Real-life Indoor MIMO Performance with Ultra-compact LTE Nodes

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***Abstract*—With the ever increasing demand for mobile broadband service with very high bitrates to indoor users, there is large industry traction around different types of In Building Solutions (IBS) for Long Term Evolution (LTE). Multiple Input Multiple Output (MIMO) is a key feature in LTE enabling significantly improved user bitrates, and the indoor channel characteristics are also expected to be in favor for MIMO performance. Despite this, due to deployment constraints and design constraints on the IBS antenna design and size, many IBS deployments of today do not support MIMO. As the market evolves, this is finally changing and in this paper, the 2x2 MIMO performance is measured in real-life with small-size radio equipment, a commercial smartphone and a low-power radio head, both with a size of approximately a wavelength. Despite the small antennas, the performance is found to be very good supporting rank-2 transmission on almost the whole 2500 m^2 office floor with only 100 mW transmission power. In more than half of the area, the user bitrate exceeds the maximum rank-1 bitrate, demonstrating the value of MIMO. Also in Line-Of-Sight (LOS) conditions, traditionally a weakness for MIMO performance, the indoor channel richness facilitates rank-2 transmission. The 2x2 MIMO performance is found to be limited rather by propagation loss than MIMO channel characteristics and antenna size, which demonstrates the potential for ultra-compact 2x2 MIMO indoor antenna heads.**

***Keywords*—E-UTRA, LTE, MIMO, IBS, Small Cells**

I. Introduction

The success of smartphones in LTE networks has increased data traffic load in the networks and increased the importance of high peak bitrates. Different types of small cell solutions have been and keep being introduced in densely populated areas to meet the bit rate expectations. Most traffic is consumed by indoor users which has triggered renewed interest in In-Building Solutions (IBSs).

Legacy IBSs, such as Distributed Antenna Systems (DASs), have been used for a long time, mainly to improve coverage, as larger buildings and buildings with energy-saving glass can be challenging to cover from the outside with outdoor antennas. However, many legacy DASs do not support a fundamental LTE characteristic: support for MIMO transmissions. In the downlink, Single User (SU)-MIMO is supported already from the first release, Release 8, of LTE. Today, two layer SU-MIMO is used in almost all cells in existing LTE networks, thanks to the mandatory two receiver antennas in the LTE User Equipment (UE) and thanks to most macro network nodes already having infrastructure for two antennas for uplink coverage reasons. In contrast, when antennas are deployed indoor, one antenna has been sufficient for uplink coverage reasons and therefore most existing DAS deployments have only one antenna branch. With such an antenna solution, the full potential of LTE is not utilized, since it only enables Single Input Multiple Output (SIMO) transmission, reducing the peak bitrate and the capacity. With the expected indoor channel richness, this is an even greater performance loss from what could be achievable [1]. Therefore, alternative low-power node solutions with multiple radio branches are of large interest for LTE IBSs to reach high peak bitrate and to improve capacity.

There are cost and esthetic constraints on IBS solutions. The antenna or the radio head should be as small as possible, and therefore the same hardware performance as for macro base stations is not feasible. Also, macro deployments typically use cross-polarized antennas which give decreased correlation between layers improving two-layer SU-MIMO performance [2]. In some IBS deployments, an omni-directional antenna is desired. With a small-size omni-directional antenna, it is challenging to maintain good polarization orthogonality and isolation between antenna branches in all directions. The question is therefore how much of the MIMO gain can be realized, given cost constraints and antenna design constraints (form factors) of commercial products.

LTE MIMO performance has been extensively studied by means of simulation and measurement also in indoor environments [3,4]. However, to our knowledge there are no published results based on measurements on indoor-deployed small size nodes, investigating the impact of propagation loss and channel conditions.

In this paper, results from SU-MIMO measurements on small-size radio equipment are presented. A 2x50mW radio head with the size of less than a wavelength is deployed in an office environment. Walk tests with a smartphone are performed in different radio conditions measuring the MIMO performance and assessing channel conditions.

The paper is organized as follows: in Section II, the SU-MIMO conditions are discussed followed by the description of the measurements including test equipment and used measures in Section III. Measurement results are presented in Section IV and finally conclusions are drawn in Section V.

Fig. 1. Test equipment.

