Measurement-Based Evaluation of Link Budget Gain from 3GPP LTE Uplink Transmit Antenna Selection

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Abstract—This paper presents a measurement-based evaluation of link budget gain from uplink transmit antenna selection in 3GPP LTE. In contrast to earlier studies, the results are based on channel measurements and realistic non-omnidirectional mobile terminal antennas. Further, in addition to the impact of fast selection based on small-scale fading power, also the gain from slow selection based on average signal power is evaluated. In the evaluated measurement cases, fast and slow fading based transmit antenna selection result in up to 3.7 and 3.2 dB average power gain, respectively, with respect to the fixed uplink transmit antenna case. This implies that with practical non-omnidirectional terminal antennas a major portion of the gain can be realized based on slow selection, hence justifying a simple open-loop transmit antenna selection scheme which is also applicable to FDD systems.

I. INTRODUCTION

Cellular network performance studies and link budget calculations are typically based on the assumptions of omnidirectional antenna pattern and uniform angular power distribution at the mobile terminal end. From numerous measurement campaigns it is however evident that - while useful for simplifying analyses - neither of the assumptions hold in realistic environments [1], [2]. First, integrated handheld terminal antennas do not have omnidirectional antenna pattern (in any planar cut) when held near hand and/or head. Second, channel angle-of-arrival power spectrum is rarely uniform in realistic cellular outdoor propagation scenarios, at least when examined over a distance of a few dozens of meters or so.

The idea of 3GPP LTE uplink transmit antenna selection is that the User Equipment (UE) uses the optimum (based on some criterion) transmit antenna for uplink transmission. The selection of the UE transmit antenna can be made by the Base Station (BTS) or the UE. In case of closed-loop selection, antenna information is signalled to the UE in the uplink scheduling grant as specified in [3]. In the open-loop transmit antenna selection UE selects the transmit antenna autonomously without feedback from BTS; the actual selection method is not defined by 3GPP Release 8. The support of transmit antenna selection is optional for the UE and, in addition to the closed-loop and open-loop modes, the network may decide to configure a fixed UE transmit antenna. The antenna selection mode is set semi-statically by higher-layer signalling. From network planning and performance evaluation point of view, the question arises of the mean and outage link budget gain from the uplink transmit antenna selection.

Related work: The 3GPP Rel8 LTE uplink transmit antenna selection is a special case of the general MIMO antenna selection problem [4]. 3GPP research reports on uplink transmit antenna selection include [5], [6], [7], where some initial performance studies were made. In a more complete contribution [8], the gain of open and closed loop transmit antenna selection, including frequency-selective scheduling and Hybrid Automatic Repeat Request (HARQ) retransmissions, was considered. For the baseline case without HARQ and using frequency-unaware scheduling, the gain at 1% SNR outage was obtained at about 3dB for closed-loop and 2.5dB for open-loop antenna selection. These results were based on simulations and on fast selection of instantaneous channel. Open-loop transmit antenna selection utilizing a non-3GPP intra-subframe antenna switching scheme was studied in [9]. In [10], it was suggested that downlink cyclic delay diversity might improve uplink transmit selection gain. The contribution closest to our paper was presented in [11], where the impact of antenna directivity and uplink transmit antenna selection were evaluated based on indoor measurements for a multi-antenna setup in a non-3GPP setting. Interestingly, UE orientation statistics collected from actual smartphone users’ behaviour was included in the evaluation. Median gain of transmit antenna selection was evaluated as 3 dB, for the specific antenna selection scheme employed in [11], see therein for details. Some references can also be found in patent literature.

Contribution of this work: While uplink transmit antenna selection is well-known to practitioners in the field, evaluation of the resulting link budget gain in practical use cases has
received less attention. This paper presents a case study evaluation of the gain from UE transmit antenna selection with realistic directional terminal antennas and measured outdoor propagation channel. Here, by 'realistic terminal antenna' we mean that the antenna structure used in evaluation has been specifically designed for a dual-antenna handheld device. Compared to earlier papers, the added value of this paper include: i) evaluation is based on outdoor channel measurements; ii) non-omnidirectional terminal antennas are used, including the impact of hand grip; iii) transmit antenna selection gain based on averaged signal level is also evaluated (applicable also to FDD systems).

