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Channel measurement and characterization of interference between residential femto-cell systems

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***Abstract*—Interference between femto-cell systems is a critical factor for the deployment of such systems in, e.g., resedential areas. In this paper we report on a residential channel measurement campaign focusing on the channel properties for femto-cell systems. We characterize basic channel properties such as delay spread and interference levels between different furnished residential houses. In addition we also study the spatial separation between channels from different houses to investigate whether directional properties can be used to mitigate interference in such scenarios.**

Keywords–femto-cell; residential area; channel measurements.

I. INTRODUCTION

Femto-cell systems have attracted a lot of interest in recent years. The vision is to have independent uncoordinated femto-cell base stations in, e.g., every home in order to improve the indoor coverage and also the capacity, and at the same time achieve a unified system for all kinds of wireless access. An overview of femto-cell systems is given in [1]. One of the main technical challenges that femto-cell systems confront is mitigating the RF interference and efficiently allocating spectrum. If the femto-cell systems intend to reuse the same frequency bands with the macro-cell systems, the capacity of the femto-cell systems would be limited due to the interference from nearby macro-cells and other femto-cells. Therefore, the study of wireless channel properties of the residential femto-cell systems is very important for developing the future home-based communication systems.

However, until now there have been very few measurements reported in the open literature focusing on the channel properties for wireless systems in residential areas. And to the authors' best knowledge, there is no measurement campaign targeting interference and multi-link behavior between different residential houses, i.e. the indoor-to-outdoor-to-indoor and outdoor-to-indoor radio channels. In this paper we present the first results of a (virtual) multi-link MIMO measurement campaign. We provide an analysis of the interference levels between different houses, and we analyze the spatial separation of the channels between the different houses, with specific attention to the interference properties.

The paper is organized as follows: Section II gives the description of the residential area channel measurement, including the environment and setup of the measurement. In Section III, we provide the analysis results - the interference power levels and delay spread from different houses, and the channel spatial separation between these houses. Finally we summarize and conclude our work in Section IV.

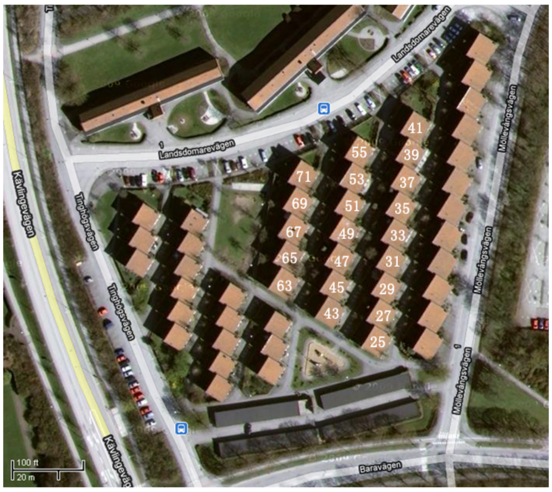

Fig. 1. Overview of the measurement residential area. North is upwards in the figure and the receiver was placed in house 63.

II. CHANNEL MEASUREMENT

A. Environment

The channel measurement campaign was carried out in a residential area to the north of Lund city center, Sweden. Fig. 1 shows the overview of the measurement area with the numbers indicating the specific houses. The receive antenna was always placed inside house 63 upstairs or downstairs for different measurements. The transmit antenna was placed indoors in other houses or outdoors, so indoor-to-outdoor-to-indoor channels and outdoor-to-indoor channels were measured, respectively.

The positions of transmit antenna and receive antenna for indoor-to-outdoor-to-indoor channel measurements are listed in Table I. On each floor of each house, the transmit antenna was moved along 4 routes (along 5-10 m lines) with antenna backplane facing the east, west, south and north directions respectively. For each route, the measurement was 20 seconds long and 100 snapshots were taken. The outdoor-to-indoor channels were also measured in between the houses, see Table II. The transmit antenna array was aligned with the back (western) door of a particular house and moved between 2

TABLE I
INDOOR TRANSMITTER POSITIONS

RX position	TX position (inside house No.)
63u	25d, 45d, 51d, 51u, 53d, 53u, 65d, 65u
63d	51d, 51u, 53d, 53u, 65d, 65u

”d” denotes downstairs position
”u” denotes upstairs position

TABLE II
OUTDOOR TRANSMITTER POSITIONS

RX position	TX position (to the west of house No.)
63u	25, 29, 33, 37, 41, 43, 45, 47, 49, 51, 53
63d	55, 65, 67, 71

”d” denotes downstairs position
”u” denotes upstairs position

houses during each 20 seconds measurement. Different from indoor measurements, the transmit antenna backplane only faced east and west or one of them. Note that in Table II the transmitter position at a particular house means it was to the west of that house.

