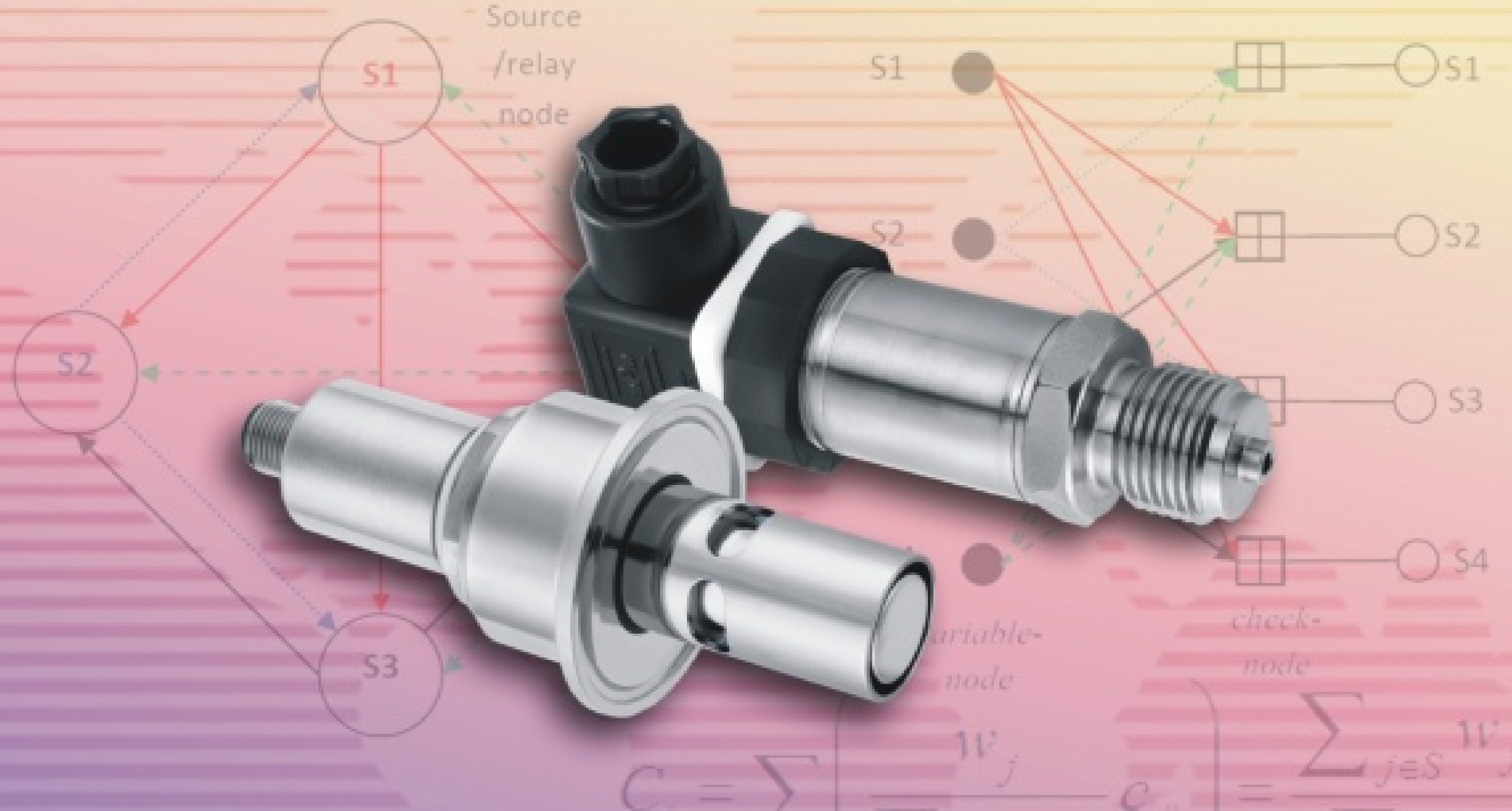
# SENSORS & TRANSDUCERS

ISSN 1726-5479

vol. 20
Special
4/13



## Sensors, Networks, Control Systems and Information Processing

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# Sensors & Transducers

## International Official Journal of the International Frequency Sensor Association (IFSA) Devoted to Research and Development of Sensors and Transducers

Volume 20, Special Issue, April 2013

**Editor-in-Chief**
Sergey Y. YURISH

IFSA Publishing: Barcelona • Toronto

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# Sensors & Transducers

**Volume 20, Special Issue, April 2013**

**www.sensorsportal.com**

**ISSN 2306-8515**
**e-ISSN 1726-5479**

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Sensors & Transducers Journal

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Volume 20
Special Issue
April 2013

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ISSN 1726-5479

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*Sensors & Transducers, Vol. 20, Special Issue, April 2013, pp. 12-20*

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# Code-Folding Scheme for Energy Efficient Cooperative Communications in Wireless Sensor Networks

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*Received: 1 February 2013 /Accepted: 17 April 2013 /Published: 30 April 2013*

**Abstract:** In order to provide high-efficiency monitoring for utilities consumption, a novel cooperative communication is investigated for Wireless Sensor Networks to overcome channel imperfections in an energy-efficient way. By matching dynamic network topologies with distributed graph network coding, a Code-Folding scheme is proposed to decrease the number of required cooperative terminals in ANCC. By converting original parallel bits transmission from a large number of nodes to serial packets transmission that relies on only a few nodes, The Code-Folding ANCC scheme can reform the cooperative scheme in an energy efficient way. Based on the Code-Folding ANCC scheme, Energy Efficient Cooperative Communications can achieve the same coding gain with a few sensor nodes, which can significantly improve transmission range, linkage reliability and energy efficiency. With experiments in an Energy Efficient Cooperative Communication testbed, the improvement of energy efficiency in the Energy Efficient Cooperative Communication network is verified. *Copyright © 2013 IFSA.*

