Multi-Cell Field Trial on a Wireless Feeder Uplink for Small Cells

Michael Grieger, Gerhard Fettweis, Sven-Einar Breuer
Technische Universität Dresden,
Vodafone Chair Mobile Communications Systems,
Email: {michael.grieger, fettweis, sven-einar.breuer}@ifn.et.tu-dresden.de

Abstract—It is expected that the ever increasing demand for higher data rates in mobile networks will force operators to deploy denser networks using a large number of additional Small Cells (SCs). However, the identification and deployment of new sites is not an easy and therefore a costly project. A major challenge is the required broadband feeder link of new sites to the backhaul network. At locations where copper and fiber are not available, wireless technologies are the alternative which today works well for line-of-sight (LOS) connections where highly directive antennas can be used. High throughput non-line-of-sight (NLOS) wireless links, which are in the focus of this work, are much more difficult to deploy because of increased path-loss and channel fading due to moving scatterers which motivate the use of more homogeneous antennas that come along with increased interference. In this paper, we apply joint signal processing of feeding macro cells (MCs) as one potential lever to solve this interference problem. In particular, we report field trial results of a joint detection (JD) feeder uplink in an urban multi-cell testbed. One focus is on multi-cell channel parameters measured at different SC locations and heights, and another on achievable rates for a deployment using up to four antennas at each SC.

I. INTRODUCTION

It is expected that the ever increasing demand for higher data rates in mobile networks will force operators to deploy denser and increasingly heterogeneous networks that consist of macro cells for coverage and SCs1 for high data rates at hotspots. However, the identification and deployment of new sites is not an easy and therefore a costly project. The list of typical SC locations includes lamp posts, traffic lights, and bus stops. At all of these, the broadband feeder link to the backhaul network is a major challenge. Wherever copper or fiber links are not available, wireless technologies are the alternative. Among wireless radio backhaul solutions, two different strategies can be distinguished: using very directive microwave antennas to achieve a high feeder link SNR and limit interference, or using rather homogeneous antennas (such as dipoles) and potentially reducing interference by other techniques such as (multi-cell) MIMO transmission and reception. The challenges that come with either approach are very different. It is more cumbersome to deploy a large number of directive microwave links, especially if the backhaul access point (which, in the following, is assumed to be a MC) is not visible in LOS, causing channels to be sensitive towards changes in the environment which, in the worst case, requires a regular re-adjustment of the antenna orientation by a technician. On the other hand, provided that directive links are established, high data rates can be achieved using rather simple communications algorithms and protocols. Another benefit is that directive antennas can be deployed in license free or low price spectrum potentially at high carrier frequency (eg. 28 GHz or 60 GHz) where large bandwidth is available.

The second option, using arrays of (homogeneous) antennas, is in the focus of this paper. Such arrays potentially allow adapting the propagation characteristics to the channel conditions and thus can be deployed flexibly as well as robust to changes in the environment. This advantage comes at a cost if each SC is served by only one MC. In this case, the signal received at all other MCs (considering the uplink), is causing interference which reduces the signal-to-interference-plus-noise ratio (SINR) and thus impairs the performance of other transmissions. One option to increase the performance on the feeder link is multi-cell signal processing (or coordinated multi-point (CoMP) in 3GPP) which permits MIMO JD in the uplink and joint transmission (JT) in the downlink [1].

A major deficit of simulation studies on this technique is that reliable channel models including all relevant MIMO channel parameters such as pathloss, delay spread, and antenna correlation are not standardized (or do not exist) for the majority of relevant small cell locations. The widely used empirical COST-231 Hata [2] and Walfish-Ikegami [3]–[5] models give a reference of the pathloss that can be expected in an area that is characterized by the most relevant morphology parameters, and the spatial channel model (SCM) is available for modeling of multi-path MIMO channels, but valid environment parameter settings have still to be established and/or validated [6], [7]. An additional aspect that differs in the evaluation of the feeder link compared to mobile user equipment (UE) is that SC conditions and for example antenna, frequency parameters can be chosen for the purpose of achieving the best performance. Previous studies that take this aspect into account are based on extensive ray-tracing simulations (e.g. [8]) which however are limited by the accuracy of the 3D models and the available precessing power.

