

## Research Letter

# Multiuser Scheduling on the Downlink of an LTE Cellular System

Raymond Kwan,<sup>1</sup> Cyril Leung,<sup>2</sup> and Jie Zhang<sup>1</sup>

<sup>1</sup> Centre for Wireless Network Design, University of Bedfordshire, Park Square, Luton, LU1 3JU, UK

<sup>2</sup> Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada V6T 1Z4

Correspondence should be addressed to Raymond Kwan, raymond.y.c.kwan@gmail.com

Received 14 April 2008; Accepted 27 May 2008

Recommended by Ibrahim Develi

The challenge of scheduling user transmissions on the downlink of a long-term evolution (LTE) cellular communication system is addressed. In particular, a novel optimal multiuser scheduler is proposed. Numerical results show that the system performance improves with increasing correlation among OFDMA subcarriers. It is found that only a limited amount of feedback information is needed to achieve relatively good performance. A suboptimal reduced-complexity scheduler is also proposed and shown to provide good performance. The suboptimal scheme is especially attractive when the number of users is large, in which case the complexity of the optimal scheme is high.

Copyright © 2008 Raymond Kwan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

## 1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation technique that has been adopted in a variety of modern communication systems such as the digital subscriber lines (DSLs), wireless local area networks (WLANs), the Worldwide Interoperability for Microwave Access (WiMAX) [1], and long-term evolution (LTE) cellular networks. In order to exploit multiuser diversity and to increase flexibility in scheduling, orthogonal frequency division multiple access (OFDMA), in which multiple users can simultaneously share the subcarriers, is employed. The problem of power and subcarrier allocation in OFDMA systems has been the subject of much research (see [2, 3], and references therein).

In practice, due to limited signalling resources, subcarriers are allocated collectively. For example, on the downlink in LTE, subcarriers are grouped into resource blocks (RBs) of 12 adjacent subcarriers with an intersubcarrier spacing of 15 kHz [4, 5]. Each RB has a time slot duration of 0.5 milliseconds, which corresponds to 6 or 7 OFDM symbols. (The actual value depends on whether an extended or normal cyclic prefix is used.) The smallest resource unit that a scheduler can assign to a user is a scheduling block (SB), which consists of two consecutive RBs, spanning a subframe time duration of 1 millisecond [4, 5]. The main issue to be

addressed is how SBs are to be allocated to users, given that the channel qualities for the set of SBs associated with each user are different. Some studies on LTE-related scheduling have been reported in [6, 7] and the references therein.

One constraint in LTE downlink scheduling is that all SBs belonging to a single user can be assigned to only one modulation and coding scheme (MCS) in each transmission time interval (TTI) or scheduling period [4, page 326]. (This applies in the non-multiple-input-multiple-output (MIMO) configuration. For the MIMO configuration, a maximum of two different MCSs can be used for data belonging to two different transport blocks.) The durations of a TTI and SB are equal. To the best of our knowledge, the impact of this restriction on LTE scheduling has not been previously studied. In this paper, the challenging problem of multiuser scheduling is examined, taking into account this restriction.

## 2. System Model

In the time domain, each SB consists of a number,  $N_{sb}$ , of OFDM symbols. Let  $L$  be the total number of subcarriers and  $L_d(\nu) \leq L$  be the number of data-carrying subcarriers for symbol  $\nu$ , where  $\nu = 1, 2, \dots, N_{sb}$ . Also, let  $R_j^{(c)}$  be the code rate associated with the MCS  $j \in \{1, 2, \dots, J\}$ ,  $M_j$  be the constellation size of the MCS  $j$  and  $T_s$  be the OFDM symbol duration. Then, the bit rate,  $r_j$ , that corresponds to a single

SB is given by

$$r_j = \frac{R_j^{(c)} \log_2(M_j)}{T_s N_{sb}} \sum_{\nu=1}^{N_{sb}} L_d(\nu). \quad (1)$$

Let  $U$  be the number of simultaneous users, and  $N_{\text{tot}}$  be the total number of SBs that are available during each TTI. In addition, let  $\mathcal{N}_i$  be a subset of the  $N_{\text{tot}}$  SBs whose channel quality indicator (CQI) values are to be reported by user  $i$ ; the size of  $\mathcal{N}_i$  is denoted by  $N_i$ . It is assumed that the  $N_i$  highest SB CQI values are fed back. Such a limited feedback scheme requires a smaller bandwidth albeit at the cost of a degraded system performance. We also assume that the total available power is shared equally among the users. As noted in [8, 9], the throughput degradation resulting from such an assumption is small when adaptive modulation and coding (AMC) is used, as is the case in LTE.

