

## Research Letter

# Design LDPC Codes without Cycles of Length 4 and 6

Jun Fan,<sup>1</sup> Yang Xiao,<sup>2</sup> and Kiseon Kim<sup>3</sup>

<sup>1</sup>Office of Academic Affairs, Central University for Nationalities, Beijing 100081, China

<sup>2</sup>Institute of Information Science, Beijing Jiaotong University, Beijing 100044, China

<sup>3</sup>Department of Information and Communications, Gwangju Institute of Science and Technology, Gwangju 500712, South Korea

Correspondence should be addressed to Yang Xiao, yxiao@bjtu.edu.cn

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We present an approach for constructing LDPC codes without cycles of length 4 and 6. Firstly, we design 3 submatrices with different shifting functions given by the proposed schemes, then combine them into the matrix specified by the proposed approach, and, finally, expand the matrix into a desired parity-check matrix using identity matrices and cyclic shift matrices of the identity matrices. The simulation result in AWGN channel verifies that the BER of the proposed code is close to those of Mackay's random codes and Tanner's QC codes, and the good BER performance of the proposed can remain at high code rates.

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## 1. Introduction

LDPC codes can be described by a bipartite graph called Tanner graph [1], and the girth of a Tanner graph is the length of the shortest cycle in the graph. Girths in the Tanner graphs of LDPC codes prevent the sum-product algorithm from converging [2–10]. Further, cycles, especially short cycles, degrade the performance of LDPC decoders, because they affect the independence of the extrinsic information exchanged in the iterative decoding [2, 3]. Hence, LDPC codes with large girth are desired. Most methods for designing LDPC codes are based on random construction techniques, the lack of structure implied by this randomness presents serious disadvantages in terms of storing and accessing a large parity-check matrix, encoding data, and analyzing code performance (e.g., determining a code's distance properties). Recent research results [4–10] about LDPC codes with large girths show that there are many possible ways to construct the LDPC codes with large girths. However, some of the code constructions [4–10] are not satisfied for application due to the complicated constraints for the structures of parity-check matrices. To solve the problem, this letter provides a different construction of LDPC codes with large girth. The column weight of our codes is 3 and the row weight is  $v$  ( $v > 3$ ). The BER performance of the proposed codes is near to those of Mackay's random codes and Tanner's QC codes.

This letter is structured as follows. In Section 2, we analyze the figures of 4-cycles and 6-cycles in the parity-check matrix.

Section 3 presents the design algorithm of the parity-check matrix. Section 4 provides three lemmas show that the proposed codes do not contain 4-cycles and 6-cycles. Section 5 evaluates the BER performance of the proposed codes for AWGN channels via computer simulations. Finally, In Section 6 we make some conclusions.

## 2. Definitions of the Cycles

An  $(n, j, k)$  LDPC code has the parity-check matrix  $H$  of  $n$  columns, where  $H$  has  $j$  ones in each column,  $k$  ones in each row, and zeros elsewhere, then the  $(n, j, k)$  parity-check matrix has  $m = nj/k$  rows [1, 2]. A bipartite graph with  $m$  check nodes and  $n-m$  bit nodes can be created with the edges between the bit and check nodes if there are corresponding 1s in the parity-check matrix  $H$ . Such a graph is frequently called a Tanner graph [1, 11]. A cycle in a Tanner graph refers to a finite set of connected edges, the edge starts and ends at the same node, and it satisfies the condition that no node (except the initial and final node) appears more than once [4–10, 12]. The length of a cycle is simply the number of edges of the cycle.

A cycle also can be shown in a tree. Figure 1 shows a 4-cycle in a tree, and Figure 2 shows a 6-cycle in a tree. Figures 1

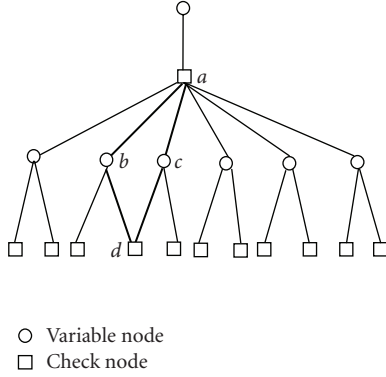


FIGURE 1: A 4-cycle in tree.