**Keywords:** Wireless sensor networks, Energy efficient, Cooperative communication.

## 1. Introduction

As an emerging technology for distributed, low-cost, self-organized and unattended monitor-control operations, Wireless Sensor Networks (WSN) have attracted world-wide attention and discussion as one of the most important technologies [1]. A WSN enables connectivity and intelligence for sensor applications that will offer advanced monitoring, real-time feedback, automation, and control solutions in almost every field [2]. The rapidly evolving WSN technologies require additional application developments and advanced signal processing implementations in order to solve a range of critical problems, including decreasing utilities consumption, saving costs and maximizing energy efficiency. For the low-power wireless sensor nodes, the channel capacity of communication links are extremely unreliable due to the significant impact of attenuation and fading in wireless channels. However, high power transmission will cause huge energy wastage and unacceptable co-channel interference.

Energy Efficient Cooperative Communication is attractive for collaborative and distributed signal processing, which can provide spatial diversity and significant improvements in energy efficiency, transmission range and reliability for WSN. Both spatial diversity gains from collaborative signal processing and coding gains from network coding are included in EECC networks [3]. Adaptive Network Coded Cooperation (ANCC) is valuable for distributed coding design based on network coding schemes to achieve energy-efficient and reliable transmission in Wireless Sensor Network [4, 5]. By matching graphic network coding with instantaneous network topology of Wireless Sensor Networks, ANCC can describe coded cooperative relay communications for EECC design to achieve a significant coding gain from spatial diversity communication [6, 7]. However, in order to obtain a significant coding gain at receivers, over 1000 sensor nodes need be involved to implement ANCC scheme in WSN [8-10]. Because of energy consumption of collaborative and distributed processing of sensor nodes, it is important to improve energy efficiency for so many of cooperative sensor nodes in ANCC scheme.

In this paper, a Code-Folding (CF) scheme is proposed to reduce the number of required nodes of ANCC scheme for Energy Efficient Cooperative Communication (EECC) networks. The CF scheme converts the LDGM encoding format from originally parallel bits transmission using a large number of nodes to serial packets transmission. In this way, an EECC system can be implemented by only a few cooperative sensor nodes based on the CF-ANCC scheme. So the significant coding gain can be achieved by using few required cooperative terminals, which can decrease the difficulty of EECC. In addition, under the CF-ANCC scheme, the wireless terminals in EECC can transmit the quality signals to the destination by using lower transmission energy. Limited by the capability of the currently used ZigBee transceivers, hard-decision is only used. The bit-flipping (BF) decoding algorithm is used to recover the encoded messages in hard-decision.

The rest of the paper is organized as follows: Section 2 presents the system model of the EECC network with ANCC scheme. In Section 3, the Code-Folding scheme is proposed to reduce the number of required cooperative nodes in the ANCC scheme. Experimental tests and performances analysis are discussed with BER performances in Section 4. Section 5 presents conclusions and future works.

## 2. System Model

The wireless sensor networks are normally deployed with a large number of terminals, where wireless terminals are closed to other neighbor nodes in a crowded network. Each sensor node transmits data to a common destination (coordinator). In a star-topology EECC networks, all sensor nodes are located close to each other and the coordinator is at a distance from the sensor nodes. Each wireless terminal transmits its own message and helps to deliver neighbors' messages by advanced user cooperation. It is assumed that only the coordinator-to-terminal links suffer from noise and fading and terminal-to-terminal channels are lossless with error correction capability.

In the EECC system, ANCC scheme combines the spatial diversity with network coding by using collaborative and distributed signal processing. As shown in Fig. 1, the process-forward processing of the ANCC scheme can be modeled as a two-user multiple access relay channel comprising of two source nodes, one relay node and one destination node.

Shown in Fig. 1(a), Source node S1 sends message $a$ and source node S2 sends message $b$ independently to a common destination $D_{ST}$ through a relay node R. For cooperative store-and-forward approach, the relay simply repeats the messages a and b received from two source nodes and the received messages from sources and relays are given by [a,b,a,b]. To improve performances by network coding, relay performs linear combination for each a and b, denoted as $a \oplus b$, and forward them to the destination $D_{ST}$. In Fig. 1 (b), two signals received at the destination $D_{ST}$ form a linear code $[a, b, a \oplus b]$. It is easy to find that the destination $D_{ST}$ can recover the S1's and S2's information by retrieving any two of three terminals' information.

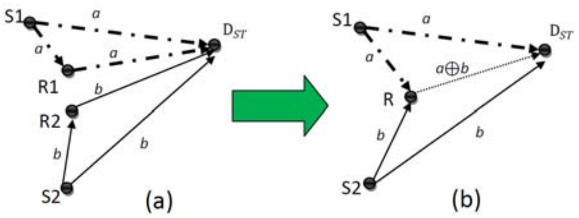

**Fig. 1.** Spatial diversity communication models.

Initially, each source node broadcasts its symbols/packets in Broadcast (BDC) phase on orthogonal channels [11]. All relay nodes decode the received signals and the successfully decoded packets are stored in the retrieve sets. Each relay node randomly selects a fixed number of symbols/packets from its retrieval set and performs a check-sum over the binary field of GF(2), to yield a single parity check bit. In the Cooperation (COOP) phase, each relay node transmits its check-sum result to the destination. After each round of BDC and COOP phases, the destination can form a Low Density Generator Matrix (LDGM) network code with the received broadcast information and encoded information.

