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On Simplifying WINNER II Channel Model for MIMO OTA Performance Evaluation

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Abstract—**The development of MIMO over-the-air (OTA) test methodology is an ongoing activity in 3GPP RAN4, CTIA and EU COST Action 2100. In this paper, the focus is on the anechoic chamber approach, which uses a uniform circular array of probe antennas to replicate directional channels for the device-under-test at the array center. In particular, we study in simulation the complexity requirements of implementing the WINNER II clustered delay line (CDL) model in RF using off-the-shelf RF components. Our results reveal that a significant reduction in complexity of the CDL model can be achieved, while keeping the change in both ergodic and outage capacities under 10% relative to the full model. This suggests that it is both feasible and cost effective in implementing state-of-the-art directional channel models in RF for MIMO OTA performance evaluations.**

I. Introduction

WITH the growing requirement for higher data transmission rates, multiple-input multiple-output (MIMO) terminals are being developed for beyond-3G wireless communication systems such as HSPA and LTE. To ensure that a terminal is capable of delivering the promises of MIMO technology, the development of test systems for the performance evaluation of MIMO terminals is ongoing in 3GPP RAN Workgroup 4, CTIA and EU COST Action 2100 [1]. Recently, the OTA (over-the-air) test system for single-antenna terminals has been standardized. However, it is inadequate for the evaluation of MIMO terminals, since it makes no attempt to introduce an OTA channel with spatial characteristics. Given that MIMO systems critically rely on the directional multipath channel and the decorrelation between multiple antennas to improve channel capacity [2], the test system for MIMO terminals should include both temporal and spatial characteristics of the propagation channel.

So far, several methodologies have been proposed and extensively discussed in COST2100 meetings. The details of these methodologies are given in [3]. In this paper, we focus on the Multipath Simulator (MPS) test method proposed by SP Sweden and Sony Ericsson. A MATLAB simulation platform is built based on this test method. In particular, the RF implementation of the WINNER II clustered delay line (CDL) channel model in the OTA test system is studied in simulation. We show that a feasible and cost effective solution can be achieved by systematic simplifications of the WINNER II channels while retaining similar performance characteristics.

II. Multipath Simulator Methodology

The MPS method does not use sophisticated commercial channel emulators that generate multipath characteristics in baseband. Instead, the multipath channel is generated in RF by the use of delay lines, phase shifters, attenuators, and splitters/combiners. The multipath signals are then distributed to an array of antenna probes, which are used to replicate the spatial characteristics of the propagation channel. The antenna probes are built into an azimuth ring structure to produce the angles-of-arrival (AoAs) corresponding to the probe directions. Fig. 1 shows the appearance of an 8-probe version of the probe ring inside an anechoic chamber. Each probe consists of a vertical antenna and a horizontal antenna to emulate the two polarizations of the signal path at the receive end of the channel. The optimal geometrical layout of the probe ring depends on detailed requirements, e.g. angular resolution, statistical properties, uncertainty in the field level and cost. During measurement, the device-under-test (DUT) is located within a test zone at the center of the probe ring so that the signals from all the probes reach the DUT over similar OTA distances. The system setup and configuration of this method are found in [3].
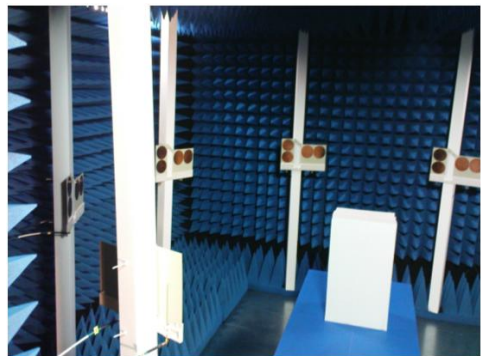
Fig. 1. Antenna probes in a ring configuration within an anechoic chamber.

III. Spatial Channel Models

The propagation channel models play a very important role in the performance evaluation of MIMO terminals. The candidate spatial channel models that have been considered for the MIMO OTA test system include 3GPP Spatial Channel Model (SCM), its extension (SCME), and models developed under the European WINNER project.