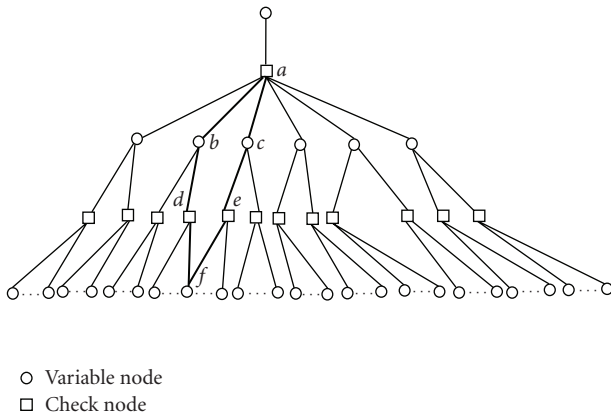


FIGURE 2: A 6-cycle in tree.

and 2 are not general descriptions for a 4-cycle and 6-cycle in a tree. It is also possible that a 4-cycle or a 6-cycle starts from a variable (bit) node, similar to the trees in Figures 1 and 2. In a tree, check nodes represent rows in parity-check matrix, and variable (bit) nodes represent columns. We try to design a parity-check matrix without 4-cycles and 6-cycles.

## 2.1. Figures of 4-Cycles in Parity-Check Matrix

In Figure 1, two 1s (we mark them as  $m_1$  and  $m_2$ ) in row  $a$  belong to column  $b$  and  $c$ , respectively, two 1s (we mark them as  $m_3$  and  $m_4$ ) in row  $d$  belong to column  $b$  and  $c$ , respectively, so the figure of the 4-cycle in the parity-check matrix as shown in Figure 3. If there is no figure as shown in Figure 3 in parity-check matrix, there is no 4-cycle in the LDPC code. We denote 4-cycles as  $G_4(m_1, m_2, m_3, m_4)$ .

## 2.2. Figures of 6-Cycles in Parity-Check Matrix

Figure 4 shows that  $m_1$  and  $m_2$  in row  $a$  belong to column  $b$  and  $c$ , respectively,  $m_3$  in column  $b$  belongs to row  $d$ ,  $m_4$  in column  $c$  belongs to row  $e$ ,  $m_5$  in row  $d$  and  $m_6$  in row  $e$  belong to column  $f$ , where  $m_1, m_2, m_3, m_4, m_5, m_6$  represent

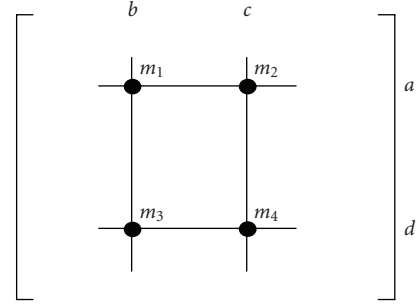


FIGURE 3: A 4-cycle in a parity-check matrix.

six 1s in 6-cycle, as shown in Figure 4. We denote 6-cycles as  $G_6(m_1, m_2, m_3, m_4, m_5, m_6)$ .

From Figure 4 we know that six 1s in a 6-cycle belong to 3 rows and 3 columns equally, so we can get the number of 6-cycles with different figures to be 6 from Figure 5.

Figure 5 shows six different kinds of figures of 6-cycles. If there is no figure as shown in Figure 5 in the parity-check matrix, there is no 6-cycle in the LDPC code.

## 3. Design Algorithm of Parity-Check Matrix

If there is a parity-check matrix  $H$ , row weight is  $\nu$  ( $\nu > 3$ ), column weight is 3. We design three submatrices  $D, E, F$ , combine them into matrix  $H_1, H_1 = [D \ E \ F]$ , transpose  $H_1$  into  $H_2$ , expand  $H_2$  into desired parity-check matrix  $H$  using identity matrices and cyclic shift matrices of the identity matrix randomly.

### 3.1. Design Algorithm of Submatrix $D$

The design algorithm of  $D$  is as following.

- (1) Design a matrix  $D_0$  with the dimension  $\nu \times \nu^2$ .  
 $D_0(1, 1) = D_0(2, 1) = D_0(3, 1) = \dots = D_0(\nu, 1) = 1$ ,  
 other elements are "0"

$$D_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & 0 & 0 & 0 & \dots & 0 \end{bmatrix}_{\nu \times \nu^2} \quad (1)$$

- (2) Let  $D_1 = D_0^1, D_2 = D_0^2, D_3 = D_0^3, \dots, D_{\nu^2-1} = D_0^{\nu^2-1}$ , where  $D_0^k$  represents circularly shift  $D_0$  in (1) for  $k$  right-shifting steps circularly.
- (3) Let  $D = [D_0, D_1, D_2, \dots, D_{\nu^2-1}]^T$  and its dimension is  $\nu^3 \times \nu^2$ .