Let  $\mathbf{x}_{i,n}$ ,  $n = 1, 2, \dots, N_i$  be a real scalar or vector reported (via a feedback channel) by user  $i$  to indicate the collective channel qualities of all the subcarriers within the  $n$ th reported SB. (The exact nature of  $\mathbf{x}_{i,n}$  depends on the feedback method adopted.) Furthermore, let  $q_{i,\max}(\mathbf{x}_{i,n}) \in \{1, 2, \dots, J\}$  be the index of the highest-rate MCS that can be supported by user  $i$  for the  $n$ th SB at CQI value  $\mathbf{x}_{i,n}$ , that is,  $q_{i,\max}(\mathbf{x}_{i,n}) = \arg \max_j (R_j^{(c)} \log_2(M_j) \mid \mathbf{x}_{i,n})$ . Due to frequency selectivity, the qualities of the subcarriers within a SB may differ; the indicator  $\mathbf{x}_{i,n}$  should provide a good collective representation of the qualities for all the subcarriers within the  $n$ th SB [10–12]. For convenience, we assume that the MCS rate  $R_j^{(c)} \log_2(M_j)$  increases monotonically with  $j$ , and that the rate of MCS 1 is zero. SBs whose CQI values are not reported back are assigned to MCS 1.

As mentioned earlier, in a non-MIMO configuration, all SBs scheduled for a given user within the same TTI must use the same MCS. If MCS  $j$  is to be used for user  $i$ , then only certain SBs can be assigned to the user. For example, suppose  $N_i = 4$ , and

$$1 \leq q_{i,\max}(\mathbf{x}_{i,2}) < q_{i,\max}(\mathbf{x}_{i,1}) < q_{i,\max}(\mathbf{x}_{i,3}) < q_{i,\max}(\mathbf{x}_{i,5}) \leq J. \quad (2)$$

Then, if MCS  $j = q_{i,\max}(\mathbf{x}_{i,3})$  is used, only SBs  $n = 3$  and 5 can be allocated to user  $i$  since only these SBs have good enough channel qualities to support an MCS index of  $q_{i,\max}(\mathbf{x}_{i,3})$  or higher. Selecting SBs  $n = 1$  or 2 with MCS  $j = q_{i,\max}(\mathbf{x}_{i,3})$  would result in unacceptably high error rates for these SBs. On the other hand, if  $j = q_{i,\max}(\mathbf{x}_{i,2})$ , all 4 SBs can be selected, at the expense of a lower bit rate for SBs 1, 3, and 5. This suggests that there is an optimal value of  $j$  which maximizes the total bit rate for user  $i$ .

### 3. Optimal Scheduler

#### 3.1. Multiuser Optimization Model

With multiple users, the optimization problem is more difficult. In addition, each SB can only be occupied by a single

user [4]. Let

$$v_{i,n}(\mathbf{x}_{i,n}) = \sum_{j=1}^{q_{i,\max}(\mathbf{x}_{i,n})} b_{i,j} r_j \quad (3)$$

be the bit rate of SB  $n$  selected for user  $i$  given the channel quality  $\mathbf{x}_{i,n}$ , where  $b_{i,j} \in \{0, 1\}$  is a binary decision variable. Let  $Q_{\max}(i) = \max_{n \in \mathcal{N}_i} \{q_{i,\max}(\mathbf{x}_{i,n})\}$ . The constraint

$$\sum_{j=1}^{Q_{\max}(i)} b_{i,j} = 1 \quad (4)$$

is introduced to ensure that the MCS for user  $i$  can only take on a single value between 1 and  $Q_{\max}(i)$ . The formulation in (3) allows the selected bit rate for SB  $n$  to be less than what  $\mathbf{x}_{i,n}$  can potentially support, as may be the case if user  $i$  is assigned more than one SB during a TTI. From (3) and (4), it can be seen that SB  $n$  might be selected for user  $i$  only if the MCS  $j^*$  chosen for user  $i$  satisfies  $j^* \leq q_{i,\max}(\mathbf{x}_{i,n})$ .