At present, the MIMO OTA test system is intended for the performance evaluation of terminals in HSPA and LTE systems,

which support a bandwidth of up to 20 MHz. The SCM is not suitable since it only supports a bandwidth of 5 MHz. Likewise, the SCME has several limitations, such as no indoor scenario, transmission-distance-dependent Rician K-factor and no XPR in the tapped delay line (TDL) model. Both WINNER I and WINNER II models satisfy the main requirements, but the latter has extended features and support more scenarios. Thus, the WINNER II model is adopted for our simulation study.

WINNER II provides two types of models. The *generic model* is the more accurate model – it aims to be applicable for many different simulations and cover many scenarios with several combinations of large- and small- scale parameters. The *CDL model* is a reduced-complexity version of the generic model. It has fixed large-scale and small-scale parameters, which are intended to provide average channel characteristics. We use the WINNER II CDL model for the development of MIMO OTA test system based on the MPS method.

According to one version of the planning document of the COST2100 round robin measurement campaign [2], the following scenarios in the WINNER II CDL model are selected for our study: large indoor hall (B3), outdoor to indoor (B4), typical urban micro-cell (B1), suburban (C1) and rural macro-cell (D1). Except for B4, these scenarios are defined for both line-of-sight (LOS) and non-LOS (NLOS) cases. For B4, the probability of LOS occurrence is approximated as zero. Based on the LOS probabilities given in [4], we choose in our simulation study the NLOS case for the C1 and D1 scenarios, and both LOS and NLOS cases for the B1 and B3 scenarios.

IV. CHANNEL MODEL SIMPLIFICATIONS

A. MIMO Channel Generation

In order to analyze the channels used in an OTA test system, MIMO channel matrices are generated from the parameters provided in WINNER II CDL model. In the simulation we focus on 2×2 MIMO channels. Measured antenna patterns of two DUTs with high correlation and low correlation, respectively, are used together with the channel model to synthesize the MIMO channel. Since it is difficult to directly emulate the base station antenna pattern and spatial information, the Kronecker model is utilized to include transmit correlation into the channel. Hence, the transmit signals from different base station antennas are pre-processed in the test system.

B. Simplification Methods and Criteria

There are between 8 and 20 clusters in the different scenarios of the WINNER II CDL model, and each cluster contains 20 rays. To implement the entire set of parameters in hardware will result in a very complicated and high-cost MPS in the OTA test system. Hence, some simplifications of the CDL channel model are needed. And as long as the figures of merit (FOMs) from the simplified model can still closely resemble those of the full channel model, they can be used to reflect real user experience. The simplification steps in our study are listed below:
- Down-scale the bandwidth supported by the model.
- Reduce the number of rays in one cluster.
- Remove intra-cluster angular spread.
- Discard some clusters with relatively low powers.

In order to ascertain the extent to which the simplification steps can be performed, several criteria are used to evaluate the simplification process. The capacity of MIMO channel is the dominant criterion, since the trend of capacity can reflect the trend of throughput [5], which is the FOM with the highest priority in MIMO OTA measurements. In our simplification process, if the changes in both ergodic and 10% outage capacity are under 10%, the throughput can be regarded as unchanged, so that the simplified channel is considered acceptable. The signal-to-noise ratio (SNR) is set to the range of 10-30 dB.

Channel properties, such as delay spread, angular spread and spatial correlation, are also used in the analysis of the simplification process. Changes in these channel properties result in a change in capacity (with high probability), so capacity is taken as the dominant criterion to assess channel simplification. When the spatial property of the channel changes in the simplification process, the change in the capacity of the DUT with high-correlation antennas is greater than that of the DUT with isotropic antennas or low-correlation antennas. Keeping the capacity change of the high-correlation antennas under 10% can thus guarantee the capacity change of both the isotropic antennas and the low-correlation antennas to be under 10%. Therefore, the capacity change of the high-correlation antennas is used as the criterion to evaluate the simplified channel when the spatial property changes. Moreover, the DUT is rotated 360° in steps of 30° in the simulations, and the average performance is obtained from these orientations.