The street view of the measurement environment is shown in Fig. 2, but note that measurements were performed summertime with leaves on trees etc. It mainly shows house 63 in which the receive antenna was positioned, but the other houses have the same structure as house 63. We can see that the first floor (downstairs) of the house is a little below the ground. On the other side of house, the windows downstairs are small and just above the ground. The interior of these furnished brick wall houses is shown for example in Fig. 3, in which the receive antenna was placed upstairs in house 63.

B. Measurement setup

The receive antenna was a stacked cylindrical patch array having 16 dual polarized elements in each circle and 4 such circles stacked on each other, giving in total 128 antenna ports, see Fig. 3 and the right in Fig. 4. The transmit antenna was a planar patch array having 2 rows of 8 dual polarized antennas, giving in total 32 antenna ports, see the left in Fig. 4.

Measurement data were recorded with the Lund RUSK LUND channel sounder. The measurements were performed at a central frequency of 2.6 GHz and a signal bandwidth of 50 MHz. The transmit power was 40 dBm; a 20 dB attenuator or a 10 dB LNA were used at some measurement positions depending on the experienced signal levels. The maximum length of the impulse response was 3.2 us; and at the receiver, the transfer function was measured at 161 frequency points. For each measurement position, the transmit antenna was moved along a 5-10 m straight line during the 20 seconds measurement time and 100 snapshots were recorded. 5 consecutive snapshots formed one block and there were no delay between those. Between each block there was an 1 second additional delay. In order to make a multi-link analysis possible, the receive antenna was not moved during successive measurements and no people were in close vicinity to this antenna. Essentially the channel can be regarded as static during measurements, though movements of people in this area in the whole measurement duration could not be avoided.


Fig. 2. View of the measurement area at street level, house 63.


Fig. 3. 128-port receive antenna in the upstairs position.

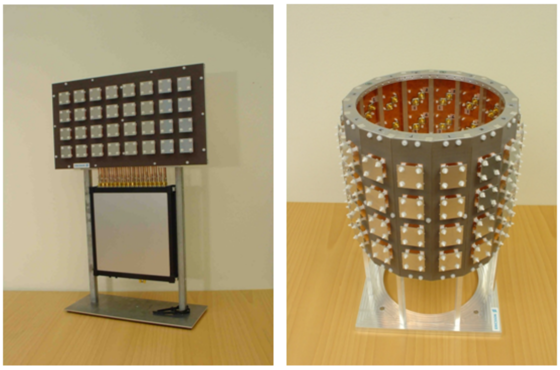
Fig. 4. Transmit antenna array (left) and receive antenna array (right).

Unfortunately post-analysis has shown that the switch for the transmit antenna port did not switch during the measurements in some scenarios. In those scenarios, the 32 transmit channels were very similar since only the first antenna port was measured. However, in our study we do not analyze the multiple antenna properties at the transmitter side. This problem will thus not affect the results provided in this paper.

III. RESULTS

In this section we analyze the scenarios when the receive antenna was in upstairs position in house 63. This is because

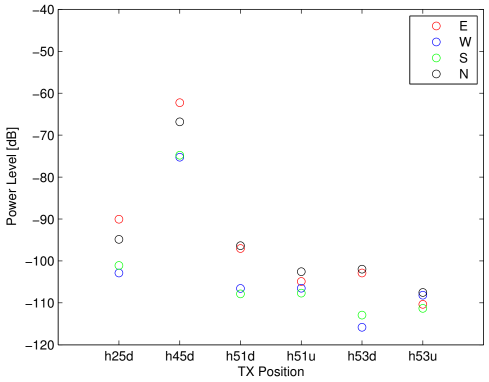

Fig. 5. Mean received power levels when TX was placed indoors with different orientation routes (antenna backplane facing the east, west, south and north directions).