The problem of jointly maximizing the sum of the bit rates for all users can be formulated as

$$(P1): \max_{\mathbf{A}, \mathbf{B}} \sum_{i=1}^U \sum_{n \in \mathcal{N}_i} a_{i,n} \sum_{j=1}^{q_{i,\max}(\mathbf{x}_{i,n})} b_{i,j} r_j \quad (5)$$

subject to (4) and

$$\sum_{i=1}^U a_{i,n} = 1, \quad n \in \mathcal{N}_i, \quad a_{i,n}, b_{i,j} \in \{0, 1\}, \quad \forall i, j, n. \quad (6)$$

In problem (P1),  $\mathbf{A} = \{a_{i,n}, i = 1, \dots, U, n \in \mathcal{N}_i\}$ ,  $\mathbf{B} = \{b_{i,j}, i = 1, \dots, U, j = 1, \dots, Q_{\max}(i)\}$ , and  $a_{i,n}$  is a binary decision variable, with value 1 if SB  $n$  is assigned to user  $i$  and 0 otherwise. The objective in (5) is to select optimal values for  $\mathbf{A}$  and  $\mathbf{B}$  to maximize the aggregate bit rate  $\sum_{i=1}^U \sum_{n \in \mathcal{N}_i} a_{i,n} v_{i,n}(\mathbf{x}_{i,n})$ .

#### 3.2. Linearized Model

Note that Problem (P1) is nonlinear due to the product  $a_{i,n} b_{i,j}$  in (5). Although solutions can be obtained using optimization techniques such as Branch-and-Bound [13], global optimality cannot be guaranteed. To avoid this difficulty, the problem can be transformed into an *equivalent* linear problem by introducing an auxiliary variable  $t_{n,i,j} = a_{i,n} b_{i,j}$ . Then, Problem (P1) can be linearized as follows:

$$(P1'): \max_{\mathbf{A}, \mathbf{B}, \mathbf{T}} \sum_{i=1}^U \sum_{n \in \mathcal{N}_i} \sum_{j=1}^{q_{i,\max}(\mathbf{x}_{i,n})} t_{n,i,j} r_j \quad (7)$$

subject to (4), (6) and

$$\begin{aligned} t_{n,i,j} &\leq b_{i,j}, \\ t_{n,i,j} &\leq a_{i,n} M, \\ t_{n,i,j} &\geq b_{i,j} - (1 - a_{i,n}) M, \end{aligned} \quad (8)$$

where  $M$  is a large positive real value. Problem (P1') can then be solved using well-known integer linear programming techniques [13].

### 4. A Suboptimal Scheduler

In the optimal scheduler formulations in (P1) and (P1'), the MCSs, SBs, and users are jointly assigned. To reduce complexity, the proposed suboptimal scheduler performs the assignment in two stages. In the first stage, each SB is assigned to the user who can support the highest bit rate. In the second stage, the best MCS for each user is determined. The idea behind the suboptimal scheduler is to assign a disjoint subset of SBs to each user, thereby reducing a joint multiuser optimization problem into  $U$  parallel single-user optimization problems.

Let  $\varphi_n$  be the index of the user which can support the highest-rate MCS for SB  $n$ , that is,  $\varphi_n = \arg \max_{i \in \{1, 2, \dots, U\}} q_{i, \max}(\mathbf{x}_{i, n})$ . Furthermore, let  $\tilde{\mathcal{N}}_i$  be the (disjoint) set of SBs assigned to user  $i$ , that is,  $\{n \text{ such that } \varphi_n = i\}$ . In the first stage, the suboptimal scheduler determines  $\{\tilde{\mathcal{N}}_i\}_{i=1}^U$ .

