Distributed Uplink Signal Processing of Cooperating Base Stations based on IQ Sample Exchange

Christian Hoymann
Ericsson Research
Aachen, Germany

Laëtitia Falconetti
Ericsson Research
Aachen, Germany

Rohit Gupta
University of Washington
Seattle, Washington, USA

***Abstract*—Cellular systems in general suffer from co-channel interference, when simultaneous transmissions in other cells use the same physical resources. In order to mitigate such co-channel interference cooperating Base Stations (BSs) can perform joint multi-antenna signal processing across cell borders.**

This paper describes a concept of distributed cooperation, where BSs communicate directly via a BS-BS interface without central control. A serving BS can serve its terminals on its own or it can request cooperation from one or more supporting BSs. By collecting IQ samples from the supporting BSs' antenna elements, the serving BS can virtually increase its number of receive antennas. Exchanging additional parameters allows applying advanced receiver algorithms, e.g., interference rejection or cancelation. Performance evaluations by means of simulation show the capability of BS cooperation applied to 3GPP LTE in terms of cell and user throughput but it also shows the trade-off in terms of increased backhaul requirement due to BS-BS communication.

I. INTRODUCTION

Cellular systems with tight frequency reuse and dense deployment of nodes tend to be interference-limited [1]. In conventional cellular systems, co-channel interference is reduced by radio resource management such as power control, frequency reuse, spreading code assignments, and inter-cell interference coordination.

Multi-antenna reception at a Base Station (BS) allows mitigating interference and increasing carrier signal strength by means of multi-antenna baseband processing. Advanced algorithms, such as Interference Rejection Combining (IRC) requires channel knowledge, while more advanced algorithms, such as Interference Cancelation (IC) receivers, require decoding of interfering data streams [1]. In theory, one can perfectly cancel co-channel interference if interference is known at the receiver and if the number of receive antennas is larger than the number of interferers. Perfect cancelation leads to non-interfered transmissions with a capacity comparable to the Shannon capacity of AWGN channels. However, channel state information of co-channel User Equipments (UEs) is, in general, not available and co-channel streams are not decodeable due to bad signal quality and due to unknown transmission parameters. The number of antenna elements per BS is limited, and multi-antenna reception at a single BS does not leverage the information available at neighbor BSs.

Leveraging antennas of several cells allows multi-user detection across cell borders leading to improved link quality. Such cooperation across cells is most often modeled as a single super-BS with remote antennas in several cells [2], [3]. This centralized approach mitigates interference between cells of the same super-BS, but interference between cells of different super-BSs remains. BS cooperation with distributed control has been presented in [4], where coded and uncoded bits are exchanged between cooperating BSs.

The concept presented in this paper is to mitigate co-channel interference by means of I/Q sample exchange between cooperating BSs. A given BS, which itself has too few antennas to mitigate co-channel interference sufficiently, collects I/Q samples from supporting BS antennas in order to process signals from a larger number of antennas. Such a BS virtually increases its number of receive antennas. BSs can request cooperation on-demand: a serving BS can virtually increase its number of receive antennas in case of high co-channel interference and it can process signals of its own antenna elements in case of low co-channel interference.

Distributed cooperation requires an appropriate BS-to-BS interface. It does not affect core network nodes. For Uplink (UL), required changes to the radio interface are expected to be minor. Thus, UL cooperation can, e.g., be integrated in the 3GPP logical LTE/SAE architecture. It is backward compatible and can be seen as a potential evolution path.

The paper is organized as follows. The concept of UL cooperation is described in section II and is exemplified using Long-Term Evolution (LTE). Section III discusses some BS algorithms affected by cooperation, whereas section IV focusses on the integration of BS cooperation into the conventional cellular system architecture. Finally, some performance results are provided in section V and section VI concludes the paper.

II. UL COOPERATION OF BASE STATIONS

A given UE is associated to one serving BS, which controls the UE. During scheduling, the BS allocates certain Resource Blocks (RBs) for UL transmission to the UE. The serving BS can then request support from one (or more) BS for a particular UE transmitting on certain RBs. Figure 1 shows the Message Sequence Chart (MSC) of the cooperation process. Having received the UE signal on the indicated RBs, the supporting BS transfers IQ samples received on its antennas to the serving BS. An IQ sample is the complex representation

This work has been partly funded by the German Federal Ministry of Education and Research under the grant 01BU0634 (EASY-C). The authors acknowledge the excellent cooperation within the project.

