Dynamic Inter-Cell Interference Coordination in Cellular OFDMA Networks

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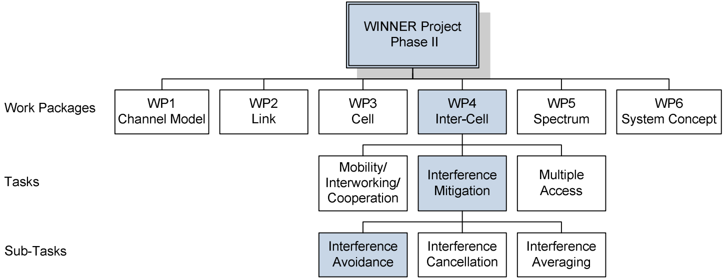
Motivation

- 4G and beyond systems adopted Orthogonal Frequency Division Multiple Access (OFDMA) air-interface technology
- Dense spectrum reuse is obvious in all cellular systems
- Consequently, high inter-cell interference and its mitigation are concerns
- Mitigation techniques:
  - Inter-cell interference cancellation
  - Inter-cell interference randomization
  - Inter-cell interference avoidance
- Literature focuses mainly on static or semi-static schemes
- Our approach: dynamic interference avoidance using network level coordination

Motivation (Cont.)

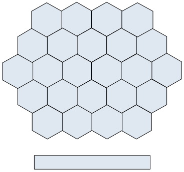


- WINNER (Phase II, 2006-2007) has been an important motivating factor
- One of the pioneers to propose dynamic ICIC

Contributions

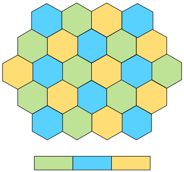
- Optimization framework for dynamic interference coordination
- Different suboptimal solutions-
    - Proposed two-level algorithm with partial central processing
    - Proposed distributed algorithm with neighboring cell coordination
    - Proposed cluster-based centralized scheme
- Evaluation of the proposed schemes using extensive system simulations
- The proposed schemes significantly outperform the reference schemes

Some Interference Coordination in Literature



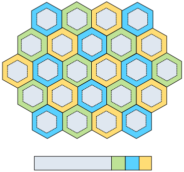
Reuse 1

- all resources available
- interferers are closer to each other
- worst interference condition and best reuse opportunity



Reuse 3

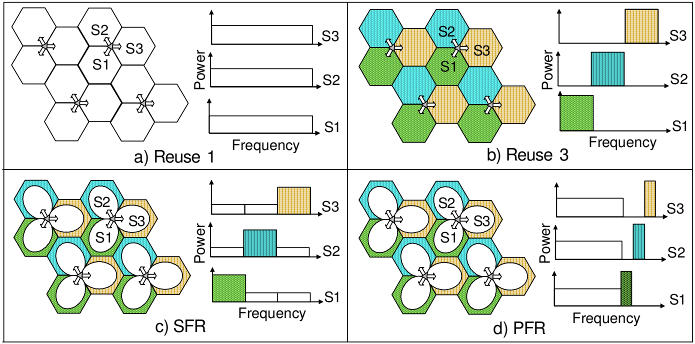
- 1/3 resources available
- interferers are further apart
- proactive static interference coordination



Fractional Frequency Reuse (FFR)

- part of the resources in the cell center with reuse 1
- compromise between the two
- different variants are available

Some Interference Coordination in Literature (cont.)

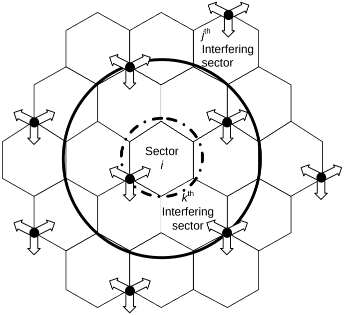


Optimization Framework

Resource unit $\rightarrow n$ and user $\rightarrow m$

Maximize

$$\sum_i \left[\sum_{m=1}^{M} \sum_{n=1}^{N} u_i^{(m,n)} \rho_i^{(m,n)} \right], \qquad (1)$$



subject to

$$\rho_i^{(m,n)} \in \{0,1\}; \forall m \text{ and } \forall n, \qquad (2)$$

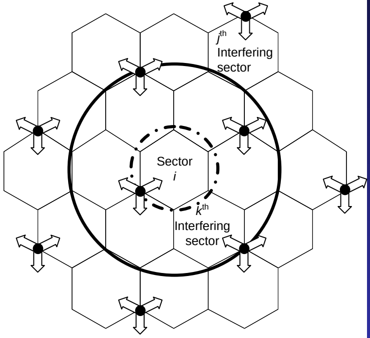
$$I_i^{(n)} = \sum_{m=1}^{M} \rho^{(m,n)} = \begin{cases} 0; & \text{resource } n \text{ is restricted in } i \\ 1; & \text{otherwise.} \end{cases} \qquad (3)$$