Let  $Q'_{\max}(i) = \max_{n \in \tilde{\mathcal{N}}_i} \{q_{i, \max}(\mathbf{x}_{i, n})\}$ , and let the MCS vector,  $\mathbf{b}_i$ , for user  $i$  be

$$\mathbf{b}_i = [b_{i,1}, b_{i,2}, \dots, b_{i, Q'_{\max}(i)}]. \tag{9}$$

In the second stage, the suboptimal scheduler determines  $\mathbf{b}_i$  which maximizes the total bit rate for user  $i$ . Similar to the approach in Section 3, the optimal  $\mathbf{b}_i$  can be obtained by solving the following problem:

$$(P2): \max_{\mathbf{b}_i} \sum_{n \in \tilde{\mathcal{N}}_i} \sum_{j=1}^{q_{i, \max}(\mathbf{x}_{i, n})} b_{i, j} r_j, \tag{10}$$

s.t.

$$\sum_{j=1}^{Q'_{\max}(i)} b_{i, j} = 1, \quad b_{i, j} \in \{0, 1\}, \quad \forall i, j. \tag{11}$$

Compared to (P1) or (P1'), (P2) is a much simpler problem.

### 5. Numerical Results

For illustration purposes, we assume  $N_{\text{tot}} = 12$  SBs per TTI,  $L = 12$  subcarriers per SB,  $N_1 = N_2 = \dots = N_U = N$ , and that the normal cyclic prefix configuration is used [4]. The fading amplitude for each subcarrier and user follows the Nakagami- $m$  model [14], with a fading figure  $m = 1$ . The average signal-to-interference plus noise ratios (SINRs) for the users are 10 dB, 11 dB, and 12 dB, respectively. It is assumed that the SINRs for all subcarriers of each user are correlated, but identically distributed (c.i.d.), and that the resource blocks follow the localized configuration [5]. The correlation coefficient between a pair of subcarriers is given by  $\rho^{|i-j|}$ , where  $i$  and  $j$  are the subcarrier indices. The SINR of each subcarrier is assumed to be independent at the beginning of each scheduling period, and constant throughout the entire period. For simplicity, it is assumed that the set of MCSs consists of QPSK 1/2 and 3/4, 16-QAM 1/2 and 3/4, as well as 64-QAM 3/4 [1], and the L1/L2 control channels are mapped to the first OFDM symbol

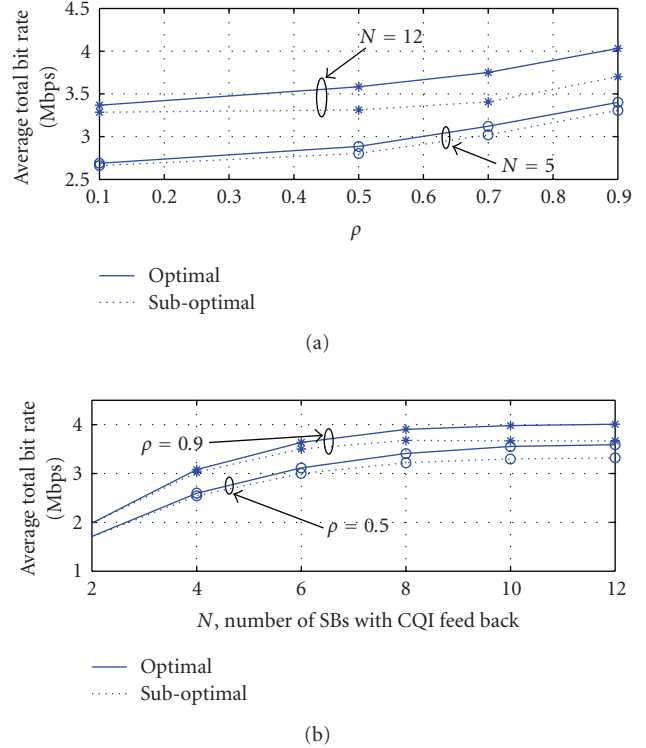


FIGURE 1: Average total bit rate as a function of  $\rho$  and  $N$ , respectively, with  $U = 3$ . (a)  $N = 5$  and  $12$  with  $U = 3$ . (b)  $\rho = 0.5$  and  $0.9$ .

within each subframe. Furthermore, each subframe consists of 8 reference symbols [4]. The feedback method is based on the exponential effective SINR mapping (EESM) [10], with parameter values obtained from [15]. Let  $R_{\text{tot}}^*$  be the total bit rate defined in (5) or (7), and  $E[R_{\text{tot}}^*]$  be the value of  $R_{\text{tot}}^*$  averaged over 2500 channel realizations.