### 2.1. Code-on-Graph of Network Topology

Based on network coding, an instantaneous network topology can be transformed to a bipartite code graph. In the network graph shown in Fig. 2 (a), the directed edge indicates a *virtual connection*. A source node is *virtually connected* to a relay node, if the source message participates in the check equation of this relay. As shown in Fig. 2 (b), the bipartite graph can be constructed as follows.

1) Connect a *variable-node* X and a *check-node* Y in code graph of Fig. 2 (b), when there is a *virtual connection* between a source node X and a relay node Y in the network graph of Fig. 2 (a).

2) Link each *check-node* with its corresponding *variable-node* in the bipartite graph of Fig. 2 (b). The *variable-node* indicates which user relays the check sum result to the destination.

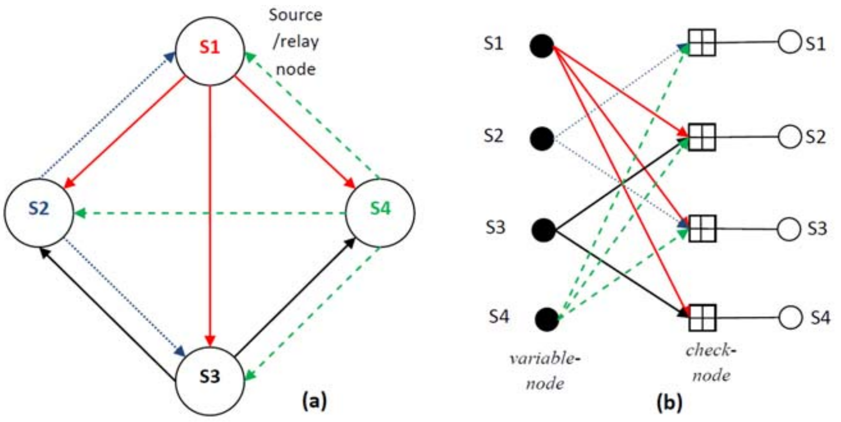

**Fig. 2.** Transforming a network graph to a bipartite code graph.

The bipartite graph represents an LDGM code, where variable-node are the nodes corresponding to the systematic bits, and check-node represent the parity-check bits generated from LDGM encoding [12]. According to Fig. 2 (b), a (8,4) LDGM code is applicable to match the instantaneous network topology at the destination. The parity check matrix H and general matrix G of the (8,4) LDGM code representing the bipartite graph code in Fig. 2 (b) is achieved by

$$\mathbf{H}=\left(\underbrace{\begin{matrix}0&1&0&1\\1&0&1&1\\1&1&0&1\\1&0&1&0\end{matrix}}_{\text{Sparse Matrix}}\middle|\underbrace{\begin{matrix}1&&&\\&1&&\\&&1&\\&&&1\end{matrix}}_{\text{Identity Matrix}}\right), \tag{1}$$

$$\mathbf{G}=\left(\underbrace{\begin{matrix}1&&&\\&1&&\\&&1&\\&&&1\end{matrix}}_{\text{Identity Matrix}}\middle|\underbrace{\begin{matrix}0&1&1&1\\1&0&1&0\\0&1&0&1\\1&1&1&0\end{matrix}}_{\text{Sparse Matrix}}\right), \tag{2}$$

## 2.2. Adaptive LDGM Network Codes

As shown in Fig. 3, the EECC of a large homogeneous WSN can be modeled as k terminals communicating to one common destination. Each source node transmits its own message and also helps other source nodes to forward the message to the destination.

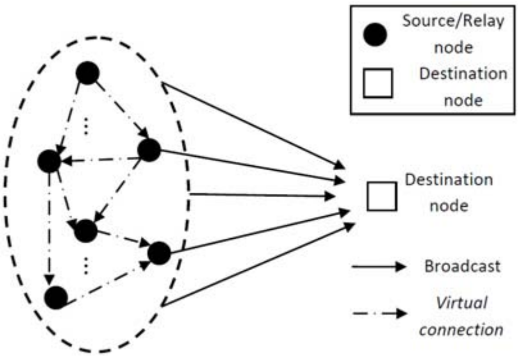

**Fig. 3.** ANCC network graph.

The ANCC bipartite code graph in Fig. 4 can be used for each BDC phase and COOP phase. In the BDC phase, each node broadcasts its own information bit/packet over source-destination channel on its assigned time-slot. In the COOP phase, each node randomly selects a small and constant number (degree D) of bits/packets successfully received from other sources and transmits their binary check sum to the destination over a relay-destination channel.

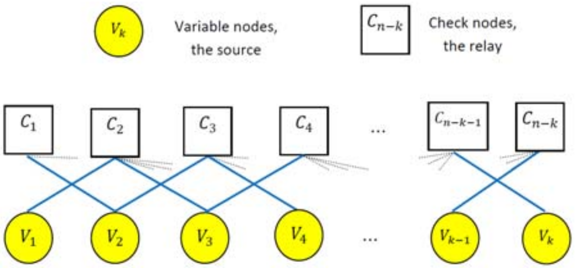

**Fig. 4.** ANCC bipartite code graph.

As a result of each round of BDC and COOP phases transmission, a randomly generated ($n$, $k$) irregular LDGM ensemble is formed in the destination, with code rate R=½, degree D and code length $n=2k$ in the generator matrix G. The G matrix generation follows the code graph structure in Fig. 4. Each round of BDC and COOP phase is called as ($n$, $k$) ANCC-LDGM super-transmission frame. The general matrix G is given in Fig. 5.