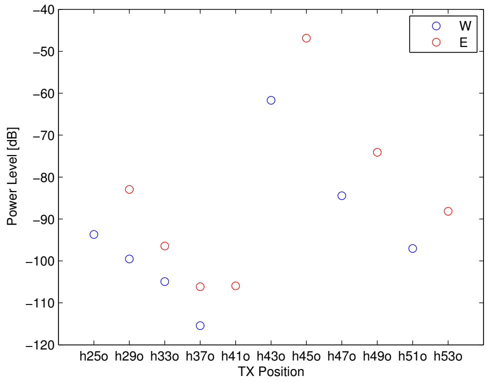

Fig. 6. Mean received power levels when TX was placed outdoors with different orientation routes (antenna backplane facing the east and west directions or only one of them).

the upstairs position of the receive antenna has more measured scenarios as well as stronger received signal power, which makes it easier to compare the channels from different houses.

A. Interference level

As mentioned in Section I, interference problem is one of the key issues that femto-cell systems are confronting, e.g. the interference between closely spaced femto-cell systems. We first study the mean received power levels when the transmit antenna is at different positions. We average the time-integrated power [2] over all the transmit and receive antenna elements and get the mean received power levels for all the orientation routes in each scenario. The mean received power levels are shown in Fig. 5 and Fig. 6 for the cases when transmit antenna is indoor and outdoor respectively.

From Fig. 5 which shows the indoor-to-outdoor-to-indoor channel power levels, we can see that the power levels are higher when the transmitter position is near house 63, as expected. And interestingly enough, there is no major difference in received power levels when the transmit antenna placed upstairs or downstairs. However, by comparing different routes, we find that the antenna orientation has less effect on the received power level when transmit antenna is placed upstairs. This is mainly due to the interior structure of these houses. Through the interference power levels, we can see that the penetration loss can insulate the femto-cell system from surrounding femto-cell transmission.

For the outdoor-to-indoor scenarios, see Fig. 6, the transmit antenna positions are to the west of the houses. From the map in Fig. 1, we can see that the positions from ”h25o” to ”h41o” are behind the row of houses from 43 to 55, and positions from ”h43o” to ”h53o” are in front of these house. Obviously we get lower received power level when the transmit antenna positions are behind the houses. It can be seen from Fig. 6 that the attenuation due to the row of houses is around 20-30 dB. And the received power levels are higher when antenna backplane is facing the east, in which case the antenna transmit the power to the direction of the receiver.

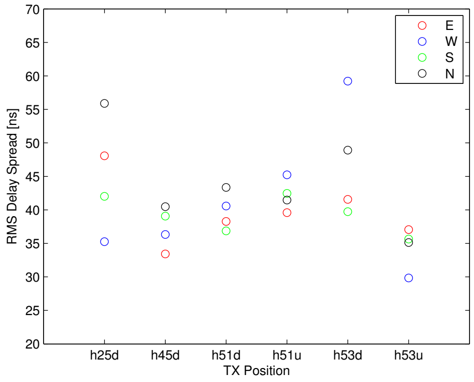

Fig. 7. RMS Delay spread when TX was placed indoors with different orientation routes.

B. Delay spread

In order to get more general characteristics of the residential area channels, we analyze the RMS delay spread. The delay spread has effect on the interference cancellation techniques [2]. Fig. 7 and Fig. 8 plot the delay spread of indoor-to-outdoor-to-indoor and outdoor-to-indoor channels respectively.

For indoor transmit antenna, the delay spread is around 30-60 ns. The antenna orientation has effect on the delay spread. There is however an interesting phenomenon when comparing the delay spread from downstairs and upstairs inside house 53. For the same antenna orientation, the delay spread nearly doubles in one route. From the power delay profiles we notice that there is a an additional large multipath component present downstairs but not upstairs.

In the outdoor-to-indoor channels, see Fig. 8, the delay spread is around 40-65 ns, which is larger than the scenarios with indoor transmit antenna. We notice that from the position outside house 37 with west direction the delay spread is very small. This is probably because there is only one relatively stronger multipath component.

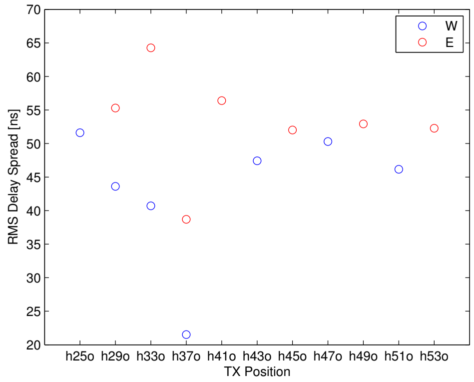

Fig. 8. RMS Delay spread when TX was placed outdoors with different orientation routes.