Organization of the paper: In Section II the problem is motivated by means of a measurement example. In Section III the channel measurements, antennas under test and measurement processing is explained. Results are given in Section IV and Section V concludes the paper.

Note on terminology: Throughout the paper we assume that the instantaneous path loss between any two pairs of receive and transmit antennas is reciprocal on the given carrier frequency. Thus, reversing the roles of transmitter and receiver, the instantaneous gain from transmit antenna selection can be evaluated based on receiver measurements.

II. MOTIVATION: A MEASUREMENT EXAMPLE

Fig. 1 shows a measurement example of the impact of antenna orientation on the received average power of a dual-antenna terminal (average is over small-scale fading). The measurement and post-processing details are given in Sec. III. In the example, the same measurement route of about 85 meters length is effectively traversed three times, in each case the UE having different orientation. Fig. 2 shows a map of the measurement site together with the coordinate system of the mobile antennas. The plots in Fig. 1 are from the route 2. The BTS antenna height\(^2\) is 13 m. It can be seen that in the middle of the measurement route, UE enters line-of-sight which can be seen in Fig. 1 as increase in received signal power. Fig. 3(a) illustrates the structure of the considered mobile handset antenna together with the hand model provided in the SEMCAD [12]. The three rotations of the mobile handset model in Fig. 1 correspond to the \(x\)-axis of the antenna pointing 0°, 90°, and 150° of the coordinate system of the measurement environment shown on the map.

From Fig. 1, depending on the azimuth rotation angle, the average received signal level of the antennas differs by up to 8 dB in non-line-of-sight and up to 10 dB in line-of-sight. It is noteworthy that the average power is consistently different between UE branches over several meters’ distance. Therefore, it is conceivable that even (slow) average-signal-based selection of transmit antenna would result in power gain at the BTS receiver.

\(^{2}\) The average rooftop height is about 25 meters.

III. MEASUREMENTS AND POSTPROCESSING

A. USED ANTENNAS

The handset antenna model used in this paper is shown in Fig. 3(a). Fig. 4 shows the azimuthal radiation patterns of
the two antenna elements implemented in a mobile handset chassis, described in more detail in [12], one in a free space and another under the influence of the hand grip. The hand grip affects the radiation pattern notably in reduced radiation efficiency and increased cross-polarization levels. Maximum gain of the antenna was $-0.5$ and $-5.8$ dBi in the antenna under the absence and presence of the hand grip. Efficiency of the two antennas was $-4.1$ dB in the free space, while it decreased to $-6.6$ and $-8.6$ dB with the hand grip. It is important to note that the hand grip made the efficiency of the two antenna elements different by $2$ dB, producing a static power imbalance between the branches.

B. Channel measurements

Here only a brief summary is given, for further details the reader is referred to [13]. Channel measurements were performed in outdoor microcellular environment in Helsinki city center at 2.154 GHz. The base station was equipped with a two-element horizontally polarized linear patch antenna array and was located in a crane. The mobile station was with a spherical antenna array consisting of 32-element dual-polarized patch antennas. The mobile was put on a trolley on 1.5 m height above the ground to measure MIMO radio channel responses on 7 measurement routes stretching over 590 m. Since the channel response was acquired every quarter-wavelength, we have obtained a total of about 16500 MIMO channel responses.

C. Embedding the antenna patterns on the measured radio channel

From the measured MIMO channel responses, multipath angle-of-arrival and polarimetric complex amplitude was estimated at the mobile end using a spatio-temporal beamformer. The beamformer compensates for the characteristics of the spherical array by the knowledge of complex multi-polarized antenna patterns. Therefore it is possible to embed our mobile handset antenna characteristics into the measured MIMO channels by combining the radiation patterns of the antennas with the estimated multipaths [13]. The resultant MIMO channel responses shows the effect of the considered mobile antennas in the measurement environment. The mobile antenna was rotated in $30^\circ$ steps on the $x$-$y$ plane in Fig. 3(a) to simulate random orientation of UE, leading to 12 realizations of MIMO channels at single mobile location.