Optimization Framework (contd.)

$$\gamma_i^{(m,n)} = \frac{P_c \mathcal{H}_{i,i}^{(m,n)}}{P_c \sum_{k=1}^{K} \mathcal{H}_{i,k}^{(m,n)} \cdot I_k^{(n)} + P_c \sum_{j=1}^{J} \mathcal{H}_{i,j}^{(m,n)} \cdot I_j^{(n)} + P_{TN}}, \quad (4)$$

Find $I_k^{(n)} = 0$ & $I_j^{(n)} = 0$; $\forall k$, $\forall j$, $\forall n$ that maximizes (1)

- $r_i^{(m,n)} \overset{BER,AMC}{\longleftarrow} \gamma_i^{(m,n)}$ and $u_i^{(m,n)} = f\left[r_i^{(m,n)}, d_i^{(m)}\right]$
- Demand factor: $d_i^{(m)} = \bar{R}_i/(R_i^{(m)} + \delta)$, where $R_i^{(m)} \to m^{th}$ user's throughput and $\bar{R}_i = \left(\sum_{m=1}^{M} R_i^{(m)}\right)/M \to$ avg. user throughput



Optimization Framework (contd.)

Challenges

- Problem is similar to 3AP which is NP-Complete
- Optimal solution requires centralized algorithm
- Large scale combinatorial optimization

Propose suboptimal solutions considering the following

- Fact: only neighboring interferers are of concern– we assume, $I_j^{(n)} = 1$
- 4G provides cell-specific orthogonal reference signals; i.e., determine $\gamma^{(m,n)}_{i|I_k^{(n)}=0}$; $\forall k$ & $\forall n$
- Cell-edge (rate deprived) users are more prone inter-cell interference

Sub-optimal Solutions

1. The proposed two-level algorithm with partial central processing
2. The proposed distributed algorithm with neighboring cell coordination
3. The proposed cluster-based centralized algorithm

Overview of the Proposed Two-Level Algorithm

- sector i selfishly finds $I_k^{(n)} = 0; \forall k$ and $\forall n$ such that $\left[\sum_{m=1}^{M} \sum_{n=1}^{N} u_i^{(m,n)} \rho_i^{(m,n)}\right]$ is maximized
- The above is a 2D assignment problem (solved using Hungarian algorithm)
  - prepare utility matrix $U_{M \times N} = \left[u^{(m,n)}\right]$ heuristically
  - Matrix $U_{M \times N}$ reflects heuristically found $I_k^{(n)} = 0$ based on users' service status and interference avoidance gains
  - Hungarian algorithm is applied to $U_{M \times N}$ to see if chosen entries have $I_k^{(n)} = 0$
- Central-level: the 3^{rd} dimension is handled at a central controller

Central Processing of the Proposed Two-Level Algorithm

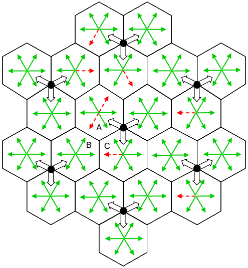
For chunk n, at the central controller

maximize

$$Z = \sum_{i,j\in\Phi} u_i^{(m_i,n)}(1 - x_i^{(n)}) + u_j^{(m_j,n)}(1 - x_j^{(n)}); \quad (5)$$