II. Single User MIMO Conditions

SU-MIMO performance and spatial multiplexing possibilities are, as mentioned above, limited partly by the antenna deployment, partly by the radio link characteristics.

The radio link is characterized by the Signal-to-Interference-and-Noise Ratio, and its rank [5]. As is well-known from theory, even a high-SINR channel might not support spatial multiplexing due to insufficient rank, caused by antenna characteristics and insufficient multipath propagation [6]. To capture varying channel characteristics, both indoors and outdoors, LTE supports rank adaptation to dynamically adapt the number of layers transmitted. One example is the Transmission Mode (TM) 3, also known as open loop spatial multiplexing [7].

For the indoor scenario studied in this paper, theory tells us to expect a large number of reflections (creating a rich channel with high rank), but also a channel with a high probability of LOS, where the direct path is often much stronger than any reflected paths (resulting in lower channel rank). The MIMO condition in LOS can be improved by using cross-polarized antennas, often deployed in macro scenarios. Perfect cross polarization is however not trivial to achieve in all directions with the small-size omni-antennas used in today's handheld UEs and indoor radio heads.

III. Measurement Description

The measurement was done on a 5 MHz LTE carrier on band 4, 2.1 GHz in downlink. There was no co-channel or other external interference on the used band allowing for in-detail studies of the indoor channel. A fully standard-compliant LTE IBS was used, the Radio Dot System [8]. The radio head is a 2x50 mW so-called dot with two integrated omnidirectional antennas, see Fig. 1. The radio head including the antenna has a diameter of 10 cm which allows for less than a wavelength in separation between the two antennas, see Fig 1.

A commercially available LTE smartphone was used: a standard-compliant, Category 4 LTE UE. The size of the terminal is 15x8x1 cm leaving room for a distance between the two antennas of less than a wavelength. To minimize hand and body loss, the terminal was mounted in a plastic car phone holder on a trolley 1.2 m above the floor, and tilted 45 degrees for a more expected user orientation, see Fig 1.

A single radio head has been used in the measurements. It was deployed in the ceiling at two different locations to investigate different environments. One location was at typical ceiling height (2.7 m above floor) in the middle of a 2500 m^2 office floor, see Fig. 2 blue circle. This is an ordinary office area with both open areas and meeting rooms and other typical office facilities such as an elevator, washroom block and office supply room. Most of the area is Non-Line-Of-Sight (NLOS) from the radio head. The other radio head deployment was at 4.3 m above the floor in one end of an 8000 m^2 office area, see Fig. 6 blue circle. This office area has a higher ceiling and is more open resulting in larger areas within LOS (Line-Of-Sight) from the radio head.

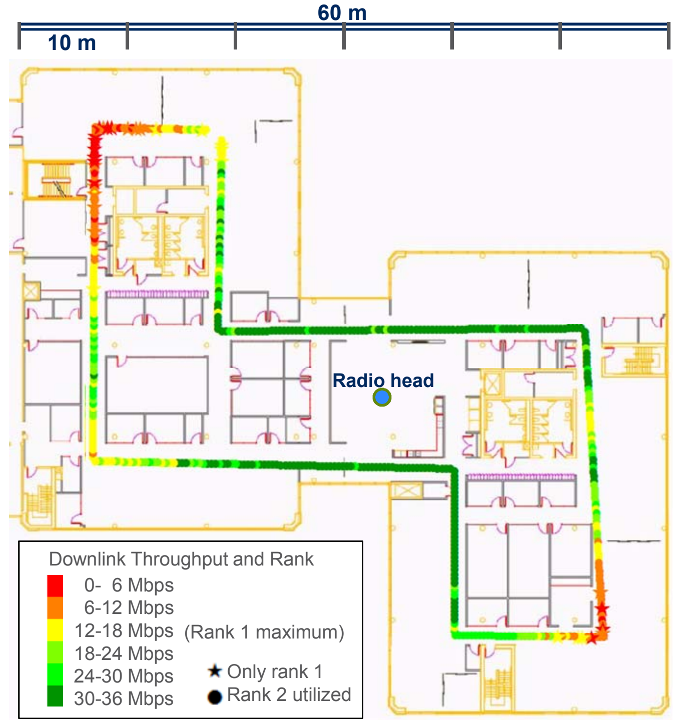

Fig. 2. NLOS route and throughput.