In order to obtain a better feeling of the channel parameters observed at different SC locations and heights, we perform multi-cell field trial measurements similar as done in [9], [10] at 2.1 GHz. As an extension, we evaluate achievable rates for a deployment using four SC antennas in the coverage area of two urban cells.

1We use the term small cell (SC) throughout this paper, even though these nodes could also be considered as a decode and forward relays, especially if the feeder link and the macro cell access links share the same spectrum.
The paper is organized as follows. The field trial setup is described in Section II. Details on the signal processing architecture are provided in Section III. The field trial results are presented and discussed in Section IV. Conclusions follow in Section V.

II. MEASUREMENT SETUP

The field trial testbed, deployed in downtown Dresden (Germany), is depicted in Figure 1. In total $M = 13$ MCs located on five sites with up to three-fold sectorization were used for the measurements. Each MC is equipped with a $N_{mc} = 2$ element, cross-polarized antenna; a KATHREIN 80010541 which has 58° horizontal and 6.1° vertical half power beam width is used at all MCs but MC6 and MC8 where a KATHREIN 80010629 with 80° horizontal and 7.5° is deployed. The basic uplink physical layer parameters are used in close compliance with the 3GPP/LTE standard (see e.g. [11]). This concerns mainly the control and data signaling. However, as a major difference, we use orthogonal frequency division multiplexing (OFDM) instead of SC-FDMA in the uplink as well. Time and frequency synchronization of MCs, which is required for joint signal processing, is done through GPS fed reference normals. The remaining sampling time offset and carrier frequency offset is very low (a couple of samples, and few 10 Hz respectively). Other general transmission parameters are stated in Table I.

A Volkswagen T4 measurement bus was used as SC location. The bus was equipped with a linear antenna array of $K = 4$ dipole antennas mounted on an extendable pole of $h = 3.5 - 8.1$ m height. As depicted in Figure 2, the antennas were placed on a horizontal line in a 1λ (wavelengths) = 11.2 cm spacing. Measurements where taken at $L = 21$ locations in an area of about 250 x 250 m². The received signals at all other cells are observed solely to evaluate the interference power caused at these locations. The building height in the measurement area is about 15-22 m (4-5) floors and the distance between buildings is about 30-50 m. Due to this building height, the SC-MC link was NLOS at most SC locations.

At each measurement location, snapshots of the 10 ms (corresponds to 10 transmit time intervals (TTIs)) signal received at all MCs were captured every 2 s while the antenna was moved up and down in the range of 3.5 - 8.1 m with a velocity of about 0.03 m/s in the upward direction and 0.05 m/s in the downward direction. This way, about 100 measurements were taken at each location.

The signal processing at the receiving MC side was done offline as presented in the following section.

III. SIGNAL PROCESSING ARCHITECTURE AND EVALUATION CONCEPT

In order to be able to evaluate different testbed configurations using the limited set of measurements available we concentrate our evaluation on important channel parameters, and we compare different setups in terms of achievable data rates using information theoretic tools.

a) OFDM Processing, Channel and Noise Estimation:

The basic signal processing steps performed for each measurement were already presented in previous field trial publications such as [12], [13]. In this section we summarize these steps and focus on the most important aspects that will be further evaluated in Section IV. After OFDM symbol synchronization, the cyclic prefix is removed and the received signals at all MCs are converted to the frequency domain using an FFT. As a next step, reference and data symbols are separated. Channel estimation is performed based demodulation reference symbols that are transmitted over a block of 30 PRB (360 subcarriers) in the 4th and 11th OFDM symbols of each TTI (1 ms). But since these resources are shared among all $K = 4$ SC antennas using code orthogonal reference symbol patterns we obtain channel information on only every forth sub-carrier. In order to obtain one channel estimate $h_{maklnj}$ per MC $m$, MC antenna $a$, SC antenna $k$, measurement location index $l$, antenna height $h$, OFDM symbol $n$, and sub-carrier index $j$ interpolation was done, first using a 5 tab moving average filter in the frequency domain and then Lagrangian interpolation in the time domain. We estimate an average channel power $p_{mklnj}$, taking the mean of $|h_{maklnj}|^2$ with respect to $a$, $n$ and $j$. Noise power $\sigma^2_n$ is estimated per MC on empty subcarriers, and we obtain signal-to-noise ratio estimates $\text{SNR}^{m,k}_{l,h}$ by dividing the average channel power of each stream by the noise power $\text{SNR}^{m,k}_{l,h} = \frac{p_{mklnj}}{\sigma^2_n}$.

