 (Outer = TILD-LDPC, Inner = BCC/Viterbi Soft Decision) shows the best BER performance. If we assume the name "*stronger code*" for TILD-LDPC and "*weaker code*" for BCC/Viterbi, we can conclude that serial concatenation of a "*stronger code*" with another "*stronger code*" does not always give a better BER performance than the concatenation of a "*stronger code*" with "*weaker code*" does (scenario 04 and scenario 01). Moreover, "*stronger code*" should be Outer and "*weaker code*" should be Inner (scenario 01 and scenario 02). Besides, concatenation of TILD-LDPC with Viterbi Decoder Hard Decision gives worse BER performance compared with only TILD-LDPC is implemented (scenario 03).

E. Free Burst-Error Solution with Internal Interleaver

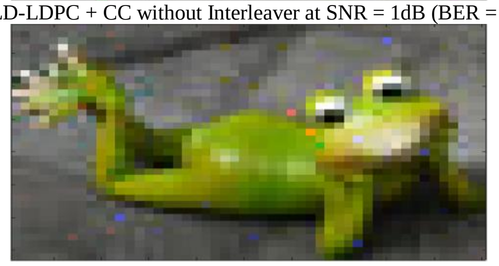
One of main drawbacks of convolutional code is burst errors exist in decoded data (Fig. 5a). We recognized burst errors by implementing image data together with random data as transmit data in MATLAB simulation model. Concatenating convolutional code with TILD-LDPC does not remove definitely burst-error (as shown in Fig. 5b). An internal interleaver is implemented in concatenation mode to provide a free burst-error FEC solution (Fig. 5c).



(a) Only BCC/Viterbi (CC) at SNR = 4dB (BER = 0.0111)



(b) TILD-LDPC + CC without Interleaver at SNR = 1dB (BER = 0.003)



(c) TILD-LDPC + CC with Interleaver at SNR = 1dB (BER = 0.0022)

Fig. 5. Received images at receiver in different test cases.

IV. Experimental Results

For evaluating error-correction performance of the proposed method, we have built a simulation model on MATLAB, which is shown in Fig. 6. Simulation parameters are also summarized in Table I. A reduced-complexity version of TILD-LDPC with 324×648 parity-check matrix is implemented and assigned as outer code. Low-constraint convolutional encoder/decoder are assigned at the position of inner code. Besides, BPSK is used for modulation block. Also, we have implemented two modes of transmit data: random data and image data. By using image data, burst errors can be recognized easily, and the effectivity of the internal interleaver could be found by eye. Fig. 7 shows BER performance of the proposed method compared with some references on all modes (Uncode, convolutional code, TILD-LDPC and concatenated mode). We see that BER performance of TILD-LDPC (code rate 1/2) is quite good compared with reference works. Whereas, error-correction performance of the soft and hard decision convolutional code are not good. However, due to low-complexity in hardware implementation of convolutional code, it can be selected in some cases as presented in Section III.A and III.C. Finally, concatenation mode of TILD-LDPC and convolutional code provides the best BER performance compared with the reference works [1], [2], [6], [7]. Besides achieving a very good error-correction performance, concatenation mode also introduce a free error-floor solution without burst errors. However, the proposed concatenation mode has low code-rate (1/4), it means that more redundant data will be attached to data frames at the transmitter side. In Section II, we gave out the theoretical points about importance of power-constraint in WSNs, compared with bandwidth-constraint. In a limited time, transmitting encoded data in concatenation mode reduces effective transmission and may cause some extra energy consumption. Nevertheless, achieving higher coding gain even in high noise area will help reduce transmitter's RF power, as well as increase transmit distance between sensor nodes.

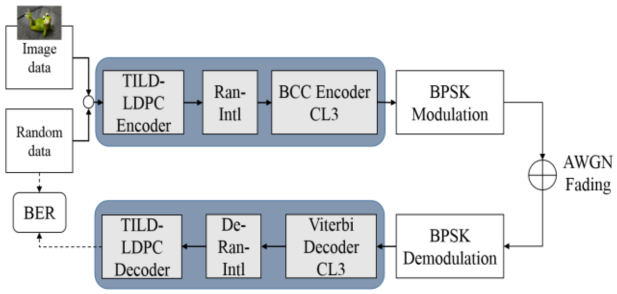


Fig. 6. Simulation model of the proposed method.

