Rethinking the Wireless Channel for OTA testing and Network Optimization by Including User Statistics:

RIMP, pure-LOS, Throughput and Detection Probability

Per-Simon Kildal, Distinguished Lecturer of IEEE Antennas and Propagation Society
Department of Signals and Systems
Chalmers University of Technology
41296 Gothenburg, Sweden
per-simon.kildal@chalmers.se

***Abstract*-The reverberation chamber has through the last thirteen years been used to emulate a rich isotropic multipath (RIMP) environment, and it has successfully been demonstrated that it can be used to test performance of multiport antennas and complete wireless terminals with MIMO and OFDM. The measured throughputs of practical LTE devices have been shown to be in excellent agreement with basic theoretical algorithms.**

Now is the time to use this concept and complete the picture so that also real-life environments can be covered. This is done by introducing the pure-LOS as another limiting edge environment, and by introducing the statistics of the user. The latter plays a major role in pure-LOS that thereby becomes a random-LOS. The two limit-environments are linked together with a real-life hypothesis, and work has started to test this by simulations.

It will be shown that the major characterizing quantity becomes the detection probability of the single or multiple bit streams (for diversity and multiplexing cases, respectively) over an ensemble of users. This detection probability becomes equal to throughput in a multipath environment, readily seen through a simple threshold receiver model representing an ideal digital receiver.

The new approach represents a way to start optimizing the wireless networks by taking the statistics of the user into account.

I. INTRODUCTION

Previously all tests of antenna systems were made in anechoic chambers, i.e. with a pure Line-Of-Sight (pure-LOS) between the wireless device (terminal) and the base station. Therefore, traditionally all accurate and repeatable characterization methods were adapted to this method. However, the wireless systems of today are designed for use in multipath i.e. a field environment with many incident waves. These are due to reflections and scattering from objects in the environment, such as houses, trees, vegetation, humans, cars and so on. Naturally, the pure-LOS environment cannot be used to test the algorithms and hardware that handle the multipath.

The reverberation chambers emulate a rich isotropic multipath environment (RIMP). It was originally, for three decades, used for EMC measurements [1]. If it is well designed and large enough, it represents an ideal RIMP environment [2]. Its performance is based on well-accepted theories [3, 4] and it has during the last decade shown its ability to accurately measure efficiency, diversity gain and maximum available MIMO capacity [2, 5] of passive antenna systems as well as radiated power, receiver sensitivity [6], diversity gain and throughput data rate [7] of active mobile devices. The early basic works [2, 5] were later updated to control the time and frequency domain characteristics of the reverberation chamber i.e. delay spread and coherence bandwidth, respectively [8] as well as fading speed and Doppler spread. The most ground breaking of the recent developments is the introduction of a simple threshold model for an advanced digital receiver. Using this, it is possible to predict curves showing throughput data rate versus signal power that are within fractions of a dB from the same measured curves in a reverberation chamber [7], both for single [9] and multiple bit streams [10]. The accuracy of the prediction is of course also due to a good understanding and accurate calibration of the reverberation chamber [11]. The threshold model is therefore a very useful representation of an advanced digital receiver. The threshold function is observed in the stationary case (i.e. with no fading) with added white Gaussian noise and is a result of advanced error correction coding.

The present paper will link the pure-LOS and RIMP environments to real-life environments by a hypothesis (initially presented in [12]), and then show how we can handle the statistics of the user in the pure-LOS environment by CDFs and detection probabilities. The latter is readily achieved via the threshold receiver described above [7].

II. TWO EDGE ENVIRENOMENTS AND A REAL-LIFE HYPOTHESIS

A real-life multipath environment will have characteristics between the two extreme or rather limiting pure-LOS and RIMP environments, also referred to as edge environments. The real-life environments may have both LOS and multipath, and the latter is not necessarily rich. Therefore, we propose to systematize the research on wireless systems and components by using a “real-life hypothesis” that quite reasonably states that: *wireless systems and devices that are optimized for best performance subject to the statistics of the user, in both the limiting pure-LOS and RIMP environments, will also have* *optimum performance in real-life.* The table in Figure 1 summarizes all this.