b) Conventional and Joint Detection:

The concepts of uplink JD in cellular networks is explained and motivated e.g. in [14]. While JD of field trial data is not carried out in this paper, we still have to discuss this concept in order to lay the basis for the evaluation of achievable results in Section IV. In particular, we distinguish JD in a cluster $C_{l,h}^\text{JD} = \{c_{l,h}^1, c_{l,h}^2\}$ of $C = 2$ MCs, from conventional detection (CD) at $C = 1$ serving MC $c_{l,h}^\text{CD} = c_{l,h}^1$. JD requires that quantized received signals are forwarded to a joint MIMO
detector which then also has full knowledge of the channel matrix $H_{JD} = \begin{bmatrix} h_{c_1,1} & \cdots & h_{c_1,K} \\ h_{c_2,1} & \cdots & h_{c_2,K} \end{bmatrix}$, where $h_{m,k}$ is a vector with $N_{mc}$ entries, and where we omitted all other indices to simplify notation.

For CD, the transmitted data streams of the SC are detected at one serving MC. Thus, using the information that is transmitted over the channel $H_{CD} = \begin{bmatrix} h_{c_1,1} & \cdots & h_{c_1,K} \end{bmatrix}$. In both cases, detection is then performance based on the available channel state information (CSI) and available data symbols as e.g. described in [13].

IV. FIELD TRIAL RESULTS

All $L = 21$ measurement locations can be roughly categorized into LOS/NLOS, but of course also the distances to the MCs and the morphology in the surrounding of the SC has a significant impact on the channel characteristics. Especially the impact of the surrounding is very complicated. Therefore, we evaluate the measurement data in order to get a better feel of what is actually happening specific locations and to see the range of different outcomes. We concentrate on two aspects:

1) multi-cell signal and interference power.

2) achievable rates in a number of different relay and (multi-cell) receiver configurations.

a) Signal and Interference Power: The signal power at each MC is measured as described in Section III. To reduce the effect of channel fading at a certain location/height, we average the measured $\text{SNR}_{m,k}^{h}$ over all four streams:

$$\text{SNR}_{m,k}^{h} = \frac{1}{K} \sum_{k=1}^{K} \text{SNR}_{m,k}^{h}.$$  

Furthermore, we average $\text{SNR}_{m,k}^{h}$ measured at any height of $2$ Averaging is done in the linear domain throughout this paper.

Fig. 3. Average $\text{SNR}_{m}^{h}$ achieved at all MCs of the testbed during the complete field trial.
one location and MC to obtain $\text{SNR}_{1}^m$. This value is depicted in Figure 3. Looking at the cells with the highest average SNR, we see that all SC locations are in the serving area of either MC2 (HBF 120°) or MC6 (Lenneplatz 300°), at 10 and 11 locations respectively.

These results are not surprising because of the vicinity of the measurement locations to these MCs. However, multiple parameters are known to affect the link SNR apart from distance $d$ and the carrier frequency $f_c$. Important ones are the MC height $h^m_c$, SC height $h$, the height of buildings in the surrounding of the SC. The field trial was done in an urban environment (see Figure 1) with building of 15-22 m height in the surrounding of the SC locations.