C. Bandwidth Down-scaling

The WINNER II channel model is designed for a bandwidth of 100 MHz. However, HSPA and LTE systems support a bandwidth of up to 5 MHz and 20 MHz, respectively, which is much smaller than 100 MHz. Therefore, the resolution in the delay domain does not need to be as high as that for a system with a 100 MHz bandwidth. In general, the delay resolution is the inverse of the system bandwidth, so we can set the delay sample spacing to 50 ns, i.e., the inverse of 20 MHz. Bandwidth down-scaling is performed in the delay domain as follows [4]:
- Create the new delay grid for required system bandwidth.
- Move the original delay samples to their nearest locations in the new grid.
- If there are two nearest locations, the delay tap should be moved to the one that has smaller delay value.
- If more than one delay taps are placed at the same location, sum them up as complex numbers.

Therefore, the channel is simplified by merging some adjacent clusters in the delay domain. This leads to fewer delay lines in the test system. The channel's spatial properties, e.g., AoAs and AoDs, are unchanged in this process, but the root mean square (RMS) delay spread is slightly changed. We find that after the bandwidth down-scaling, the ergodic capacity remains unchanged, but the 10% outage capacity decreases, which is because the channel becomes less frequency selective. In the following simplification process, the change in capacity will be calculated with respect to the channel in which the bandwidth has been down-scaled to 20 MHz.

D. Rayleigh Fading

In the CDL model, the fading process for each CIR tap is modeled by the sum-of-sinusoid approach, as each cluster is composed of 20 rays with the same power and different phases. The number of rays determines the required number of phase shifters in the OTA test system. With 20 rays per cluster, the resulting system is very complicated. Therefore, we model Rayleigh fading by pre-fading the amplitude of each cluster using an attenuator according to the Rayleigh distribution. For this approach, only 1 ray is needed for each cluster. Ray phases are randomly generated from a uniform distribution. If the LOS ray exists, the 0 ns tap may contain the dominant ray and one or more clusters, and the amplitudes are Rician distributed. We find that this method can perfectly model the fading process, so that the number of phase shifters can be significantly reduced.

E. Intra-cluster Angular Spread

The 20 rays per cluster are also used to model intra-cluster angular spreads of departure and arrival (cluster ASD and cluster ASA). The offset angles of the 20 rays form the Laplacian power angular spectrum (PAS) in each cluster [4]. Although a single ray per cluster can perfectly model Rayleigh fading using pre-fading, it is impossible for the single ray to model intra-cluster angular spread. Cluster ASD is used in the calculation of transmit correlation. Thus, only cluster ASA is relevant to the test system. However, if the cluster ASA is narrow, the DUT antennas may be unable to resolve it. Based on this hypothesis, we set the criterion that the cluster ASA can be removed, as long as the capacity change is kept under 10%.

We find that removing the cluster ASA leads to a decrease in the total angular spread (AS), which causes an increase in the coherence distance [6] in space. From our analysis, the change in the performance of the DUT with high-correlation antennas is greater than that of the DUT with isotropic antennas or low-correlation antennas. This is because the antenna spacing may not be able to sufficiently decorrelate the incoming signals anymore. Therefore, the high-correlation antennas are used for the evaluation of this channel simplification process. Table I lists the results for all the chosen scenarios in the WINNER II CDL model. We can see that the cluster ASA is not removable only in the B1 NLOS scenario, which has the largest cluster ASA (of 22°). When the cluster ASA is removed, the decrease in the total AS of the B1 NLOS scenario is the greatest in comparison with other scenarios. Fig. 2(a) shows the changes in the ergodic and 10% outage capacities, which decrease by at most 3% and 11%, respectively, for the given range of SNRs.

