Abstract—MIMO and higher-order modulation (64-QAM) have recently been introduced in the HSPA downlink (HSDPA) to extend peak data rates. Both techniques demand a high SINR operating point in order to be effective. While traditional macrocell (outdoor) deployments may provide limited high-rate coverage, indoor environments are more likely scenarios for achieving high rates due to higher SINR operating points. This paper evaluates performance for an indoor pico-cell system using a selective-PARC (S-PARC) MIMO scheme in combination with 64-QAM. A typical multi-story office building is considered with pico-cells located on each floor. Within each pico-cell both a single antenna cluster and distributed antenna clusters are considered. Results from system simulations show very large gains in both user and system throughput compared to a receive diversity only system. 90th percentile user throughput over 40 Mbps and system throughput of 30 Mbps are achieved.

I. INTRODUCTION

Both MIMO and higher-order modulation (64-QAM) have been introduced in the HSPA downlink (HSDPA) in Releases 7 and 8 of the standard. Taking advantage of these techniques requires signal-to-interference-plus-noise ratio (SINR) operating points that are higher than typically obtained in traditional macrocell (outdoor) deployment scenarios. In contrast, dedicated indoor deployment scenarios have the potential to raise SINR operating points. This is achieved by reduced path loss between base station and mobile, better controlled inter-cell interference, and less dispersive radio channels.

A number of deployment scenarios have been considered for improving data rates indoors. In [1], microcells are considered to provide coverage within buildings in a dense urban area, and it is shown how reducing cell size improves performance relative to larger macrocells. One issue is that the achievable rate indoors is subject to propagation from the external microcell; hence it is not uniform within the building.

To improve indoor coverage, dedicated in-building systems are attractive. Such systems are commonly deployed as a single cell with simultaneous transmission of the downlink signal from antennas distributed throughout the building. This type of system is considered in [2], [3], with passive coaxial or optical fiber distribution used for signal transport to the remote antennas, respectively. In this type of deployment, low transmit power coupled with the users’ close proximity to a transmitter provide good signal integrity.

Alternatively, indoor systems may be deployed as one or more pico-cells. A single pico-cell configuration together with a generic MIMO scheme is considered in [4]. Using ideal Shannon capacity as a metric, it is shown that MIMO has the potential to enhance system performance. Both single and multiple pico-cells (without MIMO) are considered in a field measurement study reported in [5]. In a multiple pico-cell deployment, controlling the inter-cell interference is a key aspect in improving both user throughput and system capacity. One basic solution is to use zoning, i.e., sectorization, and zoning coupled with antenna selection is considered in [6].

In this paper, a multiple pico-cell system is considered operating with the selective-PARC (S-PARC) MIMO scheme described in [7] in combination with 64-QAM modulation. This study extends the above work by considering both a practical MIMO scheme, similar to that in the HSPA standard, operating with a practical receiver structure. In addition, a full-blower dynamic system simulator is employed, implementing many of the key features of HSPA, e.g., fast link adaptation, fast hybrid ARQ to improve latency, and fast user scheduling to take advantage of multi-user diversity. A typical multi-story office building is considered with pico-cells located on each floor. Within each pico-cell both a single antenna cluster and distributed antenna clusters are considered. For the latter, an individual cluster is selected for transmission based on the instantaneously best propagation conditions to each user. The goal of this paper is to show that the indoor environment indeed provides SINR operating points such that both MIMO and 64-QAM can be used to full advantage in enhancing user throughput and system capacity. The goal is to additionally show that the use of distributed antenna clusters with cluster selection further enhances performance, both in terms of coverage and capacity.

II. INDOOR SYSTEM DESCRIPTION

A. Building Layout

The system under consideration contains a number of antenna clusters dispersed throughout a building. The layout of a four-story building is shown in Fig. 1, where the floor plan is the same for each floor, and the floor height is 4 meters. The building layout is specified by the locations of its floors and exterior and interior walls. For simplicity, these are assumed to be rectilinear.