subject to

$$x_i^{(n)} + x_j^{(n)} \le 1; \quad (6)$$

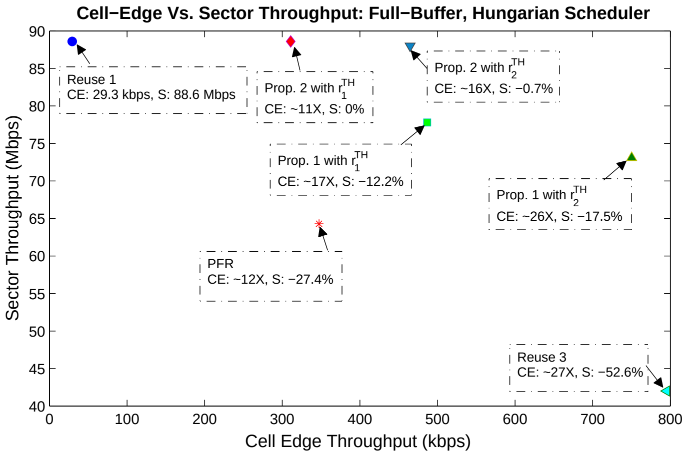


- $\Phi \rightarrow$ sectors that either request or are requested for restriction
- m_i, $m_j \rightarrow$ candidate UTs in sector i and j, respectively
- $x_i^{(n)}$, $x_j^{(n)} \rightarrow$ binary variables for restrictions

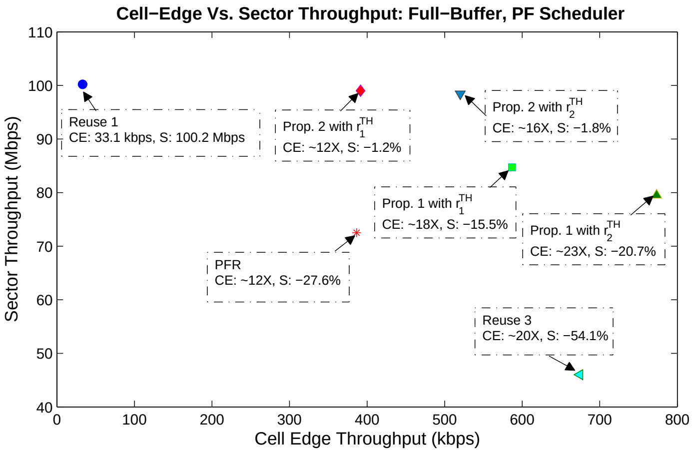
System and Simulation Parameters

Parameter	Assumption
Cellular Layout	Hexagonal grid, 19 sites, 3 sectors/site
Inter-site Distance	1000 m
Path-loss exponent	3.57
Shadowing	Independent Log-normal std. 8 dB
Antenna Pattern	$A(\theta) = \text{-min}\left[12\left(\frac{\theta}{\theta_{3\text{dB}}}\right)^2, 20\right],\ \theta_{3\text{dB}} = 70^o$
Bandwidth@Carrier	45 MHz@3.95 GHz
Channel model	20-Tap WINNER Channel
UE speeds of interest	20 km/hr
Sector TX power	39.81 Watts
Minimum UE Distance	50 m
AMC modes	BPSK, QPSK, 16- & 64-QAM with rates 1/2, 2/3 & 3/4

Some Summarized Results: Two-Level Algorithm

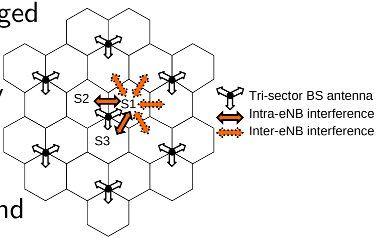


Summarized Results: Two-Level Algorithm (cont.)



Overview of the Distributed Algorithm

- Developed LTE systems; central processing discouraged
- Centralized processing is replaced by pair-wise utility comparison
- Inter-cell interference is categorized as intra-eNB and inter-eNB interference
  - Intra-eNB interference avoidance is done using a novel Hungarian method applied to multi-cellular environment
  - Inter-eNB interference avoidance is similar to the previous scheme