TABLE I
CLUSTER ASA FOR ALL THE CHOSEN SCENARIOS IN THE WINNER II CDL CHANNEL MODEL

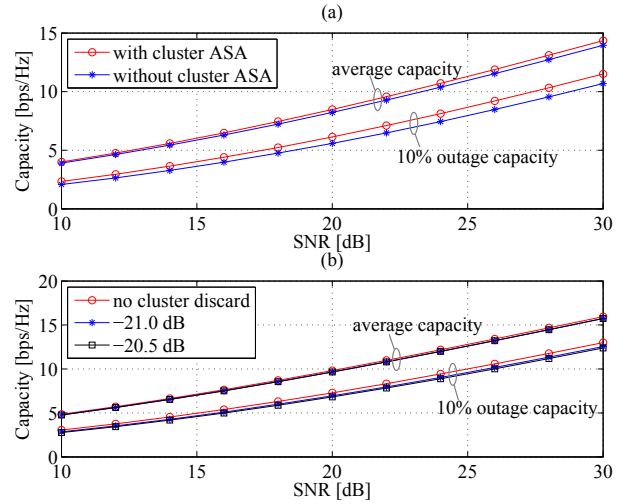| Scenario		Cluster ASA [°]	Total AS with Cluster ASA [°]	Total AS w/o Cluster ASA[°]	Cluster ASA Removable?
B3	LOS	5	34.7	34.6	Yes
	NLOS	13	46.3	45.6	Yes
B4	NLOS	5	57.0	57.0	Yes
B1	LOS	18	28.2	27.2	Yes
	NLOS	22	39.0	35.2	No
C1	NLOS	10	41.3	40.8	Yes
D1	NLOS	3	35.4	35.3	Yes

Fig. 2. (a) Ergodic and outage capacities for the B1 NLOS scenario with and without cluster ASA. The DUT with high correlation antennas is simulated; (b) Ergodic and outage capacities of C1 NLOS with different ray power thresholds for cluster discarding. The DUT with high correlation antennas is simulated.
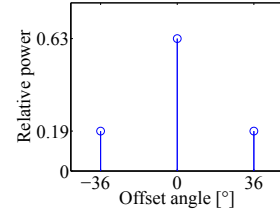

Fig. 3. Relative power distribution and offset angles of the 3 rays used to model the 22° cluster ASA in B1 NLOS, for half-wavelength antenna spacing.

The cluster ASA in B1 NLOS scenario should not be completely removed. However, it is not practical to use 20 rays per cluster in the test system. A method of using 3 rays to model the Laplacian PAS in [7] is examined here. The principle of the method is to match the intra-cluster spatial correlation at the DUT side between the 20-ray and the 3-ray cluster models. In other words, by allocating the 3 rays with specific powers and offset angles, we can get a good match to the spatial correlation derived from the original 20-ray model. Fig. 3 shows the power distribution and offset angles of the 3 rays used to model the 22° cluster ASA in the B1 NLOS scenario, for isotropic antennas with half-wavelength (λ/2) spacing. When applying the 3-ray method in our simulations, the ergodic and 10% outage capacities decrease by only 1% and 2%, respectively, relative to the 20-ray model. Arbitrary cluster ASA can be modeled using this method. To some extent, it can replace the 20-ray method. However, the agreement in the intra-cluster spatial correlation between these two models depends on the DUT antenna spacing, whereas the OTA test systems should not need to know the antenna configurations of the DUTs.

F. Cluster Discarding

The number of clusters in the channel model influences the required number of delay lines, attenuators and phase shifters in the OTA test system. To have a even simpler implementation of the channel model, we consider in the following the possibility to discard clusters with relatively low powers, as

long as the DUT performance does not change appreciably in the simplified channel. In the process of cluster discarding, the total power of all the clusters is kept unchanged.

Discarding low power clusters leads to changes in the delay distribution and the angle distribution surrounding the DUT. Thus, the capacity will change correspondingly. Our study confirms the simple intuition that both delay spread and angular spread will decrease after cluster discarding. This is because the discarded clusters with lower powers tend to have larger delays. The decrease in the delay spread leads to a decrease in the outage capacity; and the decrease in the angular spread has a significant influence on the performance of the high-correlation antennas. Therefore, the high-correlation antennas are used for the evaluation of the cluster discarding process.

The ray powers in all the chosen scenarios are given in [4]. Clusters with ray powers lower than a predefined threshold are discarded. The objective is to find the upper threshold for which the channel can have the fewest clusters while the change in capacity is kept to within 10%. Here, the WINNER II C1 NLOS model is used as a representative example to explain the cluster discarding process and threshold determination. Fig. 2(b) illustrates the ergodic and outage capacities with different ray power thresholds for cluster discarding. Compared to the channel without cluster discarding, the ergodic capacities decrease 2% for both -21.0 dB and -20.5 dB thresholds; the outage capacities experience greater changes, which are 7% and slightly above 10%, respectively. Therefore, -21.0 dB is the upper limit of thresholds for cluster discarding in the C1 NLOS scenario. Using this upper threshold, the number of clusters is reduced from 14 to 10 without affecting the performance appreciably.