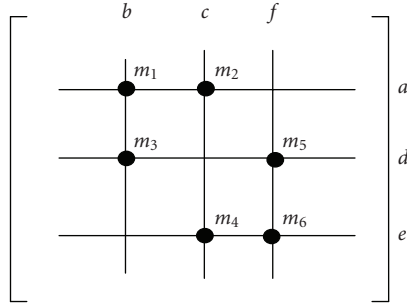


FIGURE 4: A 6-cycle in a parity-check matrix.

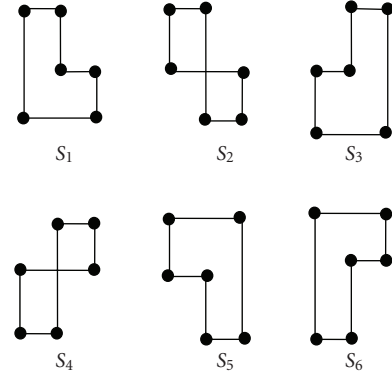


FIGURE 5: Six kinds of 6-cycles with different figures.

### 3.2. Design Algorithm of Submatrix $E$

The design algorithm of  $E$  is as following.

- (1) Design a matrix  $E_0$  with the dimension  $\nu \times \nu^2$ .  $E_0(1,1) = E_0(2,2) = E_0(3,3) = \dots = E_0(\nu,\nu) = 1$ , other elements are 0s

$$E_0 = \begin{bmatrix} 1 & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & 1 & \dots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & 0 & \vdots & \vdots \\ 0 & \dots & 0 & 1 & 0 & \dots & 0 \end{bmatrix}_{\nu \times \nu^2}. \quad (2)$$

- (2) Let  $E_1 = [E_0, E_0, \dots, E_0]^T$ , the number of  $E_0$  included in  $E_1$  is  $\nu$ .
- (3) Let  $E_2 = E_1^1, E_3 = E_1^{2\nu}, \dots, E_\nu = E_1^{(\nu-1)\nu}$ , where  $E_1^k$  represents circularly right-shifting  $E_1$  for  $k$  steps.
- (4) Let  $E = [E_1, E_2, \dots, E_\nu]^T$  with the dimension  $\nu^3 \times \nu^2$ .

### 3.3. Design Algorithm of Submatrix $F$

The design algorithm of  $F$  is as following.

- (1) Designing a matrix  $F_0$  with dimension  $\nu \times \nu^2$ .  $F_0(1,1) = F_0(2,\nu+1) = F_0(3,2\nu+1) = \dots = F_0(\nu,\nu^2-\nu+1) = 1$ , other elements are "0." For  $\nu = 4$ , we can get  $F_0$  by the following way:

$$F_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}_{\nu \times \nu^2}. \quad (3)$$

- (2) Let  $F_1 = F_0^1, F_2 = F_0^2, F_3 = F_0^3, \dots, F_{\nu-1} = F_0^{\nu-1}$ , where  $F_0^k$  represents  $F_0$  with circularly right-shifting  $k$  steps.
- (3) Let  $F_\nu = [F_0, F_1, \dots, F_{\nu-1}]^T$ .
- (4) Let  $F = [F_\nu, F_\nu, \dots, F_\nu]^T$ , there are  $\nu$  copies of  $F_\nu$  in  $F$ , so the dimension of  $F$  is  $\nu^3 \times \nu^2$ .

We can get  $H_1$  by the following way:

$$H_1 = \begin{bmatrix} D_0 & E_0 & F_0 \\ \vdots & \vdots & \vdots \\ D_{\nu-1} & E_0 & F_{\nu-1} \\ D_\nu & E_2 & F_0 \\ \vdots & \vdots & \vdots \\ D_{\nu^2-1} & E_\nu & F_{\nu-1} \end{bmatrix}_{\nu^3 \times 3\nu^2}. \quad (4)$$

Let  $H_2 = H_1^T$ , then the dimension of  $H_2$  is  $3\nu^2 \times \nu^3$ .