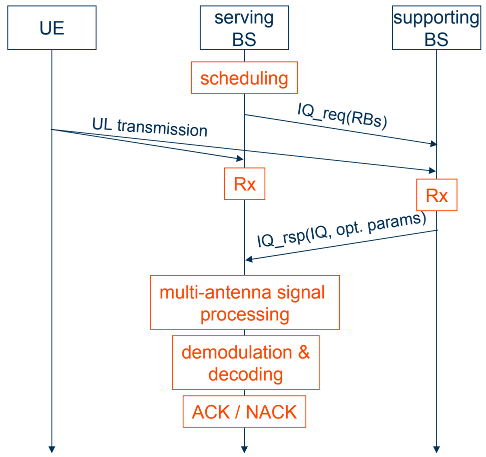

Fig. 1. (MSC) of requesting IQ samples from a supporting BS

of a constellation point of a given subcarrier received on a given antenna. It is the output of the Fast Fourier Transform (FFT) at the OFDM receiver chain and basically contains the amplitude and phase with which a particular subcarrier has been modulated, see Fig. 2. Having received IQ samples from the supporting BS, the serving BS jointly processes the received signals of all antennas.

Figure 1 shows that there is no need for a dedicated control node. Whenever the serving BS requires support, it requests it from one or more BS of choice. There are several ways to select an appropriate supporting BS. It can be based on location, on pathloss (long-term channel statistics) or on actual channel realization (short-term), see section III-A.

An example LTE user plane protocol stack of cooperating BSs is shown in Fig. 2. The right hand side of the figure focusses on the LTE BS Physical Layer (PHY) layer. The supporting BS extracts the IQ samples of the indicated RBs from its FFT module and transfers them to the serving BS via the BS-BS interface. This BS-BS interface can be any interface that fulfils the capacity and delay requirements, see section IV. The serving BS exploits the IQ samples in its own PHY layer. Thereby the serving BS's PHY layer virtually increases the number of antenna elements on which the receiver can perform signal processing. Assuming both BSs have four antenna elements each, signal processing is as powerful as if the serving BS would have eight antennas.

Usually, the BS processes signals received at its own antennas. With UL cooperation the serving BS re-uses the same receiver algorithms for processing its own received signals and the ones of the supporting BSs. Algorithms such as IRC mitigate co-channel interference. Alternatively, the serving BS could apply IC. With IC, the serving BS demodulates and decodes co-channel streams in order to re-generate the interfering signal. Then the serving BS subtracts the known interference from the received signal. In order to demodulate and decode interfering streams, the serving BS requires information about the parameters used at the transmitter, i.e., UE. Those parameters can be inserted in the supporting BS's response message (optional parameters in Fig. 1).

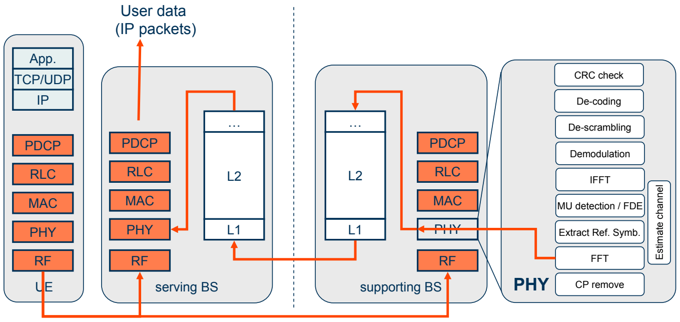

Fig. 2. User plane protocol stack of cooperating LTE BS

III. ALGORITHMS AFFECTED BY BS COOPERATION

A. *Selection of supporting BSs*

By means of cooperation, a serving BS virtually increases its number of receive antennas. Hence, advanced receiver algorithms can significantly increase Signal to Interference plus Noise Ratio (SINR) of the received signal. Although the serving BS has interest in getting cooperation from as many supporting BSs as possible, the BS's backhaul capacity puts a restriction on the number of supporting BSs per UE and on the number of UEs that are supported by that BS. As cell-edge UEs are most affected by co-channel interference, they should be prioritized to be supported. Cell-edge UEs measure on co-channel BSs for mobility purposes. The serving BS can use these reports to select a set of supporting BSs.