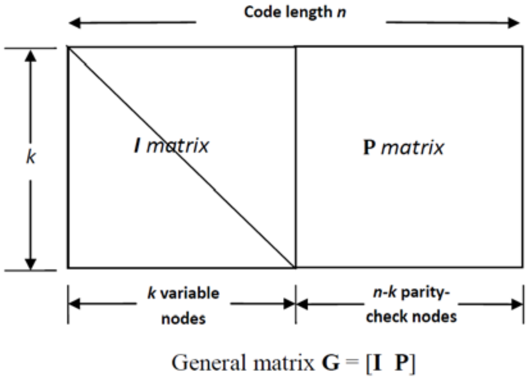

**Fig. 5.** General Matrix **G** in ANCC scheme.

Its parity check matrix H consists of a sparse matrix parity-check part $P^T$ and identity matrix part I, specified by H=[$P^T$ I]. $P^T$ is the transpose of the matrix P (in G matrix), since G×H=0. H matrix is shown in Fig. 6.

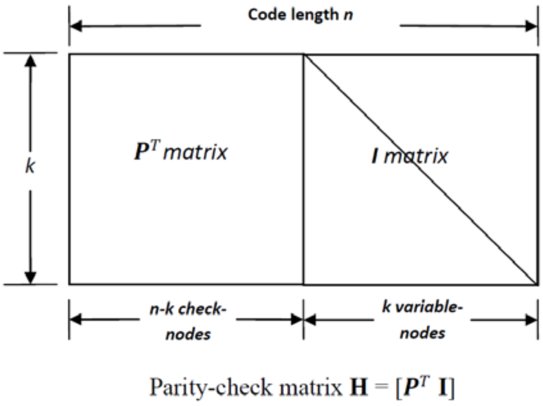

**Fig. 6.** Parity-check matrix **H** for ($n$,$k$) LDGM code.

As a ($n$,$k$) linear block code, LDGM code is spanned by k linearly independent vectors $g_0,g_1,\ldots,g_{k-1}$. It contains an $k\times k$ identity matrix **I** and a parity check matrix **P**. Corresponding vectors generated by **I** & **P** over GF(2) are $\boldsymbol{I}_0,\boldsymbol{I}_1,\ldots,\boldsymbol{I}_i,\ldots,\boldsymbol{I}_{k-1}$ and $\boldsymbol{P}_0,\boldsymbol{P}_1,\ldots,\boldsymbol{P}_j,\ldots,\boldsymbol{P}_{n-k-1}$, $i,j\in[0,k)$. $i$ is the row index of **P** and $j$ is the column index of **P**. The LDGM code in ANCC is completely specified by a $k\times n$ generator matrix **G** of the following forms.

$$\mathbf{G}=\begin{bmatrix} g_0\\ g_1\\ g_2\\ \vdots\\ g_i\\ \vdots\\ g_{k-1}\end{bmatrix}=[\mathbf{I}\ \ \mathbf{P}]$$
$$=[\boldsymbol{I}_0\ \ \boldsymbol{I}_1\ \ \boldsymbol{I}_2\ \cdots\ \boldsymbol{I}_i\ \cdots\ \boldsymbol{I}_{k-1}\ \ \boldsymbol{p}_0\ \ \boldsymbol{p}_1\ \ \boldsymbol{p}_2\ \cdots\ \boldsymbol{p}_j\ \cdots\ \boldsymbol{p}_{n-k-1}] \tag{3}$$

$$\mathbf{G}=\left[\begin{array}{ccccccccccccc} \multicolumn{7}{c}{\overbrace{\hspace{5cm}}^{(k\times k)\text{identity matrix(BDC phase)}}} & \multicolumn{6}{c}{\overbrace{\hspace{7cm}}^{(k\times(n-k))\text{P matrix(COOP phase)}}}\\ 1&0&0&\cdots&0&0&0&p_{00}&p_{01}&\cdots&p_{0,j}&\cdots&p_{0,n-k-1}\\ 0&1&0&\cdots&0&0&0&p_{10}&p_{11}&\cdots&p_{1,j}&\cdots&p_{1,n-k-1}\\ 0&0&1&\cdots&0&0&0&p_{20}&p_{21}&\cdots&p_{2,j}&\cdots&p_{2,n-k-1}\\ &\vdots&&&&\vdots&&\vdots&\vdots&&\vdots&&\vdots\\ &\vdots&&\ddots&&\vdots&&p_{i,1}&p_{i,2}&\cdots&p_{i,j}&\cdots&p_{i,n-k-1}\\ 0&0&0&\cdots&0&1&0&\vdots&\vdots&&\vdots&&\vdots\\ 0&0&0&\cdots&0&0&1&p_{k-1,0}&p_{k-1,1}&\cdots&p_{k-1,j}&\cdots&p_{k-1,n-k-1} \end{array}\right] \tag{4}$$

It is known that LDGM code, as the special case of LDPC code, is long code. The systems that adopt ANCC scheme require a large number of nodes in order to gain a significant coding gain from LDGM decoding. It is impractical to have so many wireless nodes for implementation experiments.

## 3. Code-Folding Scheme for ANCC

The implementation of an ANCC normally requires a very large number of wireless cooperative nodes ($k$). In order to implement an ANCC in a small-size wireless sensor networks (WSNs) scenario, the Code-Folding (CF) scheme is proposed to implement an (*n*,*k*) ANCC-LDGM super-transmission frame by using only a small number of cooperative nodes.