Intra-eNB Avoidance: Multi-Cellular Hungarian

$$\mathbf{U}_{\text{intra}} = \left[\overbrace{\mathbf{U}_{1|\{\}}\ \mathbf{U}_{2|\{\}}\ \mathbf{U}_{3|\{\}}}^{\text{Sectors 1,2,3 Tx}}\ \overbrace{\mathbf{U}_{1|\{3\}}\ \mathbf{U}_{2|\{3\}}}^{\text{Sectors 1,2 Tx}}\ \overbrace{\mathbf{U}_{1|\{2\}}\ \mathbf{U}_{3|\{2\}}}^{\text{Sectors 1,3 Tx}}\ \overbrace{\mathbf{U}_{2|\{1\}}\ \mathbf{U}_{3|\{1\}}}^{\text{Sector 2,3 Tx}} \right]. \tag{7}$$

$$U_{M\times N} = \begin{pmatrix} u^{(1,1)} & u^{(1,2)} & \dots & u^{(1,N)} \\ u^{(2,1)} & u^{(2,2)} & \dots & u^{(2,N)} \\ u^{(3,1)} & u^{(3,2)} & \dots & u^{(3,N)} \\ \vdots & \vdots & \dots & \vdots \\ u^{(M,1)} & u^{(M,2)} & \dots & u^{(M,N)} \end{pmatrix} \tag{8}$$

$$u^{(m,n)} = \begin{cases} r^{(m,n)} \cdot d^{(m)}; & \text{all 3 transmit,} \\ (r^{(m,n)} - r_p) \cdot d^{(m)}; & \text{1 among 3 is restricted.} \end{cases} \tag{9}$$

Inter-eNB Inter-Cell Interference Avoidance

- Preparation of utility matrix, U_{inter}
  - Similar to earlier scheme: selfishly prepares $U_{M \times N}$
  - Heuristically find potential $I_k^{(n)} = 0$, $\forall k$ in the inter-eNB sectors
- Applying Hungarian algorithm to U_{inter}
  - If a chosen entry has $I_k^{(n)} = 0$ marked, n is noted as to be masked in k
  - Prepare lists of the resource restrictions based on users' status
- Inter-eNB negotiations for resource restrictions
  - Each eNB negotiates the potential resource restrictions by pairwise comparison
  - Restriction is imposed to the sector in which utility is lower
- Resource units resulting from intra- and inter-eNB avoidance are restricted in each sector

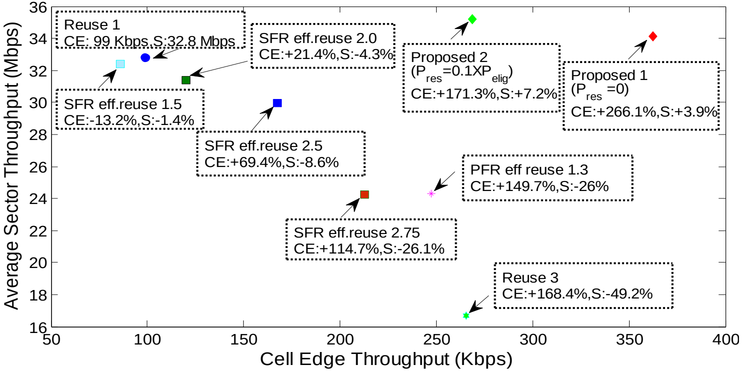
System and Simulation Parameters

Parameter	Assumption
Cellular Layout	Hexagonal grid, 19 sites, 3 sectors/site
Inter-site Distance	500 m
Path-loss	$L_D = 128.1 + 37.6 \log_{10}(D)$, D in km
Shadowing	Independent Log-normal std. 8 dB
Penetration Loss	10 dB
Antenna Pattern	$A(\theta) = \text{-}\min\left[12\left(\frac{\theta}{\theta_{3\text{dB}}}\right)^2, 20\right]$, $\theta_{3\text{dB}} = 70^o$
Bandwidth@Carrier	20 MHz (100 PRBs) @2.0 GHz
Channel model	6-Tap SCME
AMC modes	Attenuated Shannon bound for QPSK, 16- and 64-QAM with varying rates
UE speeds of interest	30 km/hr
Sector TX power	46 dBm
Minimum UE Distance	$\geq$ 35 m

Power Allocation to Physical Resource Blocks

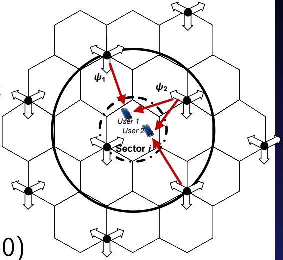
Scheme	Allocated Power
Reuse 1	P_t/N
Reuse 3	$3P_t/N$
PFR 1.3	outer resource: $2.25P_t/N$; inner resource: $1.13P_t/N$
SFR 1.5	outer resource: $1.5P_t/N$; inner resource: $0.75P_t/N$
SFR 2.0	outer resource: $2.0P_t/N$; inner resource: $0.5P_t/N$
SFR 2.5	outer resource: $2.5P_t/N$; inner resource: $0.25P_t/N$
SFR 2.75	outer resource: $2.75P_t/N$; inner resource: $0.13P_t/N$
Proposed 1	eligible resource: $P_t/(N - N_\mathrm{r})$; restricted resource: 0
Proposed 2	eligible resource: $10P_t/(10N_\mathrm{e} + N_\mathrm{r})$; restricted resource: $P_t/(10N_\mathrm{e} + N_\mathrm{r})$