C. Channel spatial separation

The femto-cell systems have reduced transmit power to limit the interference between each other. However, if multiple antennas are applied on base stations, i.e. MIMO systems, the interference can be mitigated if the channels have sufficient spatial separation. In our study of the measurement channels, the different correlation matrices at the receiver would be desirable. Therefore understanding the propagation channel is necessary for developing effective interference mitigation techniques [3]. To quantify the spatial separation between channels with different transmit antenna position, we compare the receive correlation matrices through the measure of matrix collinearity.

To measure the distance between matrices, the collinearity of two matrices $\mathbf{A}$ and $\mathbf{B}$ of same dimension is given by [4],

$$c\left(\mathbf{A},\mathbf{B}\right) = \frac{\left|\mathrm{tr}\left(\mathbf{A}\mathbf{B}^{\mathrm{H}}\right)\right|}{\|\mathbf{A}\|_{\mathrm{F}}\|\mathbf{B}\|_{\mathrm{F}}}, \tag{1}$$

where $\|\cdot\|_{\mathrm{F}}$ denotes the Frobenius norm of a matrix, and $(\cdot)^{\mathrm{H}}$ denotes the matrix conjugate transpose operation. This measure of matrix separation ranges between 0 and 1. A value close to zero indicates no collinearity, and the matrices are nearly orthogononal to each other. If the matrices are similar, the number gets closer to 1 which indicates full collinearity. A brief interpretation of (1) can be found in [3] and [5].

Let $\mathbf{H}$ denote the channel matrix, so it has the dimension of 128×32 in our measurement. For one polarization only the channel matrix $\mathbf{H}$ has the dimension of 64×16, since the co-polarized antenna elements are selected. The receive correlation matrix is calculated as $\mathbf{R} = \mathrm{E}\left\{\mathbf{H}\mathbf{H}^{\mathrm{H}}\right\}$. Averaging is performed over time and frequency domain. By using the receive correlation matrices $\mathbf{R}$ from different houses, replacing matrices A and B in Eq. (1), we obtain the collinearity between the receive correlation matrices of the two different locations.

We first analyze the cases when the two transmit positions are in the same house but on different floors, see Table III. Collinearity is calculated between the same orientation, i.e. east-east, west-west, south-south and north-north. It can be seen that the collinearity is high between downstairs and upstairs, especially when the transmit antenna backplane is facing the south. However, we get low collinearity in the cases of the east and north orientation in house 53, where the antennas are aligned towards the more open spaces. The collinearity between downstairs and upstairs in the same house is mainly due to the different interior structure of downstairs and upstairs in the house.

TABLE III
RECEIVE CORRELATION MATRIX COLLINEARITY (TX ON DIFFERENT FLOORS OF THE SAME HOUSE).

TX Positions	E	W	S	N
h51d, h51u	0.51	0.58	0.88	0.64
h53d, h53u	0.31	0.58	0.91	0.30
h65d, h65u	0.49	0.70	0.76	0.43

TABLE IV
RECEIVE CORRELATION MATRIX COLLINEARITY (TX IN HOUSES NEAR EACH OTHER)

TX Positions	E	W	S	N
h51d, h53d	0.49	0.60	0.90	0.33
h51u, h53u	0.83	0.57	0.82	0.68

Then we study the cases when the two positions are on the same floor but in houses next to each other, see Table IV. We find that the collinearity is rather high, especially in upstairs position between house 51 and 53 and when the antenna is aligned towards the receiver. This is probably due to the similar signal paths from the two neighbor houses to the receiver. And we notice that the collinearity is quite low between downstairs of house 51 and 53 with antenna backplane facing the north direction. In this case, the signal paths could be quite different due to differences in scatterering environment around the houses, thus the channels are sufficiently separated.

When the two positions are in houses far from each other, we obtain much lower collinearity, which can be seen from Table V. If the transmitter positions are at different rows of houses, see the map in Fig. 1, the collinearity is quite low, in comparison with the collinearity when the positions are at the same row of houses, i.e. house 45, 51 and 53.