In the CF, each wireless terminal transmits an *L*-bit data sequence in each round of BDC and COOP phases, rather than transmitting a single bit. An *L*-bit sequence transmitted by each wireless terminal in the network graph is referred to as a *letter*, and a bit in each *letter* is referred to as a *letter-bit*. As shown in Fig. 7, a (6,12) ANCC-LDGM code, generated by a network with two source nodes $T_1$ and $T_2$ is included. Each network terminal transmits a 3-bit *letter* (*L*=3) in both BDC and COOP phases. Let $S_i(j)$ represent the *i*-th information bit, transmitted by $T_j$-th terminal, *j*=1, 2, and $R_i(j)$ represents the *i*-th parity bit, generated by $T_j$-th terminal.

In the initial BDC phase, each network terminal broadcasts its own source letter, composed of 3 *letter-bits* $S_1(j)$, $S_2(j)$ and $S_3(j)$, *j*=1,2, to other network terminal and also to the destination. Each network terminal randomly selects a fixed number of *letter-bits* from all the source letters. For example, in Fig. 7, terminal $T_1$ selects the variable nodes $S_2(1)$ and $S_1(2)$ and performs XOR linear combination of these selected bits to generate the check-sum $R_1(1)$ and forwards it to destination. By knowing the bit-map of each check-sum equations and converting all CF bit-map into original ANCC G matrix, the destination can successfully decode the codeword transmitted from $T_1$ and $T_2$.

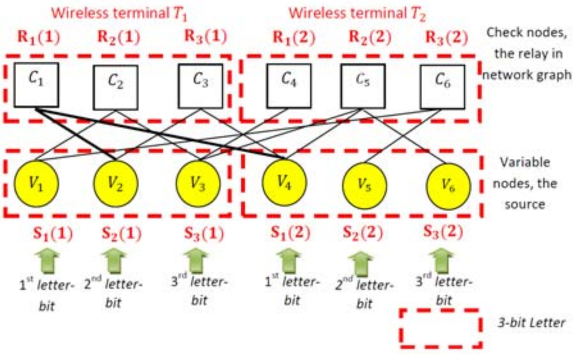

**Fig. 7.** Transforming an ANCC bipartite code graph to a CF bipartite code graph.

The number of terminals required to form an (*n*,*k*) ANCC is given by $k' = k / L$ , where *k* is divisible by *L*. If *L* is large, the number of terminals $k'$ is very small, which enables practical implementation of an ANCC. Transforming an ANCC bipartite code graph to a CF bipartite code graph is shown in Fig. 8.

However, the implementations of CF-ANCC scheme in distributed WSNs require a de-centralized construction of the code ensemble. So the CF scheme needs to employ a new index system for the generator matrix G of ANCC-LDGM code. The proposed CF scheme index structure is shown in Fig. 9.

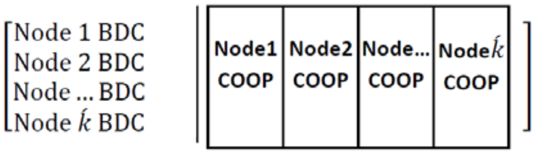

**Fig. 8.** The section block structure of the resulting **G** matrix in CF scheme.

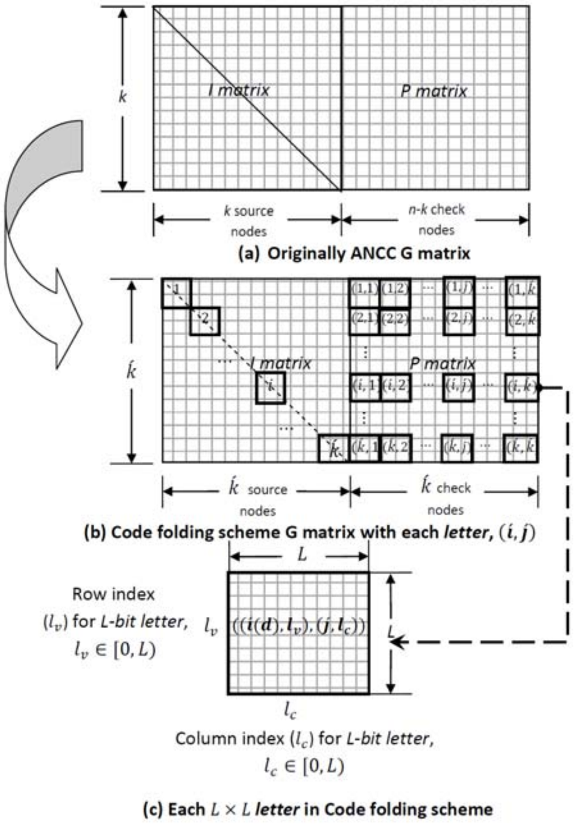

**Fig. 9.** Code Folding scheme index structure.

In the CF scheme shown in Fig. 9(b) and Fig. 9(c), a new index vector, $P'_{(I(d),l_v),(J,l_c)}$ has been proposed in order to form the P matrix. $P'_{(I(d),l_v),(J,l_c)}$ is the element in **P** with employing a new coordinate, $l_c$ and $l_v$. The column index of **P** is $(J, l_c)$, and the row index of **P** is $(I(d), l_v)$. $J$ is relay node in CF scheme, $l_c$ is the letter-bit index in each column of **P** with $l_c \in [0, L)$. $(J, l_c)$ represents $J$-th relay node's letter-bit $l_c$. $(I(d), l_v)$ is the set of randomly selected bits from $I(d)$-th node's $l_v$-th letter-bit with $l_v \in [0, L)$.