An important propagation model was developed by Hata [2], based on which the following equation is used in 3GPP for the link between an urban MC and a UE:

$$PL[dB] = (44.9 - 6.55 \log_{10}(h^m_c)) \log_{10} \left( \frac{d}{1000} \right) + 48.5 + (35.46 - 1.1h) \log_{10}(f_c) - 13.82 \log_{10}(h^m_c) + 0.7h,$$

(1)

where the constants inserted such that $f_c$ has to be inserted in MHz. Shadowing by surrounding buildings is typically modeled as a additional term that is log-normal distributed.
Fig. 6. Mean achievable rate observed at different relay antenna heights. JD observations differs from what is predicted by (1): an average decreases of pathloss of 3.5 dB was reported when \( h \) was increased from 2.5 m to 5 m, and in [10] where an pathloss decrease of 1.7 dB was observed when the SC height was increased from 2.5 m to 5 m. This observation is in line with a previous field trial measurements at 2.1 GHz in an urban environment reported in [9] where an average achievable rate \([bpcu]\) about 3 dB higher at 8.1 m. This observation is with a variance of about 5-10dB. We are interested in the impact of the SC antenna height on the pathloss towards the serving cell which, averaged over all locations, as shown as the blue curve in Figure 4. Compared to the SNR at 3.5 m height, we see an about 3 dB higher value at 8.1 m. This observation is in line with a previous field trial measurements at 2.1 GHz in a similar urban environment reported in [9] where an average pathloss decrease of 1.7 dB was observed when the SC height was increased from 2.5 m to 5 m, and in [10] where an average decreases of pathloss of 3.5 dB was reported when the SC height was increased from 4.7 m to 8.8 m. These observations differs from what is predicted by (1): an average factor of about 13 dB between 3.5 m to 8.1 m as already pointed out by [10]. We refer the reader to [10] for an extensive comparison of pathloss in measurements and different models which concludes that the COST-231 Walfish-Ikegami model [5, Eq. 4.4.8] is most accurate to predict average pathloss even beyond its specification range of up to \( f_c = 2 \) GHz. In there, SC antenna height is considered by a correction factor of \( 20 \log_1 0 (\rho_{\text{roof}} - \rho) \), which, in the observed setting, accounts for a difference of 2.8 dB comparing \( h = 3.5 \) m and \( h = 8.1 \) m.

As we not only evaluate the SNR at the serving cell but also at all other 12 MCs in the field trial setup, we are also able to evaluate how much interference is caused at these, and we define the signal-to-outer-cluster-interference ratio (SOCIR) as follows

\[
\text{SOCIR}_{l,h} = \frac{\sum_{m\in\mathcal{C}} \bar{p}_{m,l,h}}{\sum_{m\in\mathcal{C}} \bar{p}_{m,l,h}},
\]

(2)

where \( \bar{p}_{m,l,h} \) is the channel power averaged over all \( K = 4 \) SC antennas. The average impact of the height on the SOCIR for \( C = 1 \) and \( C = 2 \) is depicted in Figure 4 as well. It is about 2 dB higher at 8.1 m height compared to 3.5 m height. Thus interference is increasing slower with height as signal power at the serving macro base station (MBS). One reason for this observation is probably that the increase of the Fresnel zone which comes along with an increased SNR is smaller for further away MBS.