### 3.4. Expansion of $H_2$

The expansion algorithm is as follows.

- (1) Select an identity matrix  $I$  with dimension  $p \times p$ ,

$$I = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}_{p \times p}. \quad (5)$$

- (2) Let  $I_1 = I^1, I_2 = I^2, \dots, I_{p-1} = I^{p-1}$ , where  $I^k$  represents the matrix  $I$  with circularly right-shifting  $k$  steps.
- (3) Exchanging the 1s in  $H_2$  by the elements in the matrix set  $\{I, I_1, I_2, \dots, I_{p-1}\}$  randomly and exchanging 0s by null matrices with the same dimension as  $I$ , then we get the parity-check matrix  $H$ , whose dimension is  $3p\nu^2 \times p\nu^3$ .

From the structure of the parity-check matrix  $H$ , we can see that the proposed code is a deterministic LDPC code, so the proposed code has the advantage for encoding. To get the LDPC code with the large length ( $3p\nu^2$ ), we can expand the  $H$  by selecting the desired dimension  $p$  of the identity matrix  $I$  in (5) with stochastically shifting.

## 4. The Demonstration of the Code with Girth 8

In Section 3, we present a method for constructing parity-check matrix  $H$  with girth 8 based on the submatrices'

shifting. In this section, we add three lemmas with theoretic proofs showing that the parity-check matrix  $H$  does not contain 4-cycles and 6-cycles.

**Lemma 1.** *If a matrix  $H_1$  is constructed by (4), there is no 4-cycle in  $H_1$ .*

*Proof.* We can know from Figure 3 that if there are 4-cycles in the matrix  $H_1$  in (4), the edges connecting  $\{m_1, m_3\}$  and  $\{m_2, m_4\}$  must be in two different submatrices of  $D, E, F$ , because  $m_1$  and  $m_2$  are in the same row. The following formula must be true:

$$L(m_1, m_3) = L(m_2, m_4). \quad (6)$$

In the submatrix  $D$ , the lengths  $L(m_1, m_3)$  and  $L(m_2, m_4)$  could be  $1, 2, \dots, v - 1$ . In the submatrix  $E$ , the lengths  $L(m_1, m_3)$  and  $L(m_2, m_4)$  could be  $v, 2v, \dots, (v - 1) \times v$ . In the submatrix  $F$ , the lengths  $L(m_1, m_3)$  and  $L(m_2, m_4)$  could be  $v^2, 2v^2, \dots, (v - 1) \times v^2$ . We can easily know that  $L(m_1, m_3) \neq L(m_2, m_4)$ , so there is no 4-cycle in the matrix  $H_1$ .  $\square$

**Lemma 2.** *If a matrix  $H_1$  is constructed by (4), there is no 6-cycle in  $H_1$ .*

*Proof.* As shown in Figure 4, if there are 6-cycles in the matrix  $H_1$ , the edges connecting  $\{m_1, m_3\}$ ,  $\{m_2, m_4\}$ , and  $\{m_5, m_6\}$  must be in  $D, E$ , and  $F$ , respectively. Without loss of generality, we assume that  $L(m_2, m_4)$  is the longest length among the three lengths. The following formula must be true:

$$L(m_1, m_3) + L(m_5, m_6) = L(m_2, m_4). \quad (7)$$

In the submatrix  $D$ , the lengths  $L(m_1, m_3)$ ,  $L(m_5, m_6)$  and  $L(m_2, m_4)$  could be  $1, 2, \dots, v - 1$ . In the submatrix  $E$ , the length of  $L(m_1, m_3)$ ,  $L(m_5, m_6)$ , and  $L(m_2, m_4)$  could be  $v, 2v, \dots, (v - 1) \times v$ . In the submatrix  $F$ , the lengths  $L(m_1, m_3)$ ,  $L(m_5, m_6)$ , and  $L(m_2, m_4)$  could be  $v^2, 2v^2, \dots, (v - 1) \times v^2$ . We can know that the edge of  $L(m_2, m_4)$  must be in  $F$ , or else

$$L(m_1, m_3) + L(m_5, m_6) > L(m_2, m_4). \quad (8)$$

We know that

$$1 + v \leq L(m_1, m_3) + L(m_5, m_6) \leq (v - 1)(v + 1), \quad (9)$$

and  $L(m_2, m_4) \geq v^2$ , so

$$L(m_1, m_3) + L(m_5, m_6) < L(m_2, m_4). \quad (10)$$

Thus there is no 6-cycle in the matrix  $H_1$ , which means  $H$  to be free from 6-cycles.  $\square$

We know that  $H_2 = H_1^T$ , so the matrix  $H_2$  is also free of 4-cycles and 6-cycles.