After each round of the BDC and COOP phase, every node transmits its bit-map of the distributed check-sum equations in the CF scheme to the destination, and the destination transfers these distributed CF bit-maps into the original ANCC format, so that the destination knows how the code graph is formed and can correspondingly decode the messages. The transfer equations from the ANCC to the CF scheme are listed below:

$$J = \lfloor j / L \rfloor, \tag{5}$$

$$l_C = j \ mod \ L, \tag{6}$$

$$I(d) = \left\lfloor (i_j(d) / L) \right\rfloor, \ \ d \in [0, D), \tag{7}$$

$$l_V = i_j(d) - L \times I(d), \tag{8}$$

In the CF-ANCC based EECC system, LDGM code is used for encoding and bit flipping algorithm is used for decoding. The system encoding model can be expressed by using matrix equation

$$\mathbf{c} = \mathbf{uG}, \tag{9}$$

where **c** is the encoded codeword and the vector **u** is the message bits. For a code with *k*-length message bits and *n*-length codeword in GF(2), **G** is a *k*×*n* binary matrix as **G** = [**I P**]. The degrees D in each column of **P** are chosen as 5 and 6. Based on the hard-decision reception [13], the Bit Error Rate (BER) performances for EECC system based on CF-ANCC and BF decoding in AWGN channel are shown in Fig. 10.

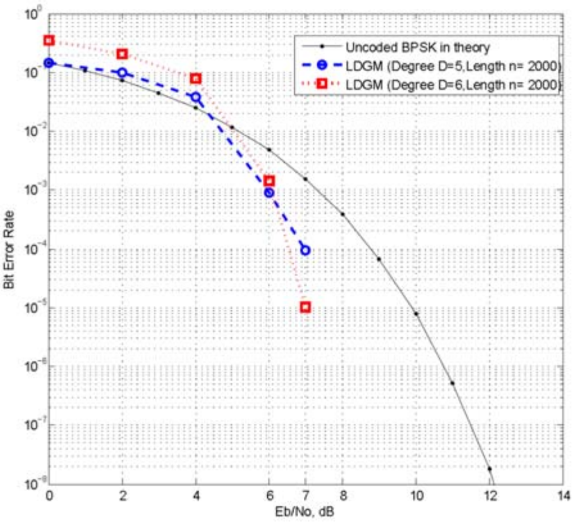

**Fig. 10.** BER performances for EECC with degree D = 5 & 6, code length n =2000 LDGM code.

## 4. Experimental Tests and Performances Analysis

Energy efficient cooperative communication (EECC) benefits from both joint network coding and leveraging the broadcast nature of the wireless sensor networks, which significantly enhances energy efficiency, performance and reliability of transmission. Although there is much literature in this area of research, it is essential to practically implement the EECC system in hardware and prove the concepts in testing experiments.

### 4.1. Experimental Testbed of EECC System

Based on available commercial ZigBee wireless sensor nodes, an EECC testbed is built in an office environment as shown in Fig. 11. The goal is to illustrate the effects in practice of EECC network on the BER performance of the indoor environments. The improvement in energy efficiency in the EECC system can be evaluated after comparing it with the performance of the original ZigBee transmission.

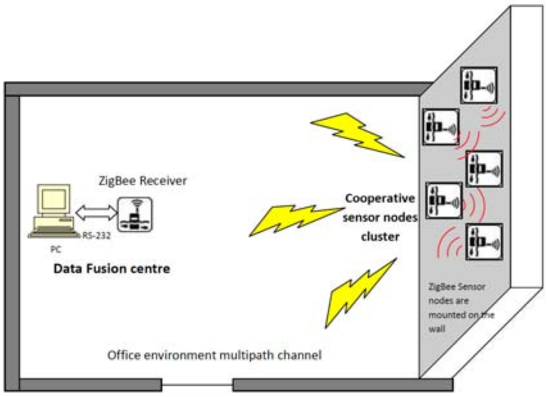

**Fig. 11.** Experimental network model of EECC system.

As a many-to-one communication model, the EECC system is composed of cooperative sensor nodes cluster as CF-ANCC message transmitter and remote Data Fusion Centre (DFC) as destination. The cooperative sensor cluster and DFC are described in the following.

The cooperative sensor nodes cluster is formed by a number of close and power limited ZigBee sensor nodes. They act as both source and relay nodes in order to form an adaptive LDGM encoded cooperation under the CF-ANCC scheme. In each round of coded cooperation, there are three steps to generate the CF-ANCC message for every cooperative node:

1) Initially, every sensor node joins the EECC network via the coordination of the DFC, so that all nodes can know the basic information of the EECC network, such as network size, neighbour nodes' addresses and quality links with other nodes.
2) The broadcast (BDC) phase of EECC allows every node to broadcast their data and hear others' transmissions in different time slots.
3) In the COOP phase, each node randomly picks up a fixed number of other nodes' information retrieved in the BDC phase, and performs XOR operations on the selected information. These check-sum results are kept in the nodes' accumulators and are transmitted to the DFC in the COOP phase. Thereby the DFC can jointly decode all messages from the EECC network.

The DFC is composed of a ZigBee coordinator and a PC. The PC is programmed to provide a graphical user interface (GUI) and jointed network code decoder. The ZigBee coordinator is connected to the PC via the RS-232 serial communication interface carrying the received message from each transmitter in the cooperative sensors cluster. The GUI and decoder software are programmed in PC in order to obtain the BER performance. The procedures for this include:

1) The DFC detects the sensor nodes and invites them to join the EECC network.
2) The DFC coordinates each BDC and COOP phase under the CF-ANCC scheme.
3) The PC program in DFC forms a LDGM code after combining all nodes' information in CF-ANCC format. The results are stored by the PC in separate TXT files.
4) Digital signal processing is performed on PC to decode the transmitted message saved in each codeword file. Therefore, the BER results of EECC are calculated by calculating the decoded results.