The effective channel matrix, after weighting the (approximately) isotropically measured channel response with the rotated antenna patterns, is denoted with

$$
H_{\text{eff},i} = \begin{bmatrix}
h_{11,i} & h_{12,i} \\
h_{21,i} & h_{22,i}
\end{bmatrix},
$$

where $i$ is the time index. We remark that the elements of $H_{\text{eff},i}$ are narrow-band channel impulse responses.

D. Calculation of transmit antenna selection gain

The received power of antenna branch $k$ (without precoding) at time instant $i$ is

$$
P_k^i = |h_{k1,i}|^2 + |h_{k2,i}|^2.
$$

As the channel is assumed reciprocal on the given frequency, this is also the received power at the base station after maximum ratio diversity combining when UE antenna $k$ is transmitting (assuming the same transmit power). The instantaneous transmit antenna selection gain for the $i$th receive time sample is

$$
G_i = \frac{P_{k}^{\text{opt}}}{P_{i}^{\text{ref}}},
$$

where $P_{i}^{\text{ref}}$ depends on the reference antenna used to calculate the gain. In this paper we evaluate the gain for $P_{i}^{\text{ref}} = P_{1}^{i}$ and $P_{i}^{\text{ref}} = P_{2}^{i}$. The optimal transmit antenna $k^{\text{opt}}$ for the $i$th measurement sample is formally defined as

$$
k^{\text{opt}} = \arg \max_k F_k[\{P_k^i\}],
$$

It should be noted that the optimal antenna can be the same as the reference antenna in which case the gain is 0 dB for that measurement sample.

The generic antenna selection cost function is denoted as $F_k[\cdot]$ and it is some function of the power samples $\{P_k^i\}$. In the sequel, transmit antenna selection gain is measured for two special cases of the antenna selection cost function $F_k[\{P_k^i\}]$: antenna selection based on instantaneous signal level (fast fading) and selection based on averaged signal level (slow fading).

1) Selection based on fast fading: In this case the antenna selection cost function is based on the instantaneous signal: $F_k[\{P_k^i\}] = P_k^i$. In terms of implementation this implies that the UE has information of the instantaneous uplink received signal either by means of assumed channel reciprocity (open-loop transmit antenna selection) or transmit antenna selection commands transmitted from BTS to UE (closed-loop transmit antenna selection).
2) Selection based on slow fading: In this case the antenna selection cost function is based on the moving average of received signal power:

\[ F_2[\{P_i^k\}] = \frac{1}{L} \sum_{i-L+1}^{i} P_i^k \]

where \( L \) is the length of the averaging window. In terms of implementation this implies that the UE averages the downlink signal and uses open-loop transmit antenna selection to select more favourable transmit antenna. Assuming that uplink-downlink path loss is reciprocal within a small frequency scaling constant defined by the duplex gap, this scheme is suitable also for FDD systems. The slow fading correlation has been shown to be in the range 0.7...0.84 between 0.9 GHz, 1.8 GHz and 2.1 GHz bands in [14], hence the slow fading correlation for duplex distance within one band is expected to be higher\(^3\). The drawback of the slow selection is the unavoidable averaging delay which occasionally results in negative gain.

3) Average branch power imbalance: To gain insight, imbalance in average received power of UE antenna branches is used as an illustrative metric. When reference antenna \( k = 1 \) is used it is defined as

\[ IB_1 = \frac{\sum_{i-L+1}^{i} P_i^1}{\sum_{i-L+1}^{i} P_i^2} \]

and the inverse of this when reference antenna \( k = 2 \).

IV. RESULTS

In this section we present measurement results of transmit antenna selection gain. The results are stated for two antenna configurations:

- UE in free space
- UE held in the position shown in Fig. 3(b)

Averaging length \( L = 100 \) (25 wavelengths, or 3.5 meters@2.1 GHz) is used in all cases with slow fading based transmit antenna selection. Tuning \( L \) impacts results slightly but is left for further study. All presented empirical distribution functions of the instantaneous gain \( G_i \) are based on aggregation of all seven measurement routes (with 12 azimuth orientations each) into a one long measurement route. In the case of slow selection, the first \( L = 100 \) measurement samples of each individual route are discarded from gain calculations to avoid edge effects.