Thus, the systematic research approach will be to: i) treat the environment as two separate edge environments i.e. the statistical pure LOS and the RIMP, both subject to the statistics of the user, ii) determine technical solutions, algorithms and new systems that are optimum in each of the two reference environments under the statistical variation of different users and user practices (by experimental and theoretical research), and finally iii) prove (mainly by numerical simulation) under which conditions the real-life hypothesis holds, and if needed re-optimize taking some special real-life situations into account with specific weights on the two edge environments.

This systematic approach is new, because the RIMP environment was not defined and used before for system analysis. The RIMP environment has the advantage of providing unique repeatable results from a performance assessment point of view, which thereby enables optimization of the system or the devices. Real-life environments cannot give unique results because the results will depend on the time when they were done, where the device was located, and even how both the user and the device were oriented with respect to both each other and the environment. However, the real-life hypothesis indicates that if performance is evaluated in a large number of real-life environments and scenarios, the overall performance will be optimum if we have ensured optimized performance in the two edge environments.

III. Random pure-LOS environment due to User Variations

Actually, the pure-LOS is also a statistical field environment, due to the arbitrariness of a mobile user both in orientation and in the way the user holds the mobile device. Such user variations have been studied before, but actually not the fact that they will introduce a statistical variation of the received signal also in a pure-LOS environment. This statistical variation is present even for stationary users, within an ensemble of users. This represents the rethinking. The LOS must be considered as being a statistical environment due to the arbitrariness of the orientation of the single user, due to variations between users, and due to different user practices related to e.g. how the mobile device is held. Thus, this also creates a new scenario for wireless communication systems, i.e. *how to deal with the angular variations among users when optimizing systems performance, and in particular in a non-rich multipath environments with a LOS component.*

Probability has previously been taken into consideration when optimizing system performance in fading, but the statistical orientation of the user has been forgotten. In particular, it has been forgotten that we need to ensure good performance for the majority in an ensemble of users. Thus, statistical optimizations must be done over an ensemble of users, not only over a single user, in order to draw fair conclusions about reception quality and data rate. We must ensure that as many users as possible have sufficient communication quality. The optimization criteria should be to minimize the power consumption needed for a certain quality of reception over an ensemble of statistically oriented different users.

The wireless channel is defined as the voltage received on the receiving terminal relative to that transmitted from the base station. Thus, this includes the antennas on both sides and the environment between them, and the user is of course part of this environment. *We claim that the statistical variation among the stationary users is equally important for the performance as the statistics of the fading of a single moving user.*

Environment	Equivalent measurement method	Antenna quality measure	MIMO and diversity capability
Free space (pure-LOS)	Anechoic chamber	Deterministic case: Realized gain User-random case: Not known	To some degree
Real-life environments		No unique quality measure	Yes
Rich isotropic multipath (RIMP)	Reverberation chamber	Total radiation efficiency e_{rad}	Yes

Hypothesis: If wireless terminals work well in RIMP and random pure-LOS environments, they will work well also in real-life environments.
It remains to be proven.

Figure 1. Two limiting reference environments (edge environments) and definition of a real-life hypothesis.

IV. Characterizing Metrics in RIMP and random-LOS

We will now discuss how to characterize the statistics of the user in RIMP and in random pure-LOS. We will also refer to the random pure-LOS case simply as random-LOS.

A. *Cumulative random-LOS- and RIMP-Diversity Gains of the 1% Worst Users in dB-Rayleigh (dBR)*

We have already defined and calculated some diversity gains in pure-LOS environments [13, 14]; similar to what we did some years ago for RIMP [2]. This is for the random-LOS case defined as the cumulative diversity gain of the 1% worst users when the terminal has a randomized orientation in pure-LOS. Initially, we have chosen a three-dimensionally (3D) random orientation, valid for smartphones that can be used with any orientation of the screen. For this case the distribution of received signal amplitudes over many arbitrary users actually turns out in practice to be very close to the Rayleigh shape obtained during normal fading. Still, this pure-LOS case does not represent fading because each terminal is approximately stationary. *This closeness to the Rayleigh distribution is found to be valid for practical small antennas when located on or close to objects of unknown complex shape like the chassis of a mobile phone and a human hand or head or body.* We have also introduced a unit for quantifying diversity gain. This is dBR meaning dB *relative to Rayleigh distribution*, see [14].