Table VI lists the receive correlation collinearities when the two positions are outdoors and not far from each other. It can be noticed that the collinearity is higher when the two positions are far from the receive antenna (in house 63). And the collinearity is low when the two positions are near house 63, i.e. "h45o" and "h49o", "h43o" and "h47o". This is because that more strong multipath components are present

TABLE V
RECEIVE CORRELATION MATRIX COLLINEARITY (TX IN HOUSES FAR FROM EACH OTHER)

TX Positions	E	W	S	N
h25d, h45d	0.27	0.27	0.40	0.24
h25d, h65d	0.16	0.25	0.32	0.06
h45d, h51d	0.34	0.21	0.42	0.24
h45d, h53d	0.54	0.41	0.43	0.44
h45d, h65d	0.11	0.18	0.34	0.05

TABLE VI
RECEIVE CORRELATION MATRIX COLLINEARITY (TX OUTDOORS NEAR EACH OTHER)

TX Positions	E	W
h45o, h49o	0.32	
h49o, h53o	0.72	
h29o, h33o	0.56	0.66
h33d, h37d	0.72	0.74
h43o, h47o		0.35
h47o, h51o		0.73

TABLE VII
RECEIVE CORRELATION MATRIX COLLINEARITY (TX AT THE SAME POSITION WITH DIFFERENT ORIENTATIONS)

TX Positions	E-W	E-N
h51d	0.47	0.67
h51u	0.76	0.87
h53d	0.59	0.97
h53u	0.61	0.90
h65d	0.53	0.39
h65u	0.77	0.85

and make the channels more ”different”.

Next we study the receive correlation collinearity between different antenna orientations at the same position, see Table VII. By comparing the upstairs and downstairs positions, we can see that collinearity between different orientations is higher in upstairs position. Thus, The certain antenna orientation has effect on the channel separation.

Lastly, we fix the target position and regard channels from other positions as interferences. Unfortunately we did not have the measurement with transmit antenna position inside house 63, which would be most desirable. Instead we fix the target position west of house 45 which is quite near house 63, and compare with the channels from other positions. We calculate the receive correlation collinearity between the ”target” and the ”interferers”, see Fig. 9 and Fig. 10. From Fig. 9 which plots the collinearity between the target position and all the indoor positions, we can see that the collinearities are all under 0.3 except for the position inside house 45 downstairs which is very near the target position. And for outdoor interferences in Fig. 10, all the collinearities are low, except for position ”h29o” with the east orientation which is near the target position and just behind the row of houses, and position ”h43o” which is next to the target position.

IV. CONCLUSIONS

Based on the residential channel measurements, we analyzed the interference characterization between femto-cell systems. We studied the interference power level, delay spread and channel separation.

The interference power level and delay spread are reasonable for different transmit antenna positions. And we found that the interference power levels can to a certain extent be limited due to the penetration loss through the brick wall of the houses, which is desirable for femto-cell systems.

We quantified the spatial separation between channels by the measure of collinearity. Receive correlation collinearity was studied. Generally, the collinearity is low if the two positions are far from each other. However, the antenna orientations also influence the collinearity. The interference mitigation techniques in MIMO systems can be developed based on these channel differences.

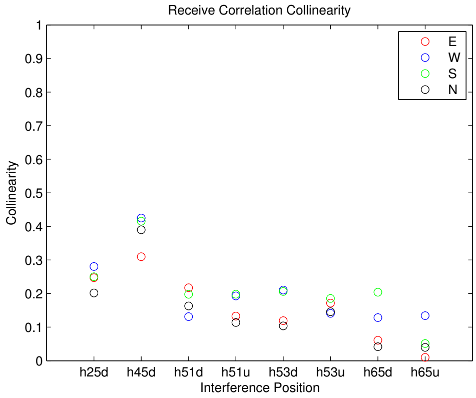

Fig. 9. Receive correlation collinearity between the position in front of house 45 and all the indoor positions.

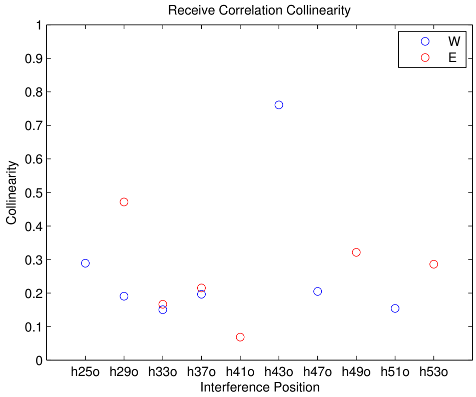

Fig. 10. Receive correlation collinearity between the position in front of house 45 and all the other outdoor positions.

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