## 4.2. Measurements and Performances Analysis

The system BER performance was evaluated by comparing the proposed EECC network and uncoded ZigBee network though the developed platform. By attenuating the signal at the transmitters of the cooperative sensor cluster, the measured results of BER were efficiently obtained. The experiment parameters are listed below:

1) There were five cooperative nodes which performed as both source and relay nodes in the cooperative sensor nodes cluster.
2) The transmission power was controlled in the set of (-34.9 dBm, -32.8 dBm, -31.2 dBm, -30 dBm, -24.9 dBm, -22.8 dBm)
3) Each BER measurement point in different transmission power contains 15000 packets. Each packet was made of 118 bytes. The total measured data was over 14 million bits.
4) For the CF scheme parameter set-up, the value of letter-bit was set to 236 for each data packet.
5) The CF-ANCC scheme generated (1180, 2360) LDGM code in the experiment, where the each column degree D was fixed to 6.

Fig. 12 shows the measured BER results of the coded EECC network compared with the performance of traditional uncoded ZigBee transmission.

In Fig. 12, each BER result in the curves is measured based on different transmission power settings of cooperative nodes. Because unpredictable effects from channel impairments, co-channel interference or even from local electromagnetic interference (EMI) can occur throughout the progress of the experiment, all measured BER results have unavoidable tolerances. As a result, the BER curves are not ideally smooth, as shown in Fig. 12. But considering the measured data sequences are as large as 14 million binary symbols, the tolerances in the measured results are still acceptable.

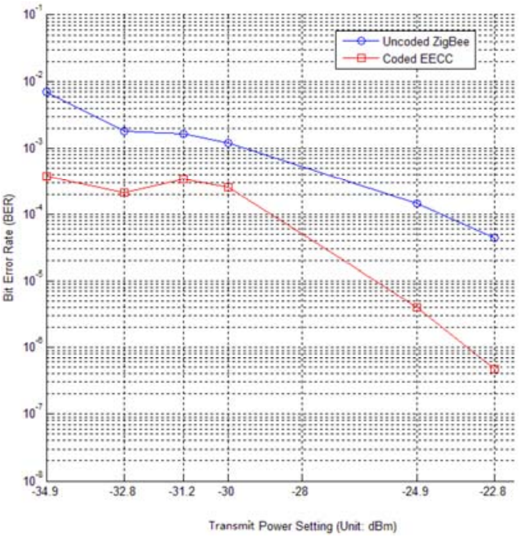

**Fig. 12.** BER performances of the proposed EECC network and uncoded ZigBee network.

As a way of proving performance improvements in an exact way, consideration was given to measuring BER performance based on the signal-to-noise (SNR) ratio at receiver side. However, considering the Radio Signal Strength Indicator (RSSI) measured from the transceiver internal circuit does not always exactly represent the SNR at receiver, especially in Multi-path fading channel, measuring the energy per bit over noise density ratio ($E_b/N_0$) is necessary for describing the actual signal quality at receiver. According to the theoretical indoor wireless channels, the measured BER performances of the experimental office environments are shown in Fig. 13.

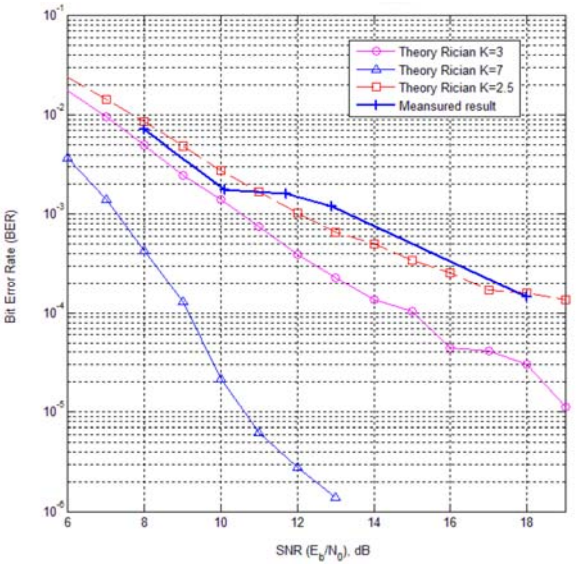

**Fig. 13.** Characteristics of indoor wireless channels.

By this means, the receiver's SNR for each measured point in the $E_b/N_0$ format ratio can be obtained. Then, the measured BER performance for the proposed EECC network and uncoded ZigBee network can be redrawn by using each measured point of SNR radio. The measured BER performance from EECC network is shown in Fig. 14. The measured result shows a maximum 8.9 dB gain in the EECC network over traditional ZigBee transmission.