**Lemma 3.** *If there is no 4-cycle and 6-cycle in the matrix  $H_2$ , there is no 4-cycle and 6-cycle in the parity-check matrix  $H$ .*

TABLE 1: Parameters of example codes with rate-1/2.

	$k$	$j$	$N$	$R$	$g$
New · 1080 · 540	6	3	1080	1/2	8
Mac · 1074 · 537	6	3	1008	1/2	6
QC · 1074 · 537	6	3	1002	1/2	8

TABLE 2: Parameters of our codes with high-rate.

	$k$	$j$	$N$	$R$	$g$
New · 5103 · 1701	9	3	5103	0.67	8
New · 5000 · 1500	10	3	5000	0.7	8
New · 5184 · 1296	12	3	5184	0.75	8

*Proof.* If there is a 4-cycle  $G_4(m_1, m_2, m_3, m_4)$  in the parity-check matrix  $H$ , from Figure 3 we can know that  $m_1, m_2, m_3$ , and  $m_4$  must be in four different identity matrices or cyclic shift matrices of identity matrices. Since an identity matrix  $I$  and a cyclic shift matrix of the  $I$  in  $H$  means a "1" in  $H_2$ , there is a 4-cycle in  $H_2$ . However, we know that there is no 4-cycle in  $H_2$ , so there is no 4-cycle in the parity-check matrix  $H$ . Using the same method, we can know that there is no 6-cycle  $G_6(m_1, m_2, m_3, m_4, m_5, m_6)$  in the parity-check matrix  $H$ .  $\square$

## 5. Performance Evaluation

To demonstrate the error-correcting performance, we constructed two rate-1/2 LDPC codes by the proposed method. For the purpose of comparison, we also construct two classes of Tanner's QC codes and Mackay's random codes [10, 11, 13]. We get Mackay's random codes from [13]. Tanner's QC codes are constructed by the method introduced in Tanner's paper [10, 11]. Both Mackay's random codes and constructed Tanner's QC codes for the comparison are good codes. The selected codes' parameters are given in Table 1.

Table 1 lists the typical values of the row weight  $k$ , the column weight  $j$ , the code length  $N$ , the code rate  $R$ , and the girth  $g$  for the three codes. The girths of the LDPC codes in Table 1 are tested by the approach of [12]. Table 2 lists the typical values of the proposed codes for different high code and code lengths. In Tables 1 and 2, the New ·  $n$  ·  $m$  means the proposed code with the code length  $n$  and  $m$  parity check bits, so do the Mac ·  $n$  ·  $m$  and Qc ·  $n$  ·  $m$ .

We simulate the proposed code's error-correcting performance with the assumption that each code is modulated by BPSK and transmitted over additive white Gaussian noise (AWGN) channel. All the codes are decoded with the sum-product algorithm [2, 3]. Figure 6 shows the simulated BER versus signal-to-noise ratio ( $E_b/N_0$ ). As shown in Figure 6. The BER performance of the proposed codes is very close to MacKay's random codes and Tanner's QC codes. From Figure 7, it can be seen that the proposed codes also have a good BER performance at high code rates 0.67, 0.7, and 0.75. The BER curves of the two codes of at high code rates 0.67, 0.7 are close since two LDPC codes with different code lengths may have approximate minimum weights [10]. In the

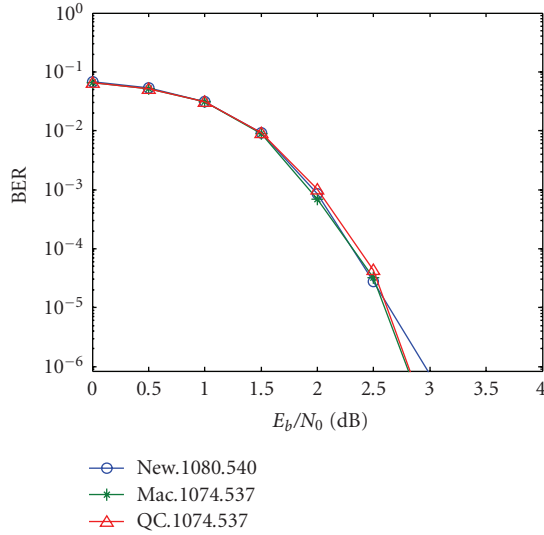


FIGURE 6: BER performance comparison of our code, Mackay's random code and Tanner's QC code.