Through simulations for all the chosen scenarios, the ray power threshold upper limits are found and listed in Table II. In all the scenarios except B1 NLOS, the cluster ASA is removed. However, the threshold upper limits and the number of preserved clusters are not the final results for cluster discarding, since the results may change if the configuration of the antenna probes is considered. In this context, the results in Table II serve as a reference for simplification in the delay domain.

TABLE II
RESULTS OF CLUSTER DISCARDING FOR ALL THE CHOSEN SCENARIOS

Scenario		Ray Power Threshold Upper Limit [dB]	Number of Preserved Clusters
B3	LOS	-26.8	6
	NLOS	-24.1	11
B4	NLOS	-19.9	4
B1	LOS	-26.9	4
	NLOS	-21.1	4
C1	NLOS	-21.0	10
D1	NLOS	-17.2	5

G. Antenna Probes

In the anechoic chamber, an array of antenna probes is used to replicate the spatial characteristics of the channel model. Currently, an azimuth ring structure, with uniform spacing between adjacent probes, is the most commonly used configuration. This structure of antenna probes can replicate any directional channel. The accuracy of the replicated AoAs

will improve with more probes. Nevertheless, the number of probes is restricted by the size of the circle, as the spacing between adjacent probes needs to be large enough to reduce mutual coupling. In addition, the size of the probes also affects the spacing and placement. For example, the dual-polarized wideband probes shown in Fig. 1 cover multiple mobile bands, including those below 1 GHz. However, they are physically large. On the other hand, the radius of the probe circle is restricted by the size of the chamber. In our study, the radius is set to 1.4 m, corresponding to SP-Sony Ericsson's test setup.

In the uniform circle, an arbitrary AoA is shifted to the nearest angle that is represented by a probe. The maximum shifting angle equals 180° divided by the number of probes. In our simulations, channel capacity is used to decide upon the minimum required number of antenna probes. We consider four cases of the number of probes, i.e., 18, 15, 12 and 9, and the corresponding maximum shifting angles are 10°, 12°, 15° and 20°. Note that the change in capacity is not only due to the shift of AoAs, but also due to the previous simplification step.

When 18, 15 and 12 probes are used, the decrease in outage capacities exceeds 10% in B1 LOS (12%), B1 NLOS (13%) and B4 NLOS (10.6%), respectively (i.e., they fail in only one scenario each). For 9 probes, the decrease in outage capacity exceeds 10% in B1 NLOS (19%) and D1 NLOS (13%).

Since the decrease in capacity is also due to cluster discarding, in order to keep the capacity change of a given scenario under 10% for a given number of probes, we can lower the upper limit of ray power threshold to retain more clusters. Therefore, there is a tradeoff between the number of RF chains and the number of antenna probes in the test system. However, since RF chains are more expensive than antenna probes, it is less desirable to choose 9 probes, where more clusters should be added for two scenarios, especially for B1 NLOS (19%). In addition, the 12-probe case has the lowest number of probes and is closest to the 10% capacity change limit among cases where only one scenario needs to retain more clusters. From this perspective, 12 is considered as the optimum number.

