and (iii) time-dependent small-scale fading traces for each eNodeB-UE pair.

1) Pathloss and Fading Maps: The large-scale pathloss and shadow fading are modeled as position-dependent maps. The large-scale pathloss is calculated according to well-known models [62, 67] and combined with the antenna gain pattern of the corresponding eNodeB. Space-correlated shadow fading is obtained from a log-normal random distribution using a low-complexity variant of the Cholesky decomposition [68]. Inter-site map correlation for shadow fading is similarly obtained.

Figure 7 shows exemplary large-scale pathloss and shadow fading maps.

2) Time-dependent Fading Trace: While the large-scale pathloss and the shadow fading are modeled position-dependent, the small-scale fading is modeled as a time-dependent trace. The calculation of this trace is based on the transmitter precoding, the small-scale fading MIMO channel matrix, and the receive filter. Currently, the receiver modeling is based on a linear ZF receiver. The small-scale fading trace consists of the signal power and the interference power after the receive filter. The break-down into these two parts significantly reduces the computational effort since it avoids many complex multiplications required when directly working with MIMO channel matrices on system level [19, 38, 55].

IV. VALIDATION OF THE SIMULATORS

Validation of the simulators was performed in two steps. Firstly, in Section IV-A we compared the link level throughput with the minimum performance requirements stated by 3GPP in the technical specification TS 36.101 [69]. Secondly, in Section IV-B we cross-validated the link and the system level simulators by comparing their results against each other. Other means of validation are being discussed in Section IV-C.

A. 3GPP Minimum Performance Requirements

The technical specification TS 36.101 [69] defines minimum performance requirements for a UE that utilizes a dual-antenna receiver. These requirements have to be met by real devices and therefore have to be surpassed by our simulator, in which not every conceivable influential factor is incorporated.² Such factors may include frequency and timing synchronization as well as other non-ideal effects, such as quantization or non-ideality of the manufactured physical components (e.g., I/Q imbalances, phase noise, power amplifier nonlinearities).

In particular, TS 36.101 specifies reference measurement channels for the Physical Downlink Shared Channel (PDSCH) (comprising bandwidth, AMC scheme, overhead, ...) and propagation conditions (power delay profiles, Doppler frequencies, antenna correlation). The considered simulation scenarios are completely specified by referring to sections and test numbers in TS 36.101. For example, in TS 36.101 Section 8.2.1.1.1, the tests for a single transmit antenna \( N_T = 1 \) and dual receive antenna \( N_R = 2 \) scenario are defined. By referring to test number one in this section, the AMC mode is defined as Quadrature Phase Shift Keying (QPSK) with a target coding rate of 1/3, Extended Vehicular A (EvHa) channel model with a Doppler frequency of 5 Hz, and low antenna correlation. For our simulations presented here, we selected four test scenarios with a bandwidth of 10 MHz but different transmit modes (single antenna port transmission, OLSM, and TxD), different AMC schemes, and different channel models. Hybrid Automatic Repeat reQuest (HARQ) is supported with

²After all, the purpose of a simulation model is to abstract and thus simplify complex situations.