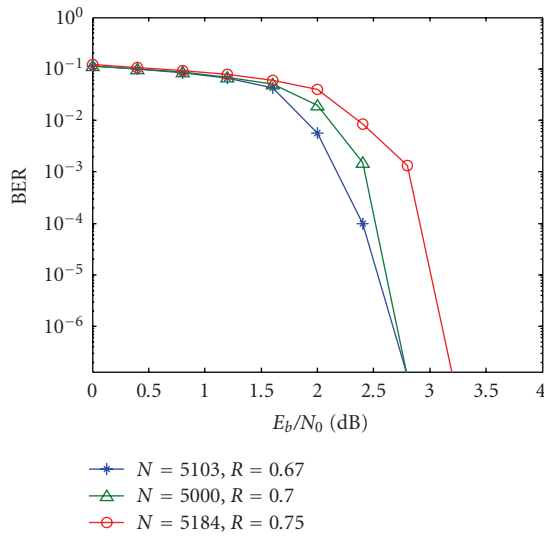


FIGURE 7: BER performance of our codes at high code rate.

expansion algorithm of the proposed code, we replace “1” in  $H_2$  by the elements in the set  $\{I, I_1, I_2, \dots, I_{p-1}\}$  randomly, which will lead to the minimum weights of the obtained codes to be different, the shorter codes may have larger minimum weights.

## 6. Conclusions

In this paper, we proposed a QC LDPC code without girth-4 and girth-6, three lemmas are provided to prove the short girths' properties of the proposed codes. Simulation verified the good error-correcting performance of the proposed code, whose BER performance is near to those of Tanner's QC codes and MacKay's random codes [10, 11, 13]. The good BER performance can remain at high code rates.

## Acknowledgments

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**Jiangchuan Liu**, School of Computing Science, Simon Fraser University, British Columbia, Canada; [jcliu@cs.sfu.ca](mailto:jcliu@cs.sfu.ca)

#### Guest Editors

**Jiannong Cao**, Department of Computing, Hong Kong Polytechnic University, Hong Kong; [csjcao@comp.polyu.edu.hk](mailto:csjcao@comp.polyu.edu.hk)

**Xiang-Yang Li**, Department of Computer Science, Illinois Institute of Technology, Chicago, IL, USA; [xli@cs.iit.edu](mailto:xli@cs.iit.edu)

**Limin Sun**, Institute of Software, Chinese Academy of Science, Beijing, China; [sunlimin@ios.cn](mailto:sunlimin@ios.cn)

**Dan Wang**, Department of Computing, Hong Kong Polytechnic University, Hong Kong; [csdwang@comp.polyu.edu.hk](mailto:csdwang@comp.polyu.edu.hk)

**Edith C.-H. Ngai**, Department of Information Technology, Uppsala University, Sweden; [edith.ngai@it.uu.se](mailto:edith.ngai@it.uu.se)

## Special Issue on Femtocell Networks

### Call for Papers

Recently, there has been a growing interest in femtocell networks both in academia and industry. They offer significant advantages for next-generation broadband wireless communication systems. For example, they eliminate the dead-spots in a macrocellular network. Moreover, due to short communication distances (on the order of tens of meters), they offer significantly better signal qualities compared to the current cellular networks. This makes high-quality voice communications and high data rate multimedia type of applications possible in indoor environments.

However, this new type of technology also comes with its own challenges, and there are significant technical problems that need to be addressed for successful deployment and operation of these networks. Standardization efforts related to femtocell networks in 3GPP (e.g., under TSG-RAN Working Group 4 and LTE-Advanced) and IEEE (e.g., under IEEE 802.16m) are already underway.