The measurements have been done along three different test routes to investigate different scenarios:

a) NLOS route: A route around the first deployment covering the floor area both near and far from the radio head, see Fig 2. The route is NLOS from the radio head except from some small areas closest to the radio head.
b) Long LOS route: A straight route starting at the radio head in the second deployment and ending in the other end of the office area, see Fig. 6. The route is in LOS from the radio head except at the end when behind a wall.
c) Short LOS route: Two rounds close around the radio head in the first deployment, see Fig. 4. The inner round is completely within LOS and the outer round is partly LOS from the radio head.

A TEMS Investigation tool was connected to the UE for logging and pin-point positioning [8]. The trolley was moved around the routes in a slow constant walking speed, approximately 1 m/s, collecting logs. Data was constantly downloading with User Datagram Protocol (UDP) utilizing all available bandwidth, closely mimicking a full buffer traffic model commonly used in simulations.

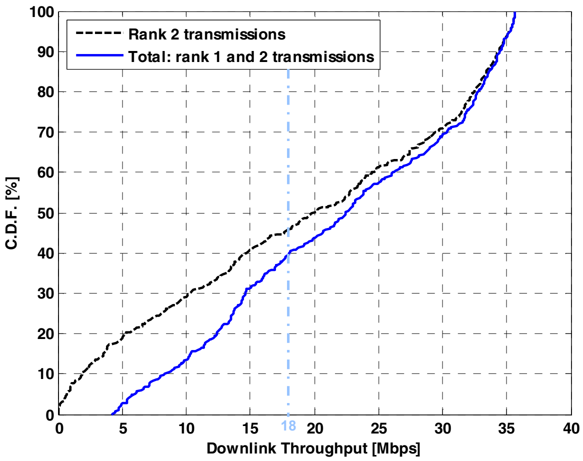

Fig 3. NLOS throughput distribution.

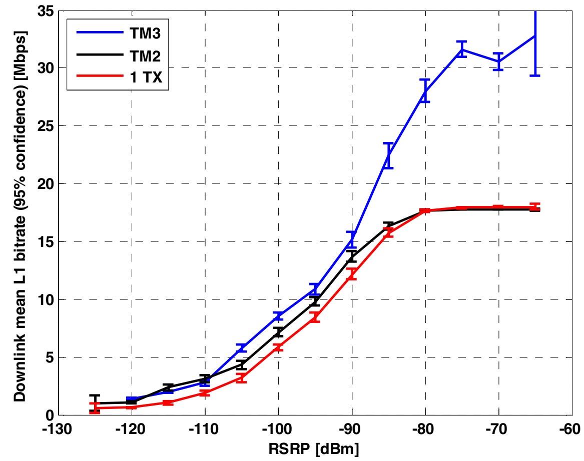

Fig 4. RSRP vs throughput for different MIMO configurations NLOS

Used measures are:

- Reference Signal Received Power (RSRP): [10] as logged every 10 ms. Presented in 5 dB bins.
- Condition Number (*CN*): [5] based on 2x2 signal strength logged every 100 ms, see below. Presented in 5 dB bins.
- Downlink layer-1 throughput: aggregated sum of correctly received bits. Aggregated over 0.5 seconds (500 data transmissions) in map plots and distributions. Aggregated over 10 ms (10 data transmissions) when correlated with RSRP and presented as mean with 95% confidence interval for each RSRP bin to allow for higher granularity.
- Average transmission rank: Correlated with RSRP and *CN* and averaged over their logging intervals, 10 and 100 ms respectively. Presented as mean with 95% confidence interval for each bin, RSRP or Condition Number.

SINR has also been analyzed regarding correlation to RSRP. As expected when there is no interference, the analysis showed similar trends and did not change any of the findings or conclusions. Therefore only RSRP results are presented in this paper, but the RSRP results could easily be translated into SINR results. Also RSRP is specified by 3GPP [10] while SINR is a UE-vendor proprietary measure.

To assess the channel condition for MIMO transmission, a Condition Number in dB is calculated as:

$$CN = 10 \cdot \log\left(\left(\left\|\widehat{Hx}\right\| \cdot \left\|\widehat{Hx}^{-1}\right\|\right)^2\right) \quad (1)$$

based on the per antenna 2x2 received signal strength $\widehat{Hx}$ where H is the MIMO channel and x the transmitted signal. The $\widehat{Hx}$ phase which can facilitate layer separation in the receiver is not available resulting in an overestimated *CN*. Assuming a random phase the average overestimation is in the order of two times in dB scale.