B. *Link adaptation*

Modulation and Coding Scheme (MCS) selection is carried out by the serving BS. Based on the UL SINR the BS selects the MCS that maximizes the user throughput under the constraint of a Block Error Ratio (BLER) target. BS cooperation increases the UL SINR perceived at the serving BS. Thus, link adaptation should be based on the increased SINR after cooperation. Thereby, the BLER target can be met with a more aggressive MCS resulting in a higher throughput.

C. *Power control*

The UE transmit (Tx) power consists of an open loop and a closed loop component. In the open loop power control mechanism, each UE selects an appropriate Tx power based on the Downlink (DL) pathloss to the serving BS. With cooperation, a UEs could consider supporting BSs, too. Then, UEs need to know which BSs currently cooperate. This reduces the serving BS ability to react quickly to changing transmission conditions.

With closed loop power control the UE Tx power is adjusted by the serving BS by sending a Transmit Power Control (TPC) command. With cooperation, TPC should adjust the UE Tx power to the aggregated receive power of the serving and the supporting BS. Thus, the same quality of service can be achieved with a lower UL Tx power.

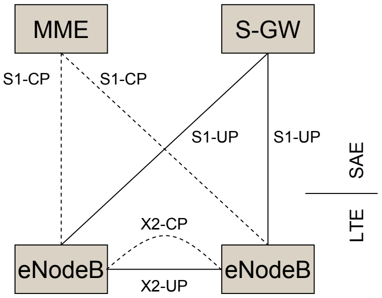

Fig. 3. LTE/SAE logical architecture

D. ARQ mechanisms

Automatic Repeat Request (ARQ) mechanisms transmit feedback after having received a packet. With cooperation, reasonable ACK/NACK feedback can be transmitted by the serving BS only after the joint signal processing has been completed. For instance, 3GPP LTE specifies that Hybrid ARQ (HARQ) feedback is sent three Transmission Time Intervals (TTIs) after the data transmission. Thus, either the process of BS cooperation including IQ exchange and joint signal processing is finished in time or the HARQ mechanism needs to be adapted to allow for longer feedback delays.

IV. INTEGRATION OF COOPERATION INTO LTE/SAE LOGICAL ARCHITECTURE

3GPP's core network (named System Architecture Evolution (SAE)) and the radio access (named Long-Term Evolution (LTE)) are evolving in parallel [5]–[7]. The resulting flat architecture is composed of only two logical nodes in the User Plane (UP): the eNodeB and the Serving Gateway (S-GW), see Fig. 3. The S-GW executes packet filtering, classification and it provides the connection to the Internet or to Public Land Mobile Network. An eNodeB provides the LTE radio access. Like in the UP, only two nodes are involved in the Control Plane (CP): the eNodeB and the Mobility Management Entity (MME). The MME handles core network control functions, such as attach/detach handling, mobility functions, bearer management, and security. eNodeBs are connected to the core network using the IP-based interface S1. The logical interface between eNodeBs, i.e., the IP-based X2 interface supports loss-less mobility and multi-cell Radio Resource Management (RRM).

Cooperative BSs with distributed control can be smoothly integrated in the logical architecture since the serving BS keeps controlling the UE. From the core network perspective the serving BS remains the point of contact for both user and control plane. From a UE perspective UL cooperation is transparent, meaning that UEs are not aware whether they are served cooperatively or not. No new node is introduced.

For UL cooperation, a BS-BS interface is required to exchange IQ data between BSs. If BSs of one eNodeB cooperate the required interface could be eNodeB internal. If BSs of different eNodeBs cooperate the required information is exchanged via the X2 interface, whose specification would have to be enhanced.

V. PERFORMANCE EVALUATION

A. Simulation environment

The behavior of cooperative BSs has been implemented in a multi-cell radio network simulator modeling OFDM transmission with multi-antenna transmitters and receivers.

In the following, BS cooperation is evaluated in a fully loaded 10 MHz FDD LTE network which consists of 7 sites with three sectors (cells) per site. The inter-site distance is 500 m. Each cell has 10 users in average and operates at a carrier frequency of 2 GHz. Each BS has four antennas using an IRC receiver for both non-cooperative reception based on its own antennas as well as cooperative reception based on its own and on supporting BS's antennas. The evaluation assumptions are essentially based on the Next Generation Mobile Networks (NGMN) recommendations [8]. The channel model used for evaluation is the urban scenario outlined in [9].