B. *Ideal threshold receiver and detection probability*

The ideal threshold receiver is a fundament of the present approach. This definition and the resulting throughput model was already published in [7]. The results (also shown in Figure 2 herein) are valid for advanced digital communication systems like LTE, and can be interpreted like this:

The throughput in RIMP shows for the stationary case a step slope, similar to the conducted AWGN case shown in Figure 2. However, when we plot the throughput versus the transmit power (or preferably versus the average received reference power P_{av} at the multi-port antenna like in this paper) in RIMP, the threshold appears to be different from conducted case due to the interference between all incoming waves. When we move to another position, the incoming waves interfere differently, so the threshold appears at a different level of P_{av}. Therefore, for a given P_{av} we will in some places in the RIMP environment be above the threshold, and in other places below it, so the throughput evaluated over many positions in the RIMP (or for a moving user) will correspond to a detection probability: In each position the user either has a channel or he doesn't. Thus, by the above explanation, we have been able to interpret the throughput of a moving user as a detection probability over an ensemble of stationary users in RIMP. This metric of detection probability is directly extendable to the random-LOS case.

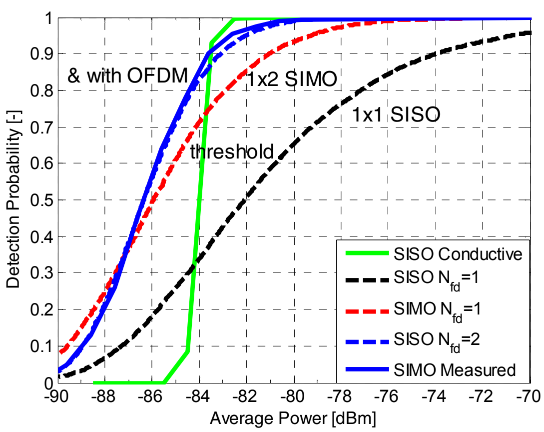

Figure 2. Detection probability of single bit stream in RIMP (i.e. normalized throughput) for 1x1, 1x2 and 1x2 MIMO system with OFDM for a commercial LTE device. The threshold is measured conducted. The dashed curves are simulated from measured threshold values.

C. *Detection probability for single bit stream in RIMP*

We have done some further studies of OFDM frequency diversity by loading the reverberation chamber for different coherence bandwidths (inverse of RMS delay spread) [9]. We have here in Figure 3 presented the throughputs in [9] as detection probabilities of 8, 16, 24 and 32 Mbps bit streams for the 5, 10, 15 and 20 MHz system bandwidths, respectively. We see that the detection probabilities are larger the lower the coherence bandwidths in the environment is (i.e. more frequency selective fading) The reason is that then the OFDM algorithms improve performance, representing diversity gain in frequency domain. (Note that it is only the large detection probabilities that are of interest, and at large values the small coherent bandwidth is better.) It can be seen that the theoretical and measured detection probabilities are very similar. The theoretical curves are based on thresholds measured for the conducted case with a cable connected to the wireless device [9], but the values have been adjusted by 1.0 - 1.3 dB to match the measurements better, meaning that the threshold is about 1 dB lower (i.e. better) with the antennas connected to the device than what we measure conducted.

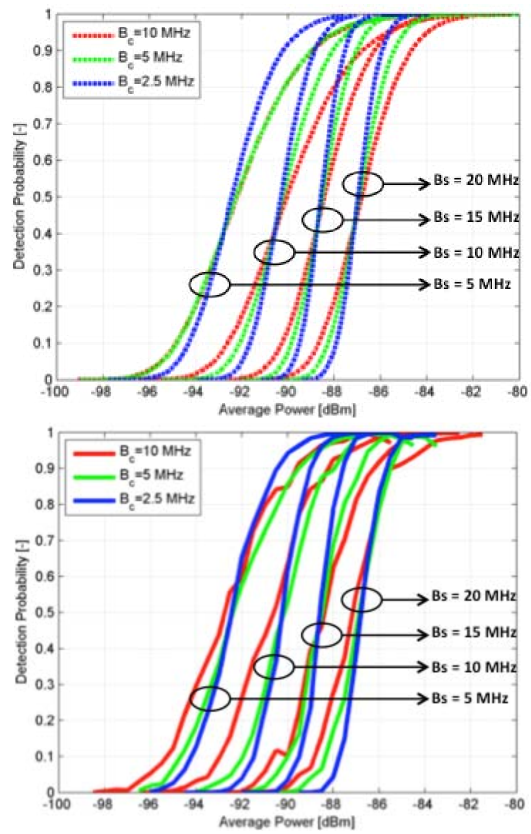

Figure 3. OTA Simulations (top) & OTA measurements (bottom) of 2×2 MIMO LTE throughput in RIMP for system bandwidths of 20, 15, 10, and 5 MHz, and for coherence bandwidths of 10, 5, and 2.5 MHz. The thresholds used in the theoretical model are adjusted by about 1 dB relative to the thresholds in conducted case as explained in the text.