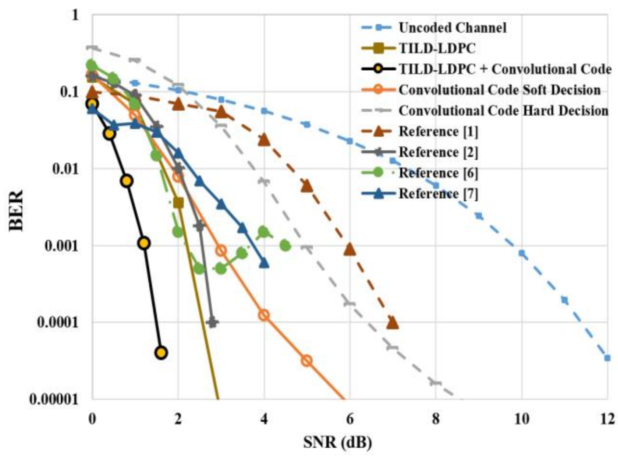


Fig. 7. BER performance of proposed method (concatenated TILD-TILD + Convolutional Code) compared with other related works.

TABLE I: SIMULATION PARAMETERS

Software	MATLAB 2015a
Channel	AWGN, Fading
Modulation	BPSK
TILD-LDPC	Matrix size 324×648, Layered Decoding, Offset Min-Sum, Iteration number = 5
Convolutional Code	Hard Decision, Soft Decision, Code rate 1/2, Constraint Length (3,4,5,7)
Packet size	324 bits
Number of packets	1000, 10000

Besides, we have conducted simulation with "SNR per bit" scale (EbN0) to evaluate coding gain and transmit-power efficiency of the proposed approach. Fig. 8 shows BER performance of the proposed modes in both AWGN (Fig. 8a) and Fading channel (Fig. 8b). Some typical convolutional code versions are also implemented for evaluation; these versions include convolutional code in low-constraint (CL3) and high-constraint (CL7), which use soft and hard decision as decoding method. In this paper, BER = 10^{-5} is selected as performance comparison limit for FEC algorithms and this limit is also used for coding gain evaluation. Fig. 8 also shows the effectivity of concatenating TILD-LDPC with low-constraint convolutional code (the area marked in hyphen circle). We found that although high-constraint convolutional code gives better performance in split-single mode compared with the low-constraint candidate; but the low-constraint convolutional code always show better performance when it is concatenated with TILD-LDPC. From this casual discovery, we propose using low-constraint (CL3) convolutional code for split-single mode, and concatenation mode with TILD-LDPC. In Section III.C, we have also demonstrated the complexity reduction of using low-constraint convolutional code compared with high-constraint convolutional code. Therefore, due to the low-complexity of low-constraint convolutional code, and high-performance of TILD-LDPC, our proposed method is expected to create a robust and compact error-correction solution for wireless sensor nodes.

Transmit-power reduction efficiency of the four proposed modes in AWGN channel is shown in Fig. 9. We have selected low-power sub-1Ghz RF front-end CC1100 (Fig. 9a) and 2.4Ghz low-power Zigbee transceiver CC2591 (Fig. 9b) to evaluate transmit power efficiency. Also, various output power settings which are in low-to-high dBm range, which represents for different transmit-power configurations of RF front-end devices. We have estimated power efficiency of the proposed method from achieved coding-gain results and (1). Besides, coding gain performance and transmit power gain of split-single and concatenation modes are summarized in Table II. The proposed solution provides four modes with different levels of:

- Error-correction performance: Coding gain results of 4 modes in AWGN channels are: 0 (M01), 5.5 (M02), 9.2 (M03), 10 (M04). In Fading channel, coding gain results are larger apart, 0 (M01), 27.4 (M02), 34.2 (M03), 37.8 (M04).
- Required transmit-power: Uncoded mode will requires the highest transmit power configuration for reliability transmission. In AWGN channel, transmit-power reduction of low-constraint convolutional code, TILD-LDPC and concatenated mode are 71.8%, 88%, 90% respectively. We did not evaluate transmit power gain of proposed modes in Fading channel due to the lack of theoretical foundations and related works.
- Scalability: Uncoded, split-single and concatenated modes bring out an integrated FEC solution which inherits effective FEC solutions of popular wireless standards such as Zigbee, Wi-Fi, WiMAX, Bluetooth etc. Complexity of each constitutive FEC block varies from low-complexity (low-constraint convolutional code) to higher complexity (TILD-LDPC) and highest complexity (serial concatenation mode).
- Code-rate: 1, ½, ¼; when code-rate gets smaller, more redundant data will be added to original data to make encoded data more robust, so that a higher transmit power gain can be achieved. Whereas, in case of code-rate equals '1', which is in uncoded mode (M01), this mode can be set up for sensor nodes to operate in low-noise environment, or near distance transmission, without redundant data in transmit data.

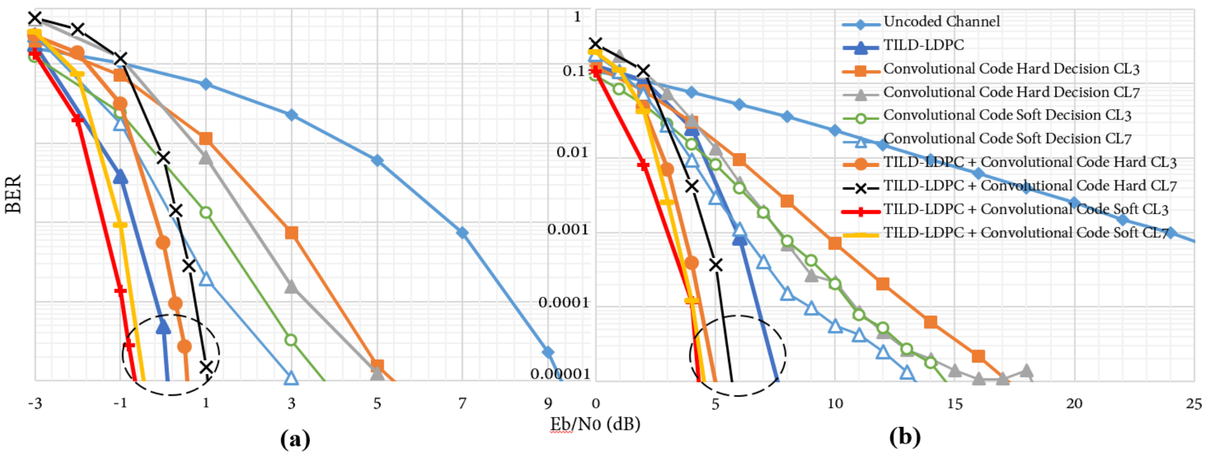


Fig. 8. BER performance of the proposed modes in: (a) AWGN; (b) fading channel.