On the NLOS route three different MIMO configurations were tested to allow for comparison

1) TM3: Spatial Multiplexing enabling SU-MIMO transmission with rank adaptation.
2) TM2: Transmit diversity with rank-1 only.
3) 1 TX: SIMO single antenna transmission mimicking a single antenna branch IBS.

On the other two routes only TM3 was used, which allows comparison to the TM3 results on the other two walk routes.

IV. Measurement Results

A. Non-Line-Of-Sight Performance

The throughput measure on the NLOS route is shown in Fig. 2. Spatial multiplexing was extensively used, 75% of all downlink data transmissions were rank-2 transmissions, and rank-2 transmissions are seen on the whole walk route, covering the entire floor plan. The areas where only rank-1 is used are marked as stars in Fig.1, circles marks periods with at least some rank-2 transmissions. The only portion of the floor plan that exhibits a significant portion of rank-1 transmissions is the upper left part, 40 m from the radio head. This area is behind several walls and exhibits RSRP values (and in this case equivalently SINR values) which would typically not support MIMO. Additional radio heads are needed to get rank-2 coverage throughout the whole floor plan.

The throughput accumulated per 0.5 s period as seen on map in Fig.2. is shown as distribution function with solid line in Fig. 3. In 60% of the scanned area the throughput exceeds the maximum rank-1 throughput of 18 Mbps on the used 5 MHz band. This maximum rank-1 throughput is also the maximum for SIMO transmission in a single branch DAS system. SU-MIMO improves the user quality significantly in this environment. The area where the throughput exceeds maximum SIMO throughput is also seen in Fig. 2 as green circles along the scanned walk route. Within 20 m or more from the radio head the throughput exceeds SIMO capability, thanks to sufficient channel rank and good RSRP.

In Fig.3. the contribution from rank-2 transmissions for each 0.5 s period is also shown as distribution function with dashed line. The contribution is large throughout the whole floor plan. Only 2% of the 0.5 s samples do not contain any rank-2 transmissions, seen as dashed line at 0 Mbps in Fig. 3. which corresponds to the fraction of stars in Fig. 2.

Results with different configurations are shown in Fig.4 as throughput vs RSRP. TM 2 and 1 TX with rank-1 only are

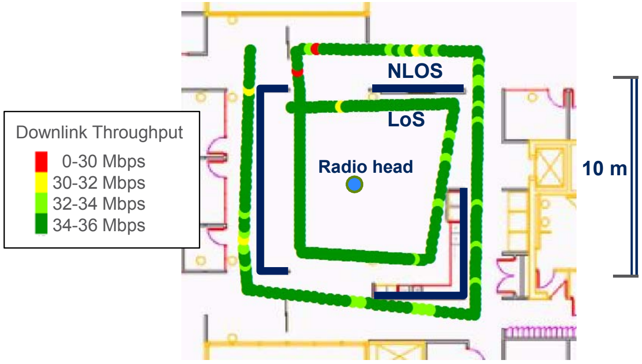

Fig. 5. Short LOS route and throughput.

clearly limited in good radio conditions above 90 dBm RSRP, conditions which are exhibited on more than half of the floor plan. On the remaining areas, below 90 dBm RSRP, TM 3 still gives a higher throughput than 1 TX. As seen comparing with TM 2, this is explained by transmit diversity gain from 2 transmit antennas in the lowest RSRP region, from -125 dBm to -110 dBm. In the middle RSRP region between -110 dBm and -90 dBm, TM3 adds a spatial multiplexing gain from rank-2 transmissions. This together result in a substantial MIMO gain, across both average and good RSRP conditions, and show that overall, there is a large benefit of SU-MIMO spatial multiplexing in this NLOS scenario.

B. *Line-Of-Sight Performance*

In Fig. 5, the walk route and resulting throughput for the short LOS walk route measurement is shown. It is for the same deployment as the NLOS measurement but at short distance around the radio head. Note that the color legend is different compared to Fig. 2. The performance is very good using almost only rank-2 transmission with highest Modulation and Coding Scheme (MCS), green circles in Fig. 5, still resulting in 10 % or fewer retransmissions,. The interesting part of the result in this case is that MIMO transmissions are seen almost throughout these LOS conditions, despite the small radio node size and the limited separation between the two transmit antennas. Furthermore, this is true in all directions around the radio head, showing that the two antennas are sufficiently decorrelated in all directions. The resulting average results for the whole route are shown in Table I.