B. Base Station and Antenna Deployment

Possible antenna cluster placements for the different floors are indicated in Fig. 1. The cluster locations on the odd and even-numbered floors are marked by ‘x’ and ‘+’ symbols, respectively. It was not attempted to optimize the location of the antenna clusters, other than to avoid placing them in
the same location on adjacent floors. Each cluster consists of 
$M = 1, 2, \text{ or } 4$ transmit antennas, depending on the MIMO 
configuration in effect. The transmit antennas are assumed to 
be omni-directional with a gain of 0 dB.

Three different pico-cell configurations are considered. The 
first one (C1) consists of one pico-cell (one base station) per 
floor and connects the base station to only one antenna cluster. 
Arbitrarily, the connection is chosen to be with the single clus-
ter shown at the top of Fig. 1. The second configuration (C2) 
is like the first, but connects the base station to both clusters 
shown in Fig. 1. Even so, only one cluster is active at any given 
time. The cluster with the instantaneously best propagation 
conditions to a given user is selected for transmission. The 
third configuration (C3) consists of two pico-cells (two base 
stations) per floor. For this configuration, the base stations are 
connected to only one cluster each, one to the cluster shown 
at the top of Fig. 1, the other to the one shown at the bottom.

C. User Placement and Mobility

To obtain a certain system loading, a number of users are 
placed randomly in the building, both across floors and across 
the floor plan. With a uniform placement of a user within 
the floor plan, it is easy to visualize that some users have LOS 
paths while others are shadowed by walls, floors or both. In 
addition to each user’s location, the user is placed into one of 
two states: static or in-motion, with a probability that the user 
is initially in motion equal to 0.4.

For users in motion, each user is given an initial random 
direction and velocity. Initial values are drawn from uniformly 
random distributions, with direction from [0,2$\pi$] radians, and 
velocity from [0,3] km/hr. During the simulation, each user can 
make a state change between the in-motion and the static states 
with a transition probability set according to that specified in 
[8]. A user’s motion is restricted to one floor throughout the 
simulation.

D. MIMO Configuration

Fig. 2 shows the S-PARC transmit structure with $M$ transmit 
antennas per cluster used in this study. In this diagram, the 
transmitter is configured for mode-$N$, i.e., $N \leq M$ data 
streams are transmitted. The selected data rate for each stream 
is based on the feedback of channel quality indicators (CQIs) 
from the mobile. The CQIs are simply quantized versions of the 
signal-to-interference-plus-noise ratios (SINRs) at multiple 
stages of a successive interference cancellation (SIC) receiver 
described below. Both the mode and the physical antennas on 
which the streams are transmitted are adaptive, and the 
adaptation is based upon a maximization of the sum data rate 
across streams. In this way, the transmitter adapts to poor 
propagation conditions by selecting lower order modes, and 
good propagation conditions by selecting higher order modes.

In addition to the high-speed downlink shared channel (HS-
DSCH) transmitted on $N$ antennas, Fig. 2 also shows the 
transmission of a pilot on all $M$ antennas to facilitate channel 
estimation at the receiver. Overhead (control) channels are 
transmitted on from antenna 1 only. The multiple channel-
ization codes used for the HS-DSCH data streams are reused 
across antennas in order to extend peak data rates.

Note that for two transmit antennas ($M = 2$), S-PARC is 
similar to the recently standardized MIMO scheme for Rel-
7 of the WCDMA standard known as D-TxAA. D-TxAA 
employs a form of unitary precoding based on a codebook 
of 4 phase-only weight vectors. S-PARC can be considered as 
a special case of this where the codebook is replaced by the 
columns of the $2 \times 2$ identity matrix. From our own studies we 
have found that the two systems exhibit very similar trends in 
performance.

III. System Simulation Approach

A. Link Adaptation

In this study, the receiver is based on a combination of 
 successive interference cancellation (SIC) and generalized-
Rake (GRake) concepts. The structure of the SIC-GRake 
receiver is fully described in [9]; however, we discuss the 
salient features here in order to understand the link adaptation 
process as well as the link-to-system interface.

For link adaptation, an expression for the post-combining 
SINR at each stage of the SIC-GRake receiver is required. 
According to [9], the SINR at the $n$th stage is given by

$$\rho_n = \frac{|w_n^H h_n|^2}{w_n^H R_n w_n}$$

where $w_n$ is the combining weight vector for the $n$th stage. For 
the case of G-Rake combining, this is given by $w_n = R_n^{-1} h_n$.