Figure 1 shows the average total bit rate,  $E[R_{\text{tot}}^*]$ , as a function of  $\rho$  (top) and  $N$  (bottom). In Figure 1(a), it can be observed that the performance improves with the level of correlation among subcarriers. Recall that the idea behind EESM is to map a set of subcarrier SINRs,  $\{\Gamma_i\}_{i=1}^L$ , to a single effective SINR,  $\Gamma^*$ , in such a way that the block error probability (BLEP) due to  $\{\Gamma_i\}_{i=1}^L$  can be well approximated by that at  $\Gamma^*$  in additive white Gaussian noise (AWGN) [1, 10]. The value of  $\Gamma^*$  tends to be skewed towards the weaker subcarriers in order to maintain an acceptable BLEP. At a low value of  $\rho$ , subcarriers with large SINRs are not effectively utilized, leading to a relatively poor performance. In Figure 1(b), it can be seen that the performance improves with  $N$ , but the rate of improvement decreases. There is little performance improvement as  $N$  increases beyond 8.

Figure 2(a) shows  $E[R_{\text{tot}}^*]$  as a function of the number,  $U$ , of users for  $\rho = 0.9$  and  $N = 12$ . The average SINRs for all users are set to 10 dB. As  $U$  increases,  $E[R_{\text{tot}}^*]$  increases due to the more pronounced benefits from multiuser diversity. Figure 2(b) shows the percentage gain in  $E[R_{\text{tot}}^*]$  for the optimal scheduler relative to the suboptimal scheduler as a function of  $U$ . As  $U$  increases, it becomes increasingly likely

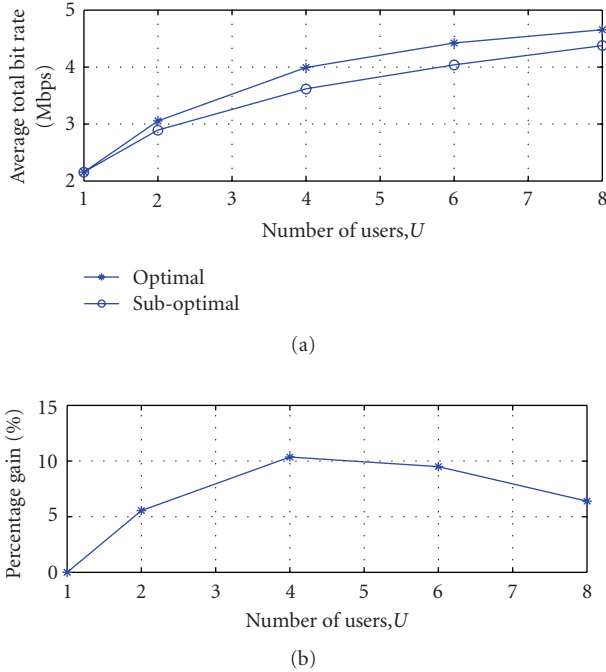


FIGURE 2: Average total bit rate and percentage gain as a function of the number of users,  $U$ , with  $\rho = 0.9$  and  $N = 12$ .

that a given user will be assigned at most one SB in the first stage operation of the suboptimal scheduler. In this event, the suboptimal scheduler is actually optimal. It is therefore expected that the difference in performance between the optimal and suboptimal schedulers will be small when  $U$  is large, as illustrated in Figure 2(b). The result indicates that the suboptimal scheduler is especially attractive for large values of  $U$  since it provides a significant reduction in complexity and its performance approaches that of the optimal scheduler.