H. Effective Test Area

In [8], 15 probes are needed in relation to the effective test area of the DUT. And for the uniform placement of probes in a ring configuration, an odd number of probes is suggested to avoid wave reflection from the probe on the opposite end. To determine the effective test area in our study, we first consider the far field distance of an antenna, which is in general regarded to be a distance larger than 10λ from the phase center of the antenna. Therefore the distance between probe antenna and DUT antenna should be larger than 10λ. In our simulation, the system frequency is 2.48 GHz, meaning that 10λ is about 1.2 m. And the radius of the probe ring is 1.4 m, so the far field area has the radius of about 0.2 m, as shown in Fig. 4. In our study, the performance of the DUT antennas at different locations in the far field area is simulated. Effective area is found with regard to the change in capacity of under 10%. Vertical and horizontal probe antenna patterns are used in the simulation. The free-space path loss from the probe antenna to the DUT antenna is also considered. The effective area is found for the
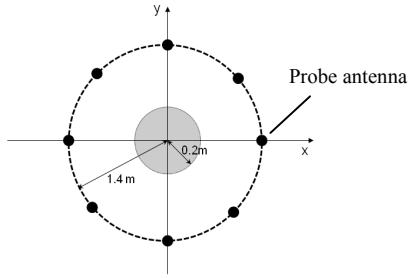
Fig. 4. The far field area in the 8-probe ring corresponds to the gray region.

simplified channel after cluster discarding and AoA shifting to 12 or 15 probes. The DUT with isotropic antennas is used here, since the effective area is found to be the same with high-correlation or low-correlation antennas.

In order to support the DUTs with antenna spacing of up to 3λ, for example, laptops, the radius of the effective area should be larger than 1.5λ, which is just within the far field area. If the radius of the effective area for the simplified channel is less than 1.5λ, more clusters should be preserved in the process of cluster discarding to have larger effective area. We find that when the number of probe is 12, even if no cluster discarding is performed, the radius of the effective area for B3 LOS is less than 1.5λ. When the number of probes is 15, all the scenarios can support an effective area with a radius of 1.5λ. Therefore, 15 probes are needed in the test system.

V. RESULTS

From the above analysis, the chosen scenarios of the WINNER II CDL model can be simplified to reduce the complexity of the MIMO OTA test system. Considering the number of antenna probes and the effective test area, the cluster discarding threshold and the corresponding number of preserved clusters for each scenario are listed in Table III.

TABLE III
FINAL RESULTS OF CLUSTER DISCARDING FOR ALL THE CHOSEN SCENARIOS

Scenario		Ray Power Threshold Upper Limit [dB]	Number of Preserved Clusters
B3	LOS	-26.8	6
	NLOS	-24.1	11
B4	NLOS	-19.9	4
B1	LOS	-27.8	5
	NLOS	-21.6	5
C1	NLOS	-21.0	10
D1	NLOS	-17.2	5

In the simplified channel, the AoDs and the cluster ASDs are kept the same as the original channel model to generate the transmit correlation matrix. The K-factor for the LOS case and the XPR are also unchanged. There is only one ray per cluster in all chosen scenarios, except for B1 NLOS where the cluster ASA is irremovable. The AoAs in the original channel model are shifted to the 15 probes placed uniformly around a circle.

Table IV compares the number of delay lines and phase shifters that are needed for the original full channel and the simplified channel. The number of attenuators is the same as the number of phase shifters. It can be noticed that the number of RF components is greatly reduced for the simplified channel.

TABLE IV
RF IMPLEMENTATION OF THE CHANNEL MODELS

Scenario / Channel		No. of Delay Lines		No. of Phase Shifters	
		Full Channel	Simplified Channel	Full Channel	Simplified Channel
B3	LOS	12	3	200	6
	NLOS	13	3	300	11
B4	NLOS	12	2	240	4
B1	LOS	12	3	160	5
	NLOS	19	3	320	$\geq$15
C1	NLOS	16	4	280	10
D1	NLOS	10	2	200	5

Note: To be consistent with the convention of the WINNER II model, the number of delay lines and phase shifters are specified for the RF chains from *one* base station antenna.

VI. CONCLUSIONS

In this paper, the MPS test method is introduced to evaluate the OTA performance of MIMO terminals in HSPA and LTE systems. The RF implementation of the WINNER II CDL channel model in the MIMO OTA test system is investigated. To reduce the cost and complexity of the test system, the channel model is simplified according to a systematic approach, and implemented through a comprehensive simulation study. Channel capacity is used as the dominant criterion to evaluate the simplification process. The results show that the channel can be greatly simplified and still provide similar performance characteristics as the original channel. Thus, implementing the simplified channel in the MPS based MIMO OTA test system will significantly reduce the required number of RF components, rendering it both feasible and cost-effective. In addition, the channel simplification steps introduced in this paper can be used for any other CDL channel model.

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