In these expressions, the vector $h_n$ is the spatial net response 
and is a function of the channel response between the physical 
antenna from which the $n$th stream is transmitted and all 
receive antennas. In addition, it is a function of the finger 
delays and the combined response of the transmit and receive 
filters. The matrix $R_n$ is the spatio-temporal covariance of 
the impairment process consisting of interference (own-cell 
and other-cell), noise, as well as interference due to code reuse 
across streams. The covariance matrix is necessarily a function 
of the stage index $n$ to reflect the progressive reduction of 
interference inherent in the successive cancellation of previ-
ously decoded streams. Furthermore, it reflects the fact that 
pilot subtraction is also implemented in the receiver.

To enable link adaptation, the mobile terminals feed back 
quantized values of the per-stream SINRs $\{\rho_1, \rho_2, \cdots, \rho_N\}$ 
corresponding to the preferred mode (number of streams) and 
the preferred antenna selection for that mode. The preferred 
mode/antenna selection is determined by considering all pos-
ible antenna subsets, and for each subset the per-stream SINRs 
are mapped to data rates through a look-up-table. The per-
stream rates are then summed, and the mode/antenna selection 
with the largest sum data rate is selected. The selection is then 
indicated through a feedback channel which incurs some delay.

The modulation and coding scheme (MCS) look-up ta-
ble used for mapping per-stage SINRs to per-stream data 
rates contains a number of SNR-rate combinations plotted in 
Fig. 3. Each data rate corresponds to a particular combination.
of modulation type, number of channelization codes, and encoding rate. In this study, the number of channelization codes per-stream used for the HS-DSCH is fixed at 12. The SNR switching point for each MCS is determined through AWGN simulation and corresponds to the 10% block-error-rate (BLER) level. As indicated in Fig. 3, QPSK is used for per-stream SINRs below about 5.5 dB, 16-QAM is used for SINRs between 5.5 dB and 13 dB, and 64-QAM is used for SINRs greater than 13 dB. Using this table, the peak aggregate rate is 17.3N where N is the number of transmitted streams, i.e., mode. It is useful to note that the largest per-stream rate for the 16-QAM MCSs is 9.85 Mbps. Hence, if the aggregate rate over streams selected through link adaptation is greater than 19.7 (2-streams) or 39.4 (4-streams), one can infer that 64-QAM MCSs are being utilized.

B. Indoor Propagation Modeling

The path gain from each antenna cluster to each mobile user consists of the distance gain from the transmitter to receiver and shadow fading. Additionally, the path gain is smoothed to avoid discontinuities as users move. Fast fading is modeled using the IndoorA/IndoorB fading models from [8], assigned to each user with a 50% probability.

1) Distance Gain: The Keenan-Motley model is used to compute the distance path gain according to the expression

\[ G_p(d) = G_{fs}(d)10^{-0.1(kK+wW)} \]

where \( d \) is the distance between the transmitter and receiver; \( k \) is the number of floors between the transmitter and receiver; \( K \) is the floor attenuation factor (20 dB / floor); \( w \) is the number of walls between the transmitter and receiver; \( W \) is the wall attenuation factor (4 dB / wall); \( G_{fs} \) is the free space path gain given by \((\lambda/(4\pi d))^2\); and \( \lambda \) is the wavelength corresponding to the carrier frequency (2 GHz). Indirect propagation from one floor to the next through indoor-outdoor-indoor paths (e.g., such as those paths through windows) is not considered here.

2) Shadow Fading: Shadow, i.e., slow, fading is used to model additional objects within the building aside from wall and floor obstructions. This is implemented as the log-normal distribution

\[ G_s = \log_{10}N(\nu, \sigma) \]

where the mean \( \nu \) equals zero and the standard deviation \( \sigma \) equals 3 dB. Shadowing is assumed to be uncorrelated from one antenna cluster to the next. User correlation distance is set to one meter.