Summarized Results: Distributed Algorithm



Cluster-based Centralized Scheme: Size 3

- UE forms cluster with two most dominant interferers- ψ_1 & ψ_2
- UEs' rates are computed with combinations (Π) of these interferers restrictions



maximize

$$\sum_i \sum_\Pi \left[\sum_{m=1}^{M} \sum_{n=1}^{N} u_{i|\Pi}^{(m,n)} \rho_{i|\Pi}^{(m,n)} \right], \qquad (10)$$

subject to

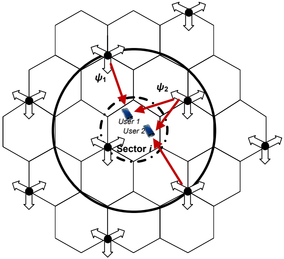
$$\rho_{i|\Pi}^{(m,n)} \in \{0,1\}; \forall m \text{ and } \forall n, \qquad (11)$$

$$I_i^{(n)} = \sum_\Pi \sum_{m=1}^{M} \rho_{i|\Pi}^{(m,n)} = \begin{cases} 0; & \text{resource } n \text{ is restricted in } i \\ 1; & \text{otherwise.} \end{cases} \qquad (12)$$

Cluster-based Centralized Scheme: Size 3 (contd.)

$$\gamma_i^{(m,n)} = \frac{P_c \mathcal{H}_{i,i}^{(m,n)}}{P_c \sum_{\substack{x \neq i \\ x \notin \mathcal{G}_i^{(m)}}} \mathcal{H}_{i,x}^{(m,n)} + P_c \sum_{\psi \in \mathcal{G}_i^{(m)}} \mathcal{H}_{i,\psi}^{(m,n)} \cdot I_\psi^{(n)} + P_{TN}}, (13)$$

- $\gamma_{i|\psi_1}^{(m,n)} = \gamma_i^{(m,n)}$ given, $I_{\psi_1}^{(n)} = 0$
- $r_{i|\psi_1}^{(m,n)} \leftarrow \gamma_{i|\psi_1}^{(m,n)}$
- $u_{i|\psi_1}^{(m,n)} = f\left(r_{i|\psi_1}^{(m,n)}, d_i^{(m)}\right)$



Cluster-based Centralized Scheme: Size 3 (contd.)

Constraints for inter-cluster relations:

$$
\begin{aligned}
\rho_{i|\{\psi_1\}}^{(m,n)} + I_{\psi_1}^{(n)} &= 0 \text{ or } 1, \\
\rho_{i|\{\psi_2\}}^{(m,n)} + I_{\psi_2}^{(n)} &= 0 \text{ or } 1, \\
\rho_{i|\{\psi_1,\psi_2\}}^{(m,n)} + I_{\psi_1}^{(n)} &= 0 \text{ or } 1, \\
\rho_{i|\{\psi_1,\psi_2\}}^{(m,n)} + I_{\psi_2}^{(n)} &= 0 \text{ or } 1.
\end{aligned}
\tag{14}
$$

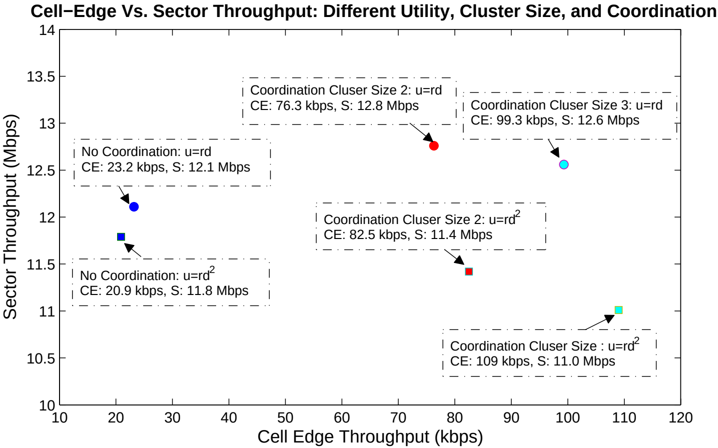
Scheduling constraints:

$$
\sum_{\Pi} \sum_{n} \rho_{i|\Pi}^{(m,n)} \leq 2; \forall i, \ \forall m. \tag{15}
$$