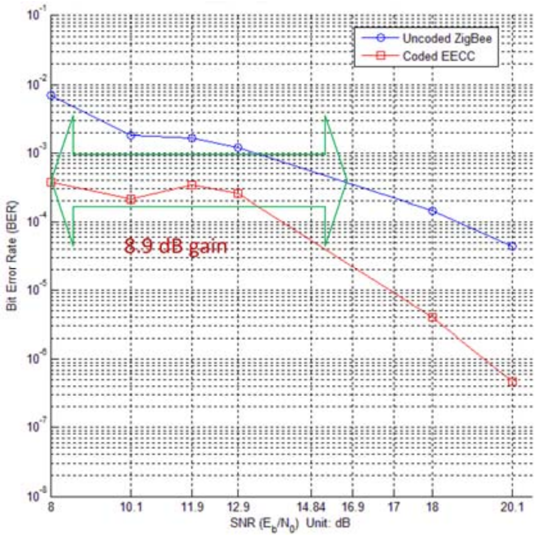

**Fig. 14.** Measured BER performances with experimental testbed environments.

## 5. Conclusion

In this paper, comprehensive and effective solutions from the applications developments down to physical layers coded cooperation implementations are investigated to provide high-efficiency monitoring for utilities consumption, dynamic optimization of consumption management and intelligent home automation for enhanced appliance control. In order to overcome channel imperfections in an energy-efficient way, the Code-Folding scheme in terms of decreasing the number for network coded cooperation of required cooperative terminals in ANCC scheme. From the measured results of EECC testbed, a spatial diversity gain as great as 8.9 dB on BER performance was obtained. Therefore, both theoretical and experimental results show that the EECC network improves energy efficiency when compared with original ZigBee transmission. Therefore, the proposed CF-ANCC scheme of EECC networks can improve system energy efficiency and reliability in common wireless sensor networks.

## Acknowledgements

Supported by National Nature Science Foundation of China (No. 61101125).

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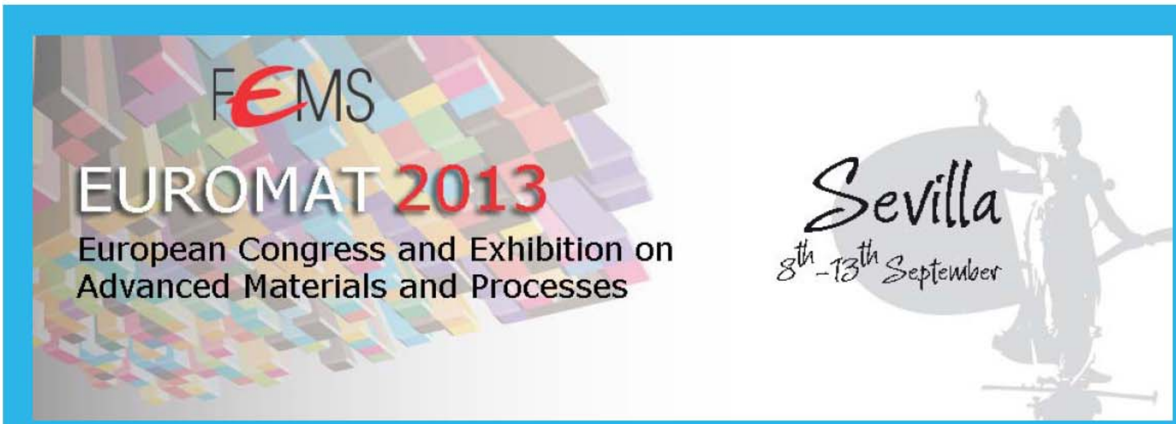
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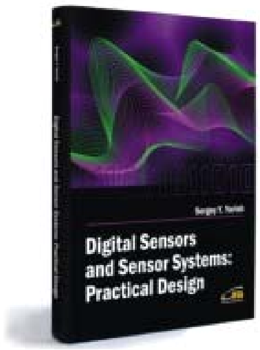

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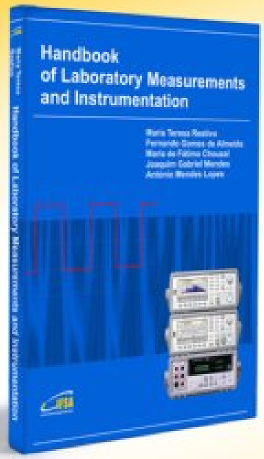

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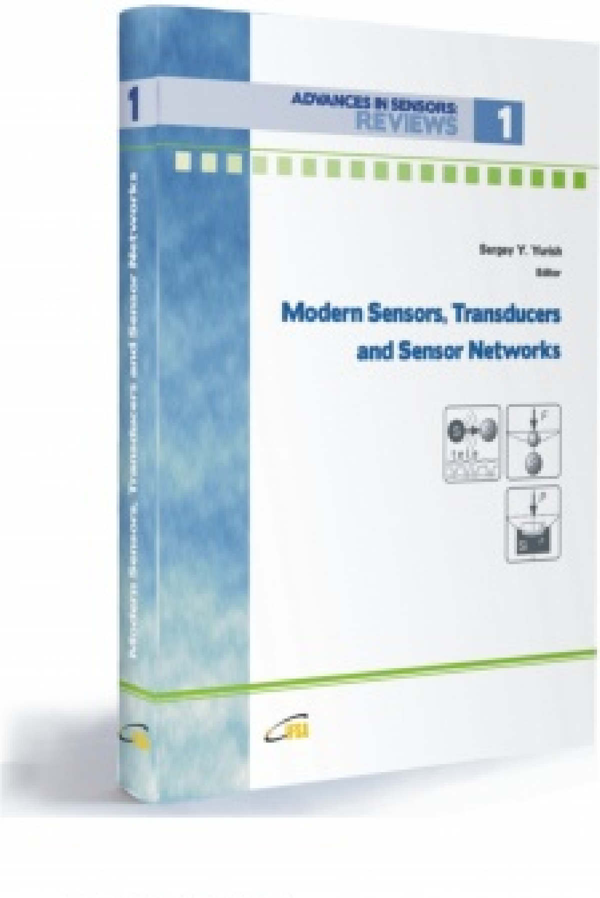
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