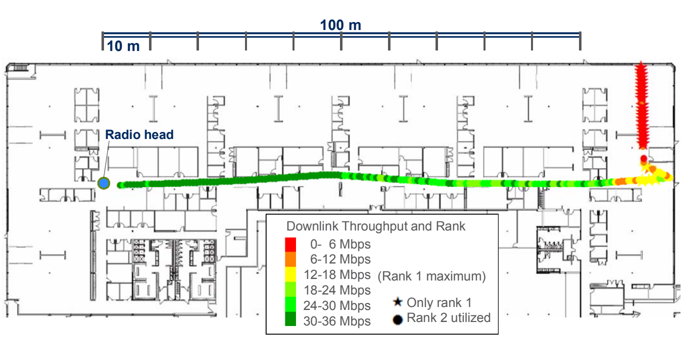

Fig. 6. Long LOS route and throughput.

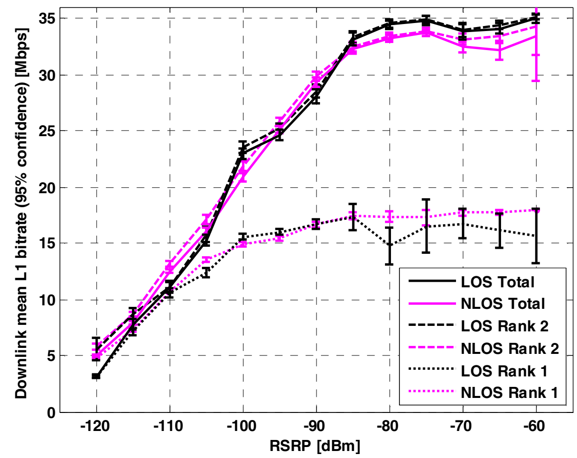

Fig 7. RSRP vs throughput with TM 3 for the long walk routes.

TABLE I. RESULTS SHORT LOS

Measure	Value
RSRP	-67 dBm
Rank-2 fraction	98 %
Throughput	34.2 Mbps
Retransmission rate	3 %

In Fig. 6, the walk route and resulting throughput for the long LOS measurement is shown with the same legend as for NLOS in Fig. 2. The rank-2 coverage is surprisingly good in this LOS environment, rank-2 transmissions are utilized all the way along the LOS path of the walk route. The throughput exceeds the SIMO capability of 18 Mbps to more than 100 m from the radio head. This indicates a rich channel resulting in good MIMO conditions also in this LOS scenario.

C. *Rank Analysis*

In Fig. 7, the throughput as a function of RSRP is shown for both the two long walk routes with TM 3. In addition rank-1 and 2 transmissions are shown separately. The short walk route is omitted since it shows a very small distribution around -67 dBm RSRP and 34 Mbps.

The total throughput which is the average of all rank-1 and rank-2 transmissions is very similar to the rank-2 throughput. The reason is that there is a majority of rank-2 transmission which dominates the statistics.

Somewhat surprising there is no significant difference between NLOS and LOS. The performance is determined by link quality only and seems to be independent of LOS conditions. This is further confirmed by Fig. 8 where average transmission rank is shown vs RSRP. The fraction of rank-2 is largely determined by link quality (in terms of RSRP) and seems to be rather independent of LOS vs NLOS conditions.

An assessment of the channel conditions is done by calculating the Condition Number according to Eq. (1). The distribution for the different walk routes is shown in Fig. 9. The short LOS walk route shows a lower condition number indicating better MIMO channel conditions than the long walk routes. In the measured indoor environment with the used small size nodes (radio head and UE) the LOS channel is surprisingly good for spatial multiplexing. The two longer