In any case, the purpose of this paper is not to validate the COST231 Hata formula or to find a new parametrization for the particular purpose of a SC feeder link at 2.6 GHz in an urban environment, because neither the amount of data nor the measurement procedure and equipment is appropriate for that task. Instead, we look at the problem of an operator who would evaluate potential SC locations by two criteria: user traffic demand, and potential backhaul connection, of which we only consider the latter. In particular, we want to observe what the impact of the height on the SNR of the two strongest MCs2 and MC6 at various locations which is plotted in Figure 5. Going through these plots we see that the impact on height on the SNR is very different from location to location. At \( l = 3 \) we have weak NLOS links to both MCs at 3.5 m, but while the SNR at MC2 is constant with height, it is increasing at MC6. At \( l = 8 \) the LOS to MC6 is blocked by a garage roof. Thus, the opening of the Fresnel zone is increasing with height for both links which can results in partially decreasing SOCIRs for \( C = 1 \) while the SOCIR for \( C = 2 \) is increasing with height. This effect can be observed more pronounced at \( l = 14 \) where SNR6,14,h does not change with height due to a LOS with a Fresnel zone opening of about 60% which does not change much with height due to the large distance of the blocking object and \( l = 14 \). On the other hand, SNR2,14,h is increasing by about 5 dB with height which is not desired for \( C = 1 \) but positive for \( C = 2 \) because of the array gain and increased potential for spatial multiplexing. Thus, a potential benefit of an increased SC height depends on the receiver configuration. At \( l = 21 \) we see that the SNR2,21,h measured at the serving MC2 is decreasing resulting in reduced performance with height regardless if JD or CD is applied.
b) Achievable Rates: In order to evaluate system performance we evaluate the achievable rate under the assumption of fixed power Gaussian signaling at the SC and optimal (e.g., maximum likelihood) detection at the MCs. Omitting indices for sub-carriers and OFDM symbols, the achievable rates for the channel realization on a particular sub-carrier using JD or CD can be computed by

$$R_{l,h}^{JD|CD} = \log_2 \left| I + \left( H_{l,h}^{JD|CD} \right)^H \Phi_{nn}^{-1} H_{l,h}^{JD|CD} \right|,$$

(3)

where $(\cdot)^H$ denotes the Hermitian transpose of a matrix and $\Phi_{nn} = \sigma_n^2 I$ is the noise covariance matrix [15]. Note that this equation does not account for any impairment such as channel estimation errors. The average achievable rates for JD and CD are depicted in Figure III-0b. We can see that the achievable rates are increased by about 60% using JD which is in line with previous field trial results on this technique (e.g., [13]).

On the downside, JD requires a massive exchange of information among the cells in the cooperation cluster. The SC antenna height has also an impact on the achievable rates. On average we see a gain of about 10% when the antennas are placed at 8.1 m instead of 3.5 m. However, this result does not include the impact of outer cluster interference because only a single relay was placed in the testbed area.

Achievable rates for the same locations as in Figure 5 are shown in Figure 7. As expected, the highest rates are achieved at those locations with the highest SNR values. The largest achievable rates over all locations and heights for both CD (5.0 bit per channel use (bpcu)) and JD (7.4 bpcu)) was measured at $l = 7$ and $h = 4.4$ m where, looking at Figure 3 which is a location with a very large SNR as well.

V. CONCLUSIONS

Multi-cell trials for an urban small cell (SC) feeder link were reported that observe the performance of conventional and joint detection mostly under NLOS conditions where directive microwave backhaul technologies are known to work rather poorly. While the great variance of achievable rates shows a large potential for a Coordinator Multi-Point (CoMP) uplink in Cellular Systems, for these we could show that the height of the SC antenna has an impact on the performance and that a good choice can bring rate gains of about 10%. However, we show that not only the link to a serving cell or cells in a cooperation cluster is important, but the interference caused at outer cells should be considered as well. Using JD was shown to achieve large gains of about 60%. On the downside, adaptive antenna techniques are algorithmically complex and not necessarily implementable within the constraints of a certain communications standard such as LTE, which might be required to use available spectral bands such as LTE TDD spectrum at 2.6 GHz in some European countries.

Even though the presented field trials were conducted in the uplink, the results give inside for the downlink as well.

One major difficulty of downlink joint transmission is the required transmitter CSI which is much easier to obtain for fixed SC location than for mobile terminals because channel fading occurs solely due to changes in the environment which is rather slow and much easier to track than fading to moving transceivers.

ACKNOWLEDGMENT

The authors would like to thank the German Ministry for Education and Research (BMBF) for funding the test equipment that is essential for the field trials presented. Further, this work would not have been possible without the support from Ainoa Navarro Caldevilla, Vincent Kotzsch, Tommy Svensson, and Eckhard Ohlmer.

REFERENCES