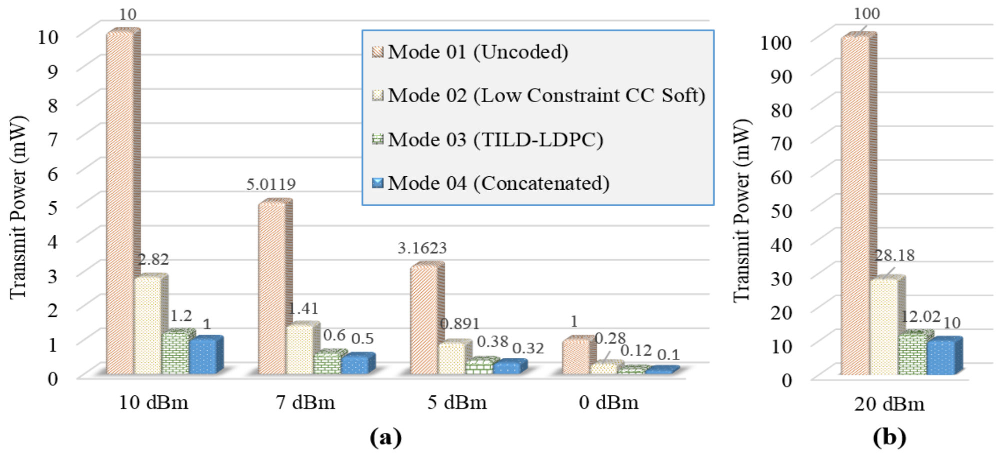


Fig. 9. Transmit-power-reduction efficiency of the proposed modes on TI's wireless sensor transceivers (AWGN channel): (a) CC1100; (b) CC2591.

TABLE II: CODING GAIN AND TRANSMIT POWER GAIN OF THE PROPOSED ERROR-CORRECTION MODES

Proposed algorithms for multi-mode FEC solution			Code rate	Coding Gain (dB)		Transmit power Gain (AWGN)
				AWGN Channel	Fading Channel	
SPLIT-SINGLE	Low-constraint Soft Decision Convolutional Code		½	5.5	27.4	3.55
	TILD-LDPC		½	9.2	34.2	8.32
CONCATENATED	Outer	Inner				
	TILD-LDPC	Low-constraint Soft Decision Convolutional Code	¼	10	37.8	10

Up till now, presented results of error-correction performance and transmit-power-gain has shown that the split-single and concatenation mode of low-constraint convolutional code and TILD-LDPC is a reduced-complexity high-performance scalable FEC solution. The proposed FEC solution could be flexible to adapt for different transmission scenarios in wireless sensor networks.

V. CONCLUSIONS

In this paper we have introduced a multi-mode error-correction solution which is based on split-concatenation of TILD-LDPC with low-constraint soft decision convolutional code. The proposed solution has: reduced-complexity, scalability, free burst-error, configurable error-correction performances, and four transmit-power-reduction options. Thus, the proposed approach could be adaptive for different transmission scenarios in WSNs applications. Moreover, good BER performance of concatenating reduced-complexity TILD-LDPC with low-complexity convolutional code (low-constraint) give a potentiality for designing low-complexity concatenated FEC encoders/ decoders.

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Duc Phuc Nguyen received the B. Sc. and M.Sc. degrees both from the University of Science, Ho Chi Minh City (HCMUS), Vietnam in 2012 and 2015. From 2012 to 2015, he was a teaching assistant and researcher at faculty of Electronics and Telecommunications (FETEL), HCMUS. Since 2015, he worked as Research Assistant at Computing Architecture laboratory and also a PhD student at Graduated School of Information Science, Nara Institute of Science and Technology (NAIST), Japan. His research interests include VLSI-based design for memory controllers, Error-Control Code and Digital Signal Processing algorithms. He is a student member of IEEE and IEICE.

Thi Hong Tran received the B.S. degree (2008) in Physics, and M.S. degree (2012) in Electronics and Telecommunication, from Ho Chi Minh City – University of Science (HCMUS), Vietnam; and Ph.D. degree (2014) in Computer Science and System Engineering from Kyushu Institute of Technology (KIT), Japan. She is currently an Assistant Professor at Nara Institute of Science and Technology (NAIST), Japan. Her research interests are MIMO-OFDM wireless LAN system, signal and image processing, wireless sensor network, etc. She is a regular member of IEEE and IEICE.

Yasuhiko Nakashima received the B.E., M.E. and Ph.D. degree in Computer Engineering from Kyoto University, Japan in 1986, 1988 and 1998 respectively. He was a computer architecture in the Computer and System Architecture Department, FUJITSU Limited from 1988 to 1999. From 1999 to 2005, he was an associate professor at the Graduated School of Economics, Kyoto University. Since 2006, he has been a professor at the Graduate School of Information Science, Nara Institute of Science and Technology. His research interests include processor architecture, emulation, CMOS circuit design, and evolutionary computation. He is a member of IEEE CS, ACM and IPSJ.