## 6. Conclusion

The problem of multiuser downlink scheduling in an LTE cellular communication system was studied. Numerical results show that both the correlation among subcarriers and the amount of information fed back play important roles in determining the system performance. It was found that limited feedback may be sufficient to achieve a good performance. A reduced complexity suboptimal scheduler was proposed and found to perform quite well relative to the optimal scheduler. The suboptimal scheduler becomes especially attractive as the number of users increases.

## Acknowledgments

This work was supported in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada under Grant no. OGP0001731, by the UBC PMC-Sierra Professorship in Networking and Communications, and by a Marie Curie Post-Doctoral Fellowship.

## References

- [1] J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX: Understanding Broadband Wireless Networking*, Prentice Hall, Upper Saddle River, NJ, USA, 2007.
- [2] H. Liu and G. Li, *OFDM-Based Broadband Wireless Networks, Design and Optimization*, John Wiley & Sons, New York, NY, USA, 2005.
- [3] G. Wunder, C. Zhou, H.-E. Bakker, and S. Kaminski, "Throughput maximization under rate requirements for the OFDMA downlink channel with limited feedback," *EURASIP Journal on Wireless Communications and Networking*, vol. 2008, Article ID 437921, 14 pages, 2008.
- [4] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G Evolution: HSPA and LTE for Mobile Broadband*, Academic Press, New York, NY, USA, 2007.
- [5] "Evolved universal terrestrial radio access (EUTRA); physical channels and modulation (Release 8)," Tech. Rep. 3GPP TS36.211, 3rd Generation Partnership Project, Sophia-Antipolis Cedex, France, September 2007.
- [6] X. Ning, Z. Ting, W. Ying, and Z. Ping, "A MC-GMR scheduler for shared data channel in 3GPP LTE system," in *Proceedings of the 64th IEEE Vehicular Technology Conference (VTC '06)*, pp. 1–5, Montreal, Canada, September 2006.
- [7] K. I. Pedersen, G. Monghal, I. Z. Kovács, et al., "Frequency domain scheduling for OFDMA with limited and noisy channel feedback," in *Proceedings of the 66th IEEE Vehicular Technology Conference (VTC '07)*, pp. 1792–1796, Baltimore, Md, USA, September-October 2007.
- [8] S. T. Chung and A. J. Goldsmith, "Degrees of freedom in adaptive modulation: a unified view," *IEEE Transactions on Communications*, vol. 49, no. 9, pp. 1561–1571, 2001.
- [9] N. Miki, Y. Kishiyama, K. Higuchi, and M. Sawahashi, "Optimum adaptive modulation and channel coding scheme for frequency domain channel-dependent scheduling in OFDM based evolved UTRA downlink," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC '07)*, pp. 1785–1790, Hong Kong, March 2007.
- [10] Ericsson, "System-Level Evaluation of OFDM—Further Considerations," TSG-RAN WG1 #35, Lisbon, Portugal, TR R1-031303, November 2003.
- [11] Y. W. Blankenship, P. J. Sartori, B. K. Classon, V. Desai, and K. L. Baum, "Link error prediction methods for multicarrier systems," in *Proceedings of the 60th IEEE Vehicular Technology Conference (VTC '04)*, vol. 6, pp. 4175–4179, Los Angeles, Calif, USA, September 2004.
- [12] M. Lampe, T. Giebel, H. Rohling, and W. Zirwas, "PER-prediction for PHY mode selection in OFDM communication systems," in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM '03)*, vol. 1, pp. 25–29, San Francisco, Calif, USA, December 2003.
- [13] R. Rardin, *Optimization in Operations Research*, Prentice Hall, Upper Saddle River, NJ, USA, 1998.
- [14] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, John Wiley & Sons, New York, NY, USA, 2nd edition, 2005.
- [15] E. Westman, *Calibration and evaluation of the exponential effective SINR mapping (EESM) in 802.16*, M.S. thesis, The Royal Institute of Technology (KTH), Stockholm, Sweden, September 2006.