In a 10 MHz LTE system, 50 RBs are available for UL transmission. A channel dependent BS scheduler allocates a group of 5 RBs to each of the 10 users according to their experienced channel conditions. If there are more than 10 users in a cell, the scheduler selects users that have been scheduled least previously. If there are less than 10 users in a cell, some RBs remain empty. BSs allocate RBs independently of each other. Once resources are allocated, BSs request support for selected RBs.

A conventional open loop power control, which is not adapted to BS cooperation, is applied. Link adaptation allows QPSK, 16QAM, and 64QAM modulation schemes. Turbo coding with adaptive rate matching allows for various combinations of MCSs. Link adaptation operates ideally on the increased SINR after BS cooperation. The MCS for the current transmission is selected based on perfect knowledge of the experienced SINR at the receiver. A link-to-system interface based on mutual information maps the packet SINR to the corresponding BLER [10]. The extra delay introduced by BS cooperation is assumed to be low enough so that HARQ feedback can be send in time.

In the following, we use the expression *cooperating* or *supporting cell* meaning that the BS serving the particular cell cooperates by providing IQ samples of the corresponding antennas. For instance, when cooperation is restricted to a maximum of 3 supporting cells, than the UE signal is received in up to 4 different cells by 16 different antennas. Another parameter named *cooperation range* determines which UEs will be served under cooperation. Only UEs measuring a signal strength of co-channel BS within a certain cooperation range below the signal strength of the serving BS are chosen for cooperation. In the following the impact of the maximum number of supporting cells per UE and the cooperation range on performance is studied.

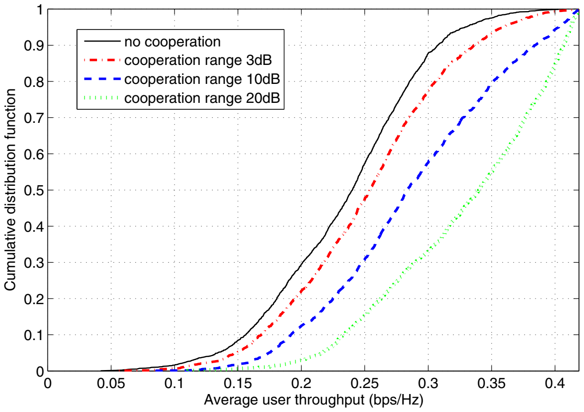

Fig. 4. CDF of average user throughput for different cooperation ranges (max. of 3 supporting cells)

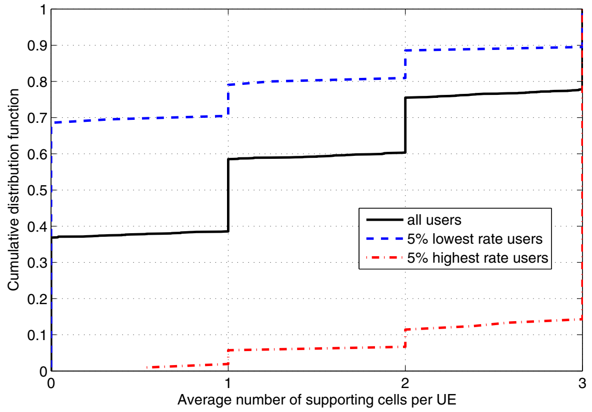

Fig. 5. CDF of average number of cooperative cells per UE (max. of 3 supporting cells, cooperation range of 10dB)

TABLE I
AVERAGE CELL THROUGHPUT AND 5%-PERCENTILE USER THROUGHPUT FOR DIFFERENT COOPERATION PARAMETERS

	Av. cell throughput		5%-percentile user throughput	
	$[{}^{bps}/_{Hz}]$	[%]	$[{}^{bps}/_{Hz}]$	[%]
No cooperation	2.35		0.134	
3 supp. cells, 3dB range	2.52	+7	0.150	+12
3 supp. cells, 10dB range	2.87	+22	0.174	+30
3 supp. cells, 20dB range	3.29	+40	0.217	+62
1 supp. cells, 10dB range	2.67	+14	0.161	+20
5 supp. cells, 10dB range	2.91	+24	0.175	+31

B. *Performance evaluation*

Figure 4 shows the enhancement in the average user throughput due to cooperation. High rate as well as low rate users benefit. When increasing the cooperation range from 3 to 10 dB a higher number of potentially supporting BSs can be received by the UEs within that range. Thus the number of UEs eligible for cooperation as well as the number of supporting cells per UE increases. With a range of 20 dB nearly all BSs are candidates for cooperation.