D. *Detection probability of multiple bit streams in RIMP*

For the purpose of illustration we have for a theoretical i.i.d. channel case (independent and identically distributed) produced detection probabilities of 1 and 2 bit streams in a 2x2 MIMO system, and up to 4 bit streams in a 4x4 MIMO system, as a function of the average received power P_{av} over the threshold power level P_t, see Figure 4. The multiple bit streams are produced with a zero-forcing algorithm [10], i.e. open loop measurements with no CSI available at the transmitter. These i.i.d. curves are reference curves for both RIMP and random-LOS cases. For practical systems the results will degrade compared to these theoretical curves, and we can measure the degradation in dBiid (dB relative to the appropriate i.i.d curve) at a certain probability level. Such curves can be used both for RIMP and random-LOS. We showed in [13, 14] that the i.i.d. makes sense as a reference also in pure-LOS environments, because a channel measured on a practical terminal with a small antenna in 3D-random-LOS will have very close to Rayleigh shape, which is also described in Section IV.A in the present paper.

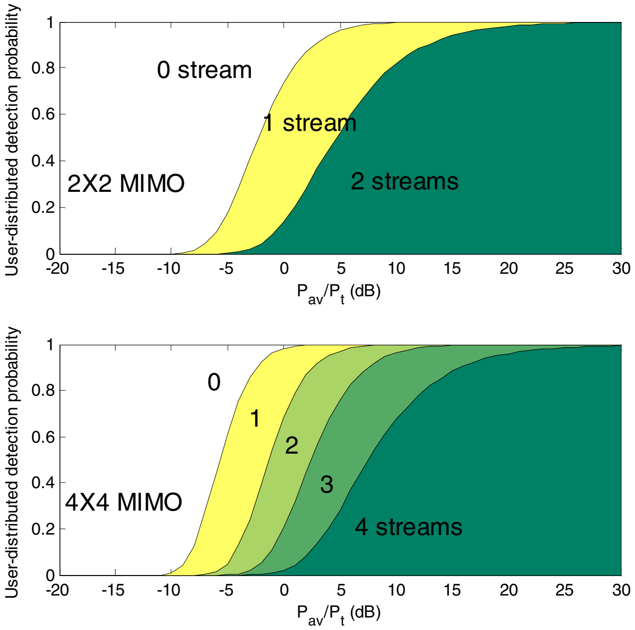

Figure 4. User-distributed detection probability of 2×2 (upper) and 4×4 (lower) open-loop MIMO systems for the i.i.d. cases. The different colors represent the probability of the maximum number of streams supported.

V. Detection Probabilities in random-LOS

The oral presentation will also contain detection probabilities in random pure-LOS. Then, we can detect a maximum of two bit streams if the multiport antenna can provide independently two orthogonally polarized beam patterns in all directions in space.

VI. Conclusion

We have introduced the detection probability as a characterizing metric that can be used in RIMP and random-LOS environments, as well as real-life environments. The detection probability takes account of both the statistics of the environment and the user, and it characterizes a moving user as well as a distribution of stationary users. The simple form of the detection probability is possible due to modern digital receivers that have a detection threshold (i.e. on/off function), so that for each position or time moment the user either has a channel or he doesn't have one.

In a practical design or measurement situation, we would need to define a minimum required detection probability, and then compare devices or solutions with respect to the average power levels required to meet this. Then, quality can be expressed in relative dB values, or we can simply compare the dBiid values of each solution, for each MIMO configuration. The chosen detection probability can be 99% corresponding to the 1% level at which we normally specify diversity gains. Then, the diversity gain improvements will be directly seen as the same improvement in detection probability for the single bit stream case. However, it may be more practical to use 90% or 95% probabilities, because then the characterization becomes less vulnerable to error sources in the measurement setups.

The new approach should enable a new level of system optimization of the complete wireless network, based on collected statistics about how the users use their phones.

VII. References

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