## Special Issue on Design, Implementation, and Evaluation of Wireless Sensor Network Systems

### Call for Papers

The recent advances in embedded software/hardware design have enabled large-scale and cost-effective deployment of Wireless Sensor Networks (WSNs). Such a network consists of many small sensor nodes with sensing, control, data processing, communications, and networking capabilities. The wireless sensor networks have a broad spectrum applications ranging from wild life monitoring and battlefield surveillance to border control and disaster relief, and have attracted significant interests from both academy and industry.

A wireless sensor node generally has limited storage and computation capabilities, as well as severely constrained power supplies, and the networks often operate in harsh unattended environments. Successful design and deployment of wireless sensor networks thus call for technology advances and integrations in diverse fields including embedded hardware manufacturing and signal processing as well as wireless communications and networking across all layers. We have seen the initial and incremental deployment of real sensor networks in the past decade, for example, the ZebraNet for wildlife tracking, the CitySense for weather and air pollutants reporting, and the Sensormap portal for generic monitoring services, to name but a few; yet the full potentials of such networks in the real world remain to be explored and demonstrated, which involves numerous practical challenges in diverse aspects.

This special issue aims to summarize the latest development in the design, implementation, and evaluation of wireless sensor systems. Topics of interest include but are not limited to:

- Practical architecture and protocol design for sensor communications and networking
- Management, monitoring, and diagnosis of sensor networks
- Implementation and measurement of experimental systems and testbeds
- Experience with real-world deployments of wireless sensor networks
- Interactions with ubiquitous communication and networking infrastructures
- Novel killer applications of wireless sensor networks

We solicit original unpublished research papers only. Papers previously published in conference/workshop proceedings can be considered, but should be substantially extended.

Before submission authors should carefully read over the journal's Author Guidelines, which are located at <http://www.hindawi.com/journals/wcn/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	February 15, 2010
First Round of Reviews	May 15, 2010
Publication Date	August 15, 2010

#### Lead Guest Editor

**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 Dynamic Spectrum Access: From the Concept to the Implementation

### Call for Papers

We are today witnessing an explosive growth in the deployment of wireless communication services. At the same time, wireless system designers are facing the continuously increasing demand for capacity and mobility required by the new user applications. The scarcity of the radio spectrum, densely allocated by the regulators, is a major bottleneck in the development of new wireless communications systems. However actual spectrum occupancy measurements show that the frequency band scarcity is not a result of the heavy usage of the spectrum, but is rather due to the inefficient static frequency allocation pursued by the regulators.

Dynamic spectrum access has been proposed as a new technology to resolve this paradox. Sparse assigned frequency bands are opened to secondary users, provided that interference generated on the primary licensee is negligible. Even if the concept constitutes a real paradigm shift, it is still unclear how the dynamic spectrum access can operate efficiently and how it can be implemented cost-effectively.

*Scope.* Original contributions are solicited in all aspects of dynamic spectrum access related to the integration of the technology in a real communication system. The special issue should give clear advice on how to make dynamic spectrum access work in practice. Topics of interest include, but are not limited to:

- Spectrum sensing and access:
  - Spectrum sensing mechanisms and protocol support
  - Interference modeling and avoidance
  - Adaptive coding and modulation for interference avoidance
  - Beamforming and MIMO for interference avoidance
  - Distributed cooperative spectrum sensing and communication
  - Ultra-wideband cognitive radio system
  - Crosslayer design and optimization
- Intelligence and learning capability:
  - Cognitive machine learning techniques
  - Game theory for dynamic spectrum access
  - Genetic and artificial intelligence-inspired algorithms

- Implementation:
  - Architectures and building blocks of dynamic spectrum access
  - Combined architectures for SDR and dynamic spectrum access
  - Wideband or multichannel transmitter design and spectrum sensing
  - Bandpass sampling receivers
  - Landau-Nyquist sampling receivers
  - Digital compensation of RF imperfections

Before submission authors should carefully read over the journal's Author Guidelines, which are located at <http://www.hindawi.com/journals/wcn/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	October 1, 2009
First Round of Reviews	January 1, 2010
Publication Date	April 1, 2010

### Lead Guest Editor

**François Horlin**, Université libre de Bruxelles (ULB), Bruxelles, Belgium; [fhorlin@ulb.ac.be](mailto:fhorlin@ulb.ac.be)