Table I shows the average cell throughput and the 5%-percentile user throughput obtained for different parameters. The average cell throughput is increased by about 22% when allowing cooperation within 10 dB range with up to 3 supporting cells. A larger gain is observable for low rate users: the 5%-percentile is improved by 30%. With an increased cooperation range of 20 dB the average cell throughput increases by 40% and the 5%-percentile increases by 62%.

Figure 5 shows the Cumulative Distribution Function (CDF) of the average number of supporting cells per UE. About 35% of all UEs do not get support at all. About 20% of all UEs are supported by the maximum of 3 cells. High rate users are more often supported: 75% are supported by 3 cells. By contrast, low rate users are supported less: about 70% get no support at all and only 10% are supported by 3 cells.

Cell-edge users usually receive signals from a number of co-channel BSs within the cooperation range so they are supported by co-channel BSs. Cell-center users are usually not supported because they do not receive signal from other BSs within the cooperation range. However, Fig. 5 indicates that the group of supported users perceive an unproportionately high throughput, meaning that the throughput of cell-edge users has exceeded the average throughput. Hence, by means of BS cooperation one could fundamentally modify the distribution of perceived capacity within the cell area, which usually decreases towards the cell edge. A more equal and fair distribution across the cell area can be achieved.

Figure 6 shows the impact of the maximum number of supporting cells per UE. If a serving BS is allowed to cooperate with more supporting BSs it can exploit signals received by more supporting BS antennas. Depending on the quality of the received signals, the SINR of the UE can be further improved and a higher order MCS can be used, resulting in a user throughput rise.

When increasing the number of supporting cells from 1 to 3, especially high rate users benefit. Those users are already supported by cooperating BSs, see Fig. 5, however, now they can be supported by even more BSs. Low rate users do not benefit much. They do not receive many BSs within the cooperation range anyway so they cannot increase the number of supporting cells.

Increasing the maximum number of cooperating cells per UE further from 3 to 5 does not enhance the user throughput much. The cooperation range of 10 dB limits the increase. The 4^{th} and 5^{th} candidate cells are simply too far away from the UE so that they do not receive the UE signal reasonably strong.

C. *Backhaul requirement*

Cooperation requires information exchange between BSs located at different sites. By means of system level simulations, the required backhaul capacity per site is measured as the sum of the input and output traffic generated by one three-sectored BS due to the exchange of I/Q vectors. Information exchange between cells of the same site is neglected. For the following evaluation one I/Q sample is assumed to be quantized with

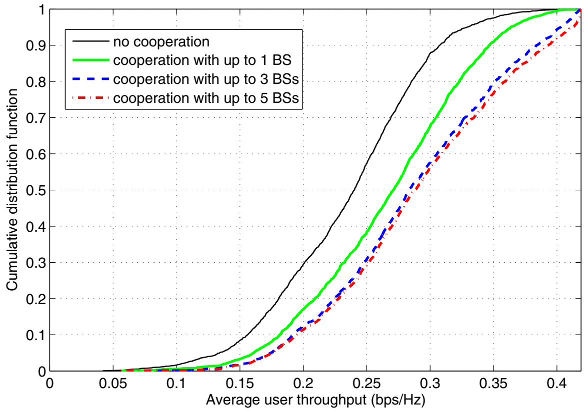

Fig. 6. CDF of average user throughput for different values of the maximum number of supporting cells (cooperation range of 10dB)