The goal of this special issue is to solicit high-quality unpublished research papers on design, evaluation, and performance analysis of femtocell networks. Suitable topics include but are not limited to the following:

- Downlink and uplink PHY/MAC design for femtocells in 3G systems, WiMAX systems, and LTE systems
- Interference analysis, avoidance, and mitigation
- Coexistence between a macrocellular network and femtocell network
- Resource allocation techniques
- Closed subscriber group (CSG) versus open-access femtocells
- Power control and power saving mechanisms (e.g., sleep/idle mode etc.)
- Mobility support and handover
- Time synchronization
- Multiple antenna techniques
- Tradeoffs between femtocells, picocells, relay networks, and antenna arrays
- Comparison with other fixed-mobile convergence (FMC) approaches such as UMA/GAN and dual-mode terminals

- Self-organizing networks and issues in self maintenance and self install
- Issues related to enterprise femtocells

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Manuscript Due	September 1, 2009
First Round of Reviews	December 1, 2009
Publication Date	March 1, 2010

### Lead Guest Editor

**Ismail Guvenc**, Wireless Access Laboratory, DOCOMO Communications Laboratories USA, Inc., Palo Alto, CA 94304, USA; [iguvenc@docomolabs-usa.com](mailto:iguvenc@docomolabs-usa.com)

### Guest Editors

**Simon Saunders**, Femto Forum, UK; [simon@femtoforum.org](mailto:simon@femtoforum.org)

**Ozgur Oyman**, Corporate Technology Group, Intel Corporation, USA; [ozgur.oyman@intel.com](mailto:ozgur.oyman@intel.com)

**Holger Claussen**, Alcatel-Lucent Bell Labs, UK; [claussen@lucent.com](mailto:claussen@lucent.com)

**Alan Gatherer**, Communications Infrastructure and Voice Business Unit, Texas Instruments, USA; [gatherer@ti.com](mailto:gatherer@ti.com)

## Special Issue on Mutual Coupling in Antenna Arrays

### Call for Papers

Mutual coupling is a general phenomenon in many antenna arrays. Its existence causes many problems in the applications of antenna arrays and has attracted many researchers to study its causes and effects. The effect of mutual coupling on antenna arrays stretches over many different areas from the conventional use of antenna arrays to the modern employment of antenna arrays in such exotic areas as MIMO systems, diversity systems, biological imaging, sonar and radar systems. Over the past years, there have been many methods suggested to study the mutual coupling problem and many solutions have been suggested to tackle this problem. The development of ever-decreasing size electronic devices has favored the emergence of small-size antenna arrays in recent years. This places the studying of mutual coupling problem in an even more important priority.

This special issue will provide an international forum for researchers in antenna mutual coupling research to disseminate their results and ideas on this area. Papers on all topics related to antenna mutual coupling are welcome. The following topics are especially suggested but not limited to them:

- Analysis and modeling methods for antenna mutual coupling
- Measurement and calibration methods for antenna mutual coupling
- Mutual coupling compensation or decoupling methods
- Mutual coupling in compact antenna arrays
- Mutual coupling in MIMO system antenna arrays
- Mutual coupling in smart/adaptive antenna arrays
- Mutual coupling in phased antenna arrays
- Mutual coupling in biomedical sensor arrays
- Mutual coupling remote sensing antenna arrays
- Mutual coupling in radar antenna arrays
- Mutual coupling in wideband and broadband arrays
- Mutual coupling in RFID tag antennas
- Mutual coupling and array signal processing
- Mutual coupling mitigation methods for antenna array design
- Any other relevant topics

Before submission authors should carefully read over the journal's Author Guidelines, which are located at <http://www.hindawi.com/journals/ijap/guidelines.html>. Prospective authors should submit an electronic copy of their complete manuscript through the journal Manuscript Tracking System at <http://mts.hindawi.com/> according to the following timetable:

Manuscript Due	November 1, 2009
First Round of Reviews	February 1, 2010
Publication Date	May 1, 2010

### Lead Guest Editor

**Hon Tat Hui**, Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576; [elehht@nus.edu.sg](mailto:elehht@nus.edu.sg)

### Guest Editors

**Marek E. Bialkowski**, School of Information Technology and Electrical Engineering, University of Queensland, St Lucia, Brisbane, Qld 4072, Australia; [meb@itee.uq.edu.au](mailto:meb@itee.uq.edu.au)

**Hoi Shun Lui**, Department of Signals and Systems, Chalmers University of Technology, SE-412 96 Göteborg, Sweden; [antony.lui@chalmers.se](mailto:antony.lui@chalmers.se)