Systems and Simulation Parameters

Parameter	Assumption
Cellular layout	Hex grid, 19 cell sites, 3 sectors/site,
Inter-site distance	500 m
Bandwidth@Carrier	10 MHz (50 PRBs) @ 2.0 GHz
Path-loss exponent	3.76
Shadowing std.	8 dB (independent)
UE speeds	30 km/hr
Penetration loss	10 dB
Antenna configuration	Single-input single-output
eNB antenna gain	14 dBi
UE antenna gain	0 dBi
AMC modes	Attenuated Shannon bound
	for QPSK, 16- and 64-QAM
	with varying rates
Channel model	6-Tap SCME
Total sector TX power	46 dBm
UE close-in distance	35 m
Traffic model	Full buffer

Summarized Results: Cluster-based Centralized Scheme



Complexity Comparison

Complexity Comparison among Studied Schemes[1]

Studied Scenario	No. of Variables	YALMIP Time (sec./iteration)	CPLEX Solver Time (sec./iteration)
No ICIC	1155	0.189	0.016
ICIC with cluster size 2	2310	0.520	0.076
ICIC with cluster size 3	4620	1.378	0.300

[1] Computed in a personal computer with AMD Athlon X2 6400+ CPU, 4 GB main memory, and Windows XP 64-bit OS.

Conclusions

- Dynamic interference coordination is formulated using sum-utility maximization problem
- Three sub-optimal approaches have been pursued
- A unique, two-level algorithm is investigated. The cell-edge performance reaches close to that of Reuse 3 while maintaining Reuse 1 cell throughput.
- A distributed algorithm with neighboring cell coordination is presented. The intra-eNB interference is coordinated using a novel method based on Hungarian algorithm in a multi-cellular context. The proposed schemes attains cell throughput comparable to that in Reuse 1 while achieving a comparable to or slightly better reuse 3 cell-edge throughput.
- A cluster-based centralized scheme with different cluster sizes and utility functions is studied. The presented schemes achieve significant gain in cell-edge throughput without impact on cell throughput.

Future Work

- Utility functions
- Power control
- Inclusion of MIMO
- Integration with other mitigation techniques
- Combining with PHY-layer CoMP

List of Publications

WINNER Deliverables

1. *Description of Identified New Relay Based Radio Network Deployment Concepts and First Assessment by Comparison Against Benchmarks of Well- Known Deployment Concepts Using Enhanced Radio Interface Technologies*, WINNER I Deliverable D3.1, Nov. 2004. Available online at http://www.ist-winner.org/DeliverableDocuments/D3.1v1.1.pdf.

2. *Concept and Criteria for Coordination Across Base Stations to Improve the Mutual Interference Situation*, WINNER I Deliverable D3.3, Jun. 2005.

3. *Description of Identified New Relay Based Radio Network Deployment Concepts and First Assessment by Comparison Against Benchmarks of Well-Known Deployment Concepts Using Enhanced Radio Interface Technologies*, WINNER I Deliverable D3.2, Feb. 2005. Available online at http://www.ist-winner.org/DeliverableDocuments/D3.2v1.1.pdf.

4. *Proposal of the Best Suited Deployment Concepts for the Identified Scenarios and Related RAN Protocols*, WINNER I Deliverable D3.5, Jan. 2006. Available online at http://www.ist-winner.org/DeliverableDocuments/D3.5.pdf.

5. *Interference Avoidance Concepts*, WINNER II Deliverable D4.7.2, Jun. 2007. Available online at http://www.ist-winner.org/WINNER2-Deliverables/D4.7.2.pdf.

PhD Work Included in the Thesis

6. M. Rahman and H. Yanikomeroglu, “QoS provisioning in the absence of ARQ in cellular fixed relay networks through intercell coordination,” in *Proc. IEEE Global Communications Conference (GLOBECOM2006)*, San Francisco, California, USA, Nov. 2006.