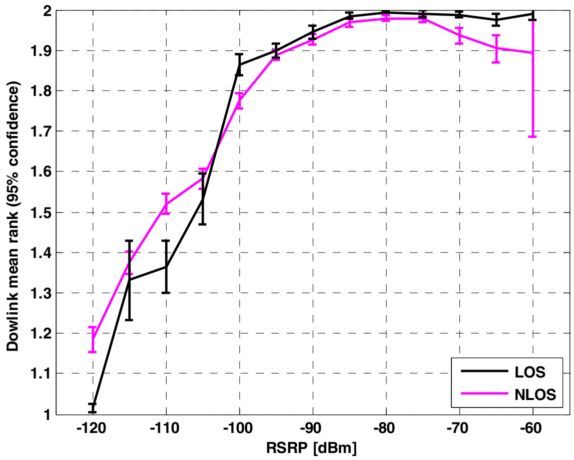

Fig 8. RSRP vs mean transmission rank for the long walk routes.

walk routes show similar *CN* distributions. More than 65% has a *CN* below 30 dB which is a well-conditioned MIMO channel assuming that this *CN* is in average overestimated with a factor of two. The good rank-2 performance also verifies this.

Fig. 10 shows the average transmission rank vs Condition Number for the three walk routes. For the short LOS walk route, the RSRP is constantly very high resulting in no significant impact from *CN*. The high SINR enables good rank-2 reception also for less well-conditioned MIMO channels and high *CN*. For the longer walk routes with a larger range of RSRP, there is a clear correlation between average rank and *CN*. The MIMO channel condition has an impact on the spatial multiplexing performance at lower RSRP. The difference between the two long walk routes is explained by a difference between the RSRP distributions resulting in different ability to utilize less well-conditioned MIMO channels.

It is expected that interference will impact link quality, and that a system with interference is better determined by SINR than by RSRP. However, these tests have been performed on clean spectrum with no interference. RSRP is therefore a good measure of link quality showing high correlation with throughput and rank.

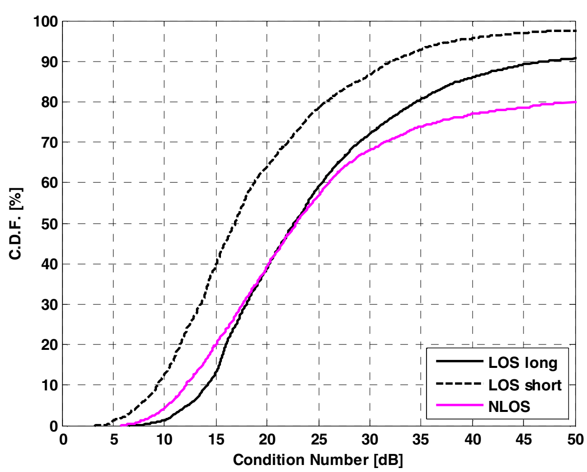

Fig 9. Condition Number distribution.

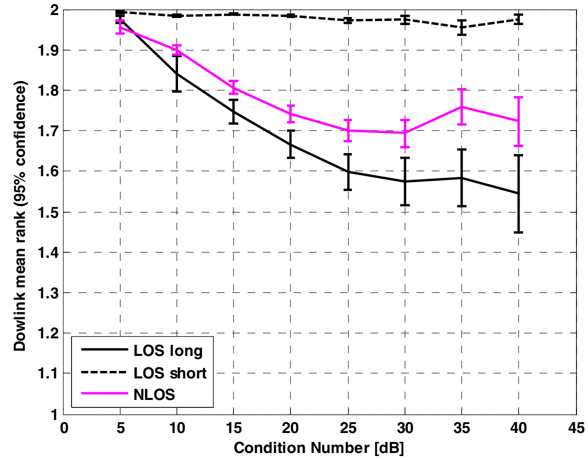

Fig 10. Condition Number vs mean transmission rank.

V. CONCLUSION

The indoor MIMO performance is very good even with a small-sized radio head and a commercial handheld terminal with antennas subject to shape and size constraints. MIMO gain over SIMO is seen almost over the whole NLOS 2500 m^2 office area measured. The throughput in the measurements exceeds maximum SIMO capability on more than half the measured area.

Surprisingly, also in LOS conditions, the MIMO performance is very good, despite the expectation of higher channel condition number in the LOS case. The throughput exceeds SIMO capability up to 100 m from the radio head. In the vicinity around the radio head maximum MCS on rank-2 is reached in all directions showing good antenna decorrelation and a lower channel condition number.

Weighed together, the 2x2 MIMO performance is determined by link quality and propagation but seemingly, and unexpectedly, independent of LOS conditions.

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