### Guest Editors

**André Bourdoux**, Interuniversity Micro-Electronics Center (IMEC), Leuven, Belgium; [bourdoux@imec.be](mailto:bourdoux@imec.be)

**Danijela Cabric**, University of California, Los Angeles (UCLA), Los Angeles, USA; [danijela@ee.ucla.edu](mailto:danijela@ee.ucla.edu)

**Gianluigi Ferrari**, University of Parma, Parma, Italy; [gianluigi.ferrari@unipr.it](mailto:gianluigi.ferrari@unipr.it)

**Zhi Tian**, Michigan Technological University, Houghton, USA; [ztian@mtu.edu](mailto:ztian@mtu.edu)

## Special Issue on Signal Processing-Assisted Protocols and Algorithms for Cooperating Objects and Wireless Sensor Networks

### Call for Papers

With the advent of the so-called Internet of Things (IoTs), we will witness an unprecedented growth in the number of networked terminals and devices. In attaining this IoT vision, a class of energy- and, in general, resource-constrained systems like Wireless Sensor Networks (WSNs), networks of cooperating objects and embedded devices such as RFIDs, or networks for Device-to-Device (D2D) and Machine-to-Machine (M2M) communications are to play a fundamental role. The paradigm shift from general-purpose data networks to application-oriented networks (e.g., for parameter or random field estimation, event detection, localization, and tracking) clearly calls for further optimization at the physical, link, and network layers of the protocol stack. Interestingly, the above-mentioned estimation/detection/localization/tracking problems have been addressed for years by the signal processing community, this resulting into a number of well-known algorithms. Besides, some inspiration could be also borrowed from other communication schemes, such as MIMO and beamforming techniques or cooperative communications that were traditionally developed for wireless data networks, or even from other fields such as mathematical biology (e.g., networks of coupled oscillators). However, the challenge now is to enhance such algorithms and schemes and make them suitable for decentralized and resource-constrained operation in networks with a potentially high number of nodes. Complementarily, the vast literature produced by the information theory community, on the one hand, reveals the theoretical performance limits of decentralized processing (e.g., distributed source coding) and, on the other, offers insight on the scalability properties of such large networks and their behavior in the asymptotic regime. Realizing the information-theoretic performance with practical decentralized networking, radio resource management schemes, routing protocols, and other network management paradigms is a key challenge.

The objective of this Special Issue (whose preparation is carried out under the auspices of the EC Network of Excellence in Wireless Communications NEWCOM++) is to gather recent advances in the areas of cooperating objects, embedded devices, and wireless sensor networks.

The focus is on how the design of future physical, link, and network layers could benefit from a signal processing-oriented approach. Specific topics for this Special Issue include but are not limited to:

- Decentralized parameter estimation
- Estimation of random fields
- Distributed MIMO and beamforming
- Decentralized and cooperative time and frequency synchronization
- Cooperative event detection
- Data gathering and data fusion
- Data-centric multihop techniques and routing
- Scalability and asymptotic laws for in-network distributed estimation/detection
- Energy-saving algorithms and protocols
- Feedback-limited scheduling and MAC protocols
- Decentralized joint source-channel coding
- Cooperative localization and tracking
- Topology control in resource-constrained networks
- Low-complexity opportunistic networking protocols

Before submission, authors should carefully read over the journal's Author Guidelines, which are located at <http://www.hindawi.com/journals/wcn/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	February 1, 2010
First Round of Reviews	May 1, 2010
Publication Date	August 1, 2010

### Lead Guest Editor

**Carles Antón-Haro**, Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), 08860 Castelldefels, Barcelona, Spain; [carles.anton@cttc.es](mailto:carles.anton@cttc.es)



**Guest Editors**

**Davide Dardari**, WiLAB, University of Bologna at Cesena, Cesena (FC), Italy; ddardari@ieee.org

**Oswaldo Simeone**, Center for Wireless Communications and Signal Processing Research, New Jersey Institute of Technology (NJIT), Newark, NJ, USA; osvaldo.simeone@njit.edu

**Roberto Verdone**, WiLAB at the University of Bologna, Bologna, Italy; roberto.verdone@unibo.it