In the legends, "FF gain" indicates the average value of \( G_i \) when fast selection is used, and "SF gain" indicates the average value of \( G_i \) when slow selection is used. \( G_i \) has been defined in (3).

\(^3\)This is also underlying assumption in 3GPP LTE uplink open-loop power control which is based on the assumption of reciprocal uplink-downlink path loss [3].

A. UE in free space

Fig. 5 shows the result for UE in free space, antenna pattern shown in Fig. 4(a). The cumulative distribution function (cdf) of the instantaneous gain \( G_i \) is shown for both antennas used as reference. Additionally, power imbalance cdf is also shown.

Average transmit antenna selection gain is 2.6 dB and 2.4 dB for the two references when transmit antenna selection is based on the fast fading signal. For the slow fading based selection the values are 1.8 dB and 1.7 dB, respectively. The result illustrates that when the UE in free space is rotated over the entire azimuth angle, the selection of reference antenna does not make a great difference, since the branch antenna patterns are rotated replicas of each other (see Sec. III-A).

For the (ideal delay-less) selection based on instantaneous signal the gain cdf obviously shows no negative gains. For about 50% of samples there is no gain since the optimal transmit antenna is the reference antenna itself; this explains the step function in the cdf. It is noteworthy that for 20% of samples the gain exceeds 5 dB. This is since for some UE rotations the reference antenna is strongly non-optimal compared to the stronger branch – a result of the directive channel and non-omnidirectional antenna patterns.

For selection based on the averaged signal the gain cdf shows some negative gains for about 10% of samples. This is due to: i) when the average antenna branch powers are roughly equal small-scale fading results in many negative gain samples due to non-optimum antenna selection; ii) averaging delay in transmit antenna selection and hence it is not possible to track the average signal power when the physical channel undergoes a quick transition. On the other hand, the gain exceeds 5 dB for 18% of samples, which is almost the same as gain from fast transmit antenna selection. From Fig. 5, slow selection results in loss of 0.7 – 0.8 dB in average gain with respect to fast selection, mainly because of the CDF tail showing negative gain values during fast channel changes.

From the two-sided power imbalance cdf it can be seen that for about 25% of samples the average power imbalance exceeds 5 dB illustrating the gain potential in slow antenna selection. Up to 10 dB branch power imbalance has also been reported in [15].

B. UE held in user’s hand

In this case the UE is held by the user as shown in Fig. 3(b). Some observations:

- Antenna 1 suffers from the 2dB efficiency loss caused by the user hand. As the user hand position is difficult to predict in practice, this demonstrates the additional robustness effect brought by the transmit antenna selection.
- The average gain from fast selection is 3.7 dB when antenna 1 is used as reference.
- The average gain from slow selection is 3.2 dB when antenna 1 is used as reference.
- The gain is 7dB or more for 20% of samples when antenna 1 is used as reference.
unaware scheduled uplink transmission. In the case where the channel coherence bandwidth is larger than the scheduled bandwidth, frequency-aware uplink channel scheduling can result in additional gain when average branch power imbalance at UE is large. However, assuming that the power imbalance is small, fast antenna selection actually consumes part of the frequency-aware scheduling gain [8].

An important implementation issue not discussed so far is that of the power loss incurred by the RF switch required to implement the transmit antenna selection with minimal duplication of RF circuitry. Typical assumption is that the RF switch results in 0.5 dB implementation loss [8].

V. Conclusion

We have presented an evaluation of the gain from uplink transmit antenna selection by using outdoor channel measurements and realistic handheld terminal antenna model. The average gain from fast and slow selection was 3.7 and 3.2 dB, respectively, when the terminal is held in hand grip position. For 20% of measurement samples the gain exceeded 7 dB for both antenna selection modes. The advantage of slow selection is that it can be used in open-loop mode and is also usable in FDD systems without uplink sounding reference signal.

References

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