7. M. Rahman and H. Yanikomeroglu, “Multicell downlink OFDM subchannel allocations using dynamic intercell coordination,” in *Proc. IEEE Global Communications Conference (GLOBECOM2007)*, Washington DC, USA, Nov. 2007.

List of Publications (contd.)

8. M. Rahman and H. Yanikomeroglu, "Interference avoidance through dynamic downlink OFDMA subchannel allocation using intercell coordination," in *Proc. IEEE Vehicular Technology Conference (VTC2008-Spring)*, May 2008, pp. 1630–1635.
9. M. Rahman, H. Yanikomeroglu, and W. Wong, "Interference avoidance with dynamic inter-cell coordination for downlink LTE system," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC2009)*, Budapest, Hungary, Apr. 2009.
10. M. Rahman and H. Yanikomeroglu, "Enhancing cell-edge performance: A downlink dynamic interference avoidance scheme with inter-cell coordination," *IEEE Transaction on Wireless Communications*, vol. 9, April 2010, pp. 1414-1425.
11. M. Rahman and H. Yanikomeroglu, "Inter-cell interference coordination in OFDMA networks: a novel approach based on integer programming," *Proc. IEEE Vehicular Technology Conference (VTC2010-Spring)*, Taipei, Taiwan, May 2010.
12. M. Rahman and H. Yanikomeroglu, "A cluster-based integer linear programming approach in dynamic interference coordination," submitted to *IEEE Transactions on Vehicular Technology*, June 2011.
13. M. Rahman and H. Yanikomeroglu, "A distributed ICIC algorithm with neighbor coordination", manuscript in-preparation for a possible submission to an *IEEE* magazine.

PhD Work Not Included in the Thesis

14. M. Salem, A. Adinoyi, M. Rahman, H. Yanikomeroglu, D. Falconer, and Y.-D. Kim, "Apparatus and method for allocating subchannels and controlling interference in OFDMA systems," Patent filed by Samsung Korea, Korea patent application no: P2008-0054726 (application date: 11 June 2008); US patent application no: 12/341,933 (application date: 22 December 2008); international patent application no: PCT/KR2009/002119 (filing date: 23 April 2009).
15. M. Salem, A. Adinoyi, M. Rahman, H. Yanikomeroglu, D. Falconer, Y.-D. Kim, and E. Kim, "Fairness-aware joint routing and scheduling in OFDMA-based multi-cellular fixed relay networks," in *Proc. IEEE International Conference on Communications (ICC2009)*, Dresden, Germany, Jun. 2009.

List of Publications (contd.)

16. M. Salem, A. Adinoyi, M. Rahman, H. Yanikomeroglu, D. Falconer, and Y.-D. Kim, "Fairness-aware radio resource management in OFDMA-based cellular fixed relay networks," submitted to *IEEE Transaction on Wireless Communications*, submitted Nov. 2008, revised Jul. 2009.
17. M. Salem, A. Adinoyi, M. Rahman, H. Yanikomeroglu, D. Falconer, Y.-D. Kim, E. Kim, and Y.-C. Cheong, "An overview of radio resource management in relay-enhanced OFDMA-based networks," to appear in *IEEE Communications Surveys and Tutorials*, 2010.
18. F. A. Bokhari, H. Yanikomeroglu, W. K. Wong, and M. Rahman, "Fairness assessment of the adaptive token bank fair queuing scheduling algorithm," in *Proc. IEEE Vehicular Technology Conference (VTC2008-Fall)*, Calgary, Alberta, Canada, Sep. 2008.
19. F. A. Bokhari, H. Yanikomeroglu, W. K. Wong, and M. Rahman, "Cross-layer resource scheduling for multimedia traffic in the downlink of 4G wireless multicarrier networks," *EURASIP Journal on Wireless Communications and Networking, Special Issue on Fairness in Radio Resource Management for Wireless Networks*, 2009.
20. P. Djukic, M. Rahman, H. Yanikomeroglu, and J. Zhang, "Advanced radio access networks for LTE and beyond," in *Evolved Cellular Network Planning and Optimization for UMTS and LTE*, L. Song and S. Jia, Eds. Auerbach Publications, CRC Press, Taylor & Francis Group, 2010.

Thank You!