C. Simulation Parameters

Other important parameters for the HSDPA system simulation are as follows:

- Maximum transmit power from each cluster of antennas is restricted to 25 mW (14 dBm)
- Pilot power is 10% of maximum power for \( M = 1 \), 12.5% for \( M = 2 \), and 15% for \( M = 4 \)
- Remainder of power (70-75%) allocated to HS-DSCH after power requirement is met for pilots and overhead channels
- Hybrid ARQ employs Chase combining. Block error on any one data stream forces retransmission of all data streams.
- Continuous traffic model, i.e., full transmit buffers all of the time
- Proportional fair scheduling
- Error-free CQI feedback; non-ideal link adaptation modeled through 2 TTI feedback delay (4 ms)

D. Performance Measures

Two performance measures are considered, namely user and system throughput, obtained for offered loads of 1, 2, 4, 6, 8, and 10 users/cell. User throughput is defined as the number of correctly delivered bits to each user (accounting for retransmissions) divided by the simulation time. User throughput is a random variable across the ensemble of users. The 10th and 90th percentiles are adopted as a measure of performance for the 10% most disadvantaged (worst-case) and 10% most advantaged (best-case) users, respectively. System throughput is defined as the number of correctly delivered bits to all users in the system normalized by the total number of floors. Recall that depending on the pico-cell configuration, there can be either 1 or 2 cells per floor (see Section II-B).

For reference, throughput results for receive diversity (single transmit, two receive antennas) are generated. The receiver for this system is a special case of the SIC-GRake receiver in that only one stage is required since only 1 stream is transmitted.

IV. Results

Figs. 4 and 5 show the 10th and 90th percentile user throughput vs. system throughput, respectively. Here, one pico-cell per floor and one or two antenna clusters per cell are compared. This corresponds to configurations C1 and C2 described in Section II-B. Results for different numbers of transmit and receive antennas (\( M \) and \( L \)) are shown. Evidently, the use of distributed clusters (C2) offers approximately a 25% gain in user throughput and a 10% gain in system throughput compared to a single cluster (C1).

Fig. 6 shows the distribution of the receiver post-combining SINR (for stage-1), and Fig. 7 shows the distribution of the data rates selected through link adaptation. The improvement in SINR and MCS rate using distributed clusters could additionally allow for improved coverage by either allowing for larger cells (or fewer base stations). The cross-over of some of the curves may be related to the fact that users sometimes connect to cells from different floors.

Fig. 8 shows the number of antennas selected for transmission (i.e., transmit mode). Clearly, for all of the \( M \times L \) MIMO systems considered, the maximum number of streams supported by the channel (2 or 4) is selected a very large percentage of the time. Furthermore, one can infer from this as well as Figs. 3 and 7, that the 64-QAM MCSs are selected 30-40% of the time, depending on the antenna configuration. This indicates that the indoor environment offers an SINR operating regime that is well-suited to exploit the data rate gains offered by both MIMO and 64-QAM.
Fig. 4 compares the 10th percentile user throughput vs. system throughput between configurations C2 and C3. Recall that C2 and C3 correspond to different number of pico-cells per floor — one in the former and two in the latter. It is useful to note that the same number of users per cell corresponds to different numbers of users per floor, hence the normalization used on the x-axis. Clearly, by investing in more base stations, a system capacity gain is achieved; however, the increase is less than a factor of two due to increased inter-cell interference.

V. CONCLUSIONS

We show in this paper that indoor environments provide the SINR levels required to enable high data rates for the HSPA downlink, making significant use of both 64-QAM and 4-stream MIMO transmission. Multiple pico-cells are used to improve both user throughput and system capacity. Introducing distributed antenna clusters provides a trade-off of coverage for system capacity, although system capacity still improves moderately when the number of base stations remains the same. It is observed that good performance requires careful cell definition and antenna placement, as propagation between floors may occur, blurring the desired cell boundaries. Future work includes incorporating practical hardware impairments to determine their effect on performance.

REFERENCES


Fig. 4. 10th Percentile User and System Throughputs, Config C1 vs. C2

Fig. 5. 90th Percentile User and System Throughputs, Config C1 vs. C2

Fig. 6. CDF of Receiver Post-Combining SINR, Config C1 vs. C2

Fig. 7. CDF of MCS Rate Selection, Config C1 vs. C2

Fig. 8. PDF of Transmitter Mode Selection, Config C1 vs. C2

Fig. 9. 10th Percentile User and System Throughputs, Config C2 vs. C3