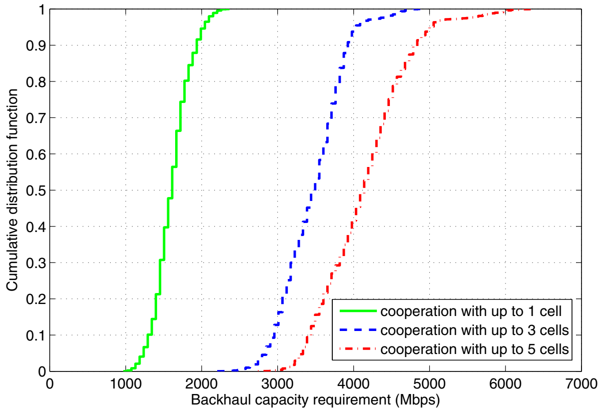

Fig. 7. CDF of backhaul capacity requirement per site for different values of the maximum number of supporting cells (cooperation range of 10dB)

16 bit. Figure 7 shows the resulting backhaul capacity requirement per site for different numbers of cooperating cells for a given cooperation range of 10 dB. Cooperating with only 1 supporting cell results in an average backhaul capacity of 1.6 Gbps. The required average backhaul capacity increases to 3.45 Gbps and 4.1 Gbps when cooperating with 3 and 5 cells, respectively.

Obviously, increasing the maximum number of cooperating cells increases the backhaul requirement, however, user throughput is increased as well. The optimum number of cooperating cells depends on the operator's core network capacity. In order to support the operators' decision, a new metric can be introduced: how much average backhaul capacity do I need to spend in order to increase average cell throughput? Table II answers that question.

VI. CONCLUSION

Cooperative BSs allow mitigating co-channel interference and increasing received signal strength by means of distributed multi-antenna signal processing, an effective and highly efficient method. The number of antenna elements with which a serving BS jointly processes received signals can be virtually increased. The maximum number of elements is only limited by the transmission capability of the BS-BS interface and the processing power at the serving BS.

TABLE II
REQUIRED BACKHAUL CAPACITY PER INCREASED CELL THROUGHPUT

	required backhaul capacity [bps] per increased cell throughput [bps]
1 supp. cell, 3dB range	24
3 supp. cells, 3dB range	35
1 supp. cells, 10dB range	60
3 supp. cells, 10dB range	120
5 supp. cells, 10dB range	140

Performance evaluation by means of simulation showed the great capability of BS cooperation applied to LTE: the average cell throughput could be increased between 7 and 40%; the 5%-percentile user throughput increased between 12 and 62%. As a trade-off, the requirement on backhaul capacity increases, too: between 1.6 and 4.1 Gbps are required for the information exchange between three-sectored sites.

Finally, cooperation can be integrated in the 3GPP logical LTE/SAE architecture either as an intra-eNodeB or as an inter-eNodeB feature. The approach is implicitly backward compatible and can be seen as a potential evolution of cellular LTE systems.

REFERENCES

[1] J. Andrews, "Interference cancellation for cellular systems: a contemporary overview," *IEEE Wireless Communications*, pp. 19–29, Apr 2005.

[2] S. Venkatesan, "Coordinating base stations for greater uplink spectral efficiency in a cellular network," in *Proceedings of the 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2007.

[3] P. Marsch and G. Fettweis, "A framework for optimizing the uplink performance of distributed antenna systems under a constrained backhaul," in *Proceedings of the IEEE International Conference on Communications ICC*, 2007.

[4] L. Falconetti, C. Hoymann, and R. Gupta, "Distributed uplink macro diversity for cooperating base stations," in *Proceedings of the International Workshop on LTE Evolution*, June 2009.

[5] 3GPP, "3GPP TS 36.300, Technical Specification Group Radio Access Network; E-UTRA and E-UTRAN; Overall description," Sep 2006.

[6] 3GPP, "3GPP TS 23.401, Technical Specification Group Services and System Aspects; GPRS enhancements for E-UTRAN access," Mar 2008.

[7] E. Dahlman, S. Parkvall, J. Skold, and P. Beming, *3G Evolution: HSPA and LTE for Mobile Broadband*, 2nd ed. Academic Press, October 2008.

[8] Next Generation Mobile Networks (NGMN) Alliance, "NGMN Radio Access Performance Evaluation Methodology," NGMN White Paper, January 2008.

[9] 3GPP, "3GPP TR 25.996, Technical Specification Group Radio Access Network; Spacial channel model for Multiple Input Multiple Output simulations," June 2007.

[10] K. Brueninghaus, D. Astely, T. Salzer, S. Visuri, A. Alexiou, S. Karger, and G. Seraji, "Link performance models for system level simulations of broadband radio access systems," *IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005*, 2005.