Investigation of Wraparound Techniques for the Simulation of Wireless Cellular Networks

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***Abstract*—A common approach to obtaining analytical results for the performance of wireless cellular networks relies on assuming an infinite amount of interferers. For simulations with finite dimensions, interference is often inadequately represented for users in the border region. These border effects can be circumvented by a wraparound that allows signals that leave the region of interest on one side to reappear on the opposite side, thus mirroring the missing interferers beyond the scenario boundary. In this paper, we determine a minimal network size for which the simulation with wraparound strategy approximates the infinitely stretched out network. We compare this strategy to the interference region strategy, for which dummy interferers are placed outside of the simulated network. The effects of the chosen network size and path loss exponent on the accuracy of the two strategies are discussed.**

***Index Terms*—System level, wrap around, wireless networks, stochastic geometry, simulations, finite network area**

I. INTRODUCTION

A widely used tool for predicting and evaluating the expected performance of new technologies in wireless networks is system level (SL) simulations [1]. The two main alternative approaches, analytical evaluation and network measurements, come with their own downsides. Analytical evaluation often relies on stochastic geometry that offers a number of analytical tools for randomly generated networks [2]. These results are however, in general, limited to signal to interference and noise ratio (SINR) values and do not evaluate the effects of medium access control (MAC) layer procedures, such as scheduling and feedback. Network measurements, besides being expensive and difficult to perform, do not offer the option to evaluate experimental transmission schemes and do not deliver results in such a fine granularity as SL simulations. Hence, there is a high demand for system level simulators (SLSs) in industry and academia [3], [4] and a continued effort is made to make SLSs computationally less expensive, while maintaining accuracy.

In simulations of interference limited networks with a finite region of interest (ROI), the lack of interference from transmitters outside of the ROI leads to a misrepresentation of the SINR for users approaching the border of the simulation region. The closer a user moves to the border of the ROI, the more the distances to the serving base station (BS) and to the interfering BSs are misrepresented and the more distorted the evaluated SINR becomes [5]. To circumvent these border effects, different border effect mitigation strategies (BEMSs) have been considered and utilized for SL simulations.

A straight-forward BEMS is to add additional interferers around the simulated ROI, as it is done in the Vienna Cellular Communications Simulators (VCCS) 5th generation (5G) SLS, which is part of the VCCS suite [6]. This approach leads to a significant increase in computational complexity and thus simulation time. This is especially true since the size of the interference region is substantial [5]. In an attempt to reduce this computational complexity, wraparound methods for hexagonal grid networks have been proposed [7]–[10].

To achieve a network wraparound in downlink (DL), the transmitters in the network are replicated outside the ROI as depicted in Figure 1a. Then, for each user, the closest of the BS replications of each BS is chosen for the evaluation of the link quality [11]. The user is thus virtually at the center of the network in a simulation with wraparound. For uplink (UL) scenarios, the same procedure can be applied with interchanged transmitter and receiver roles for BSs and users.

With the wraparound strategy virtually placing each user in the center of the simulated network, a minimal ROI size has to be evaluated, for which the user at the center experiences no, or a negligible amount, of border effects. This minimal ROI size will be evaluated by comparing the simulated coverage probability of a user in networks of different sizes to the analytical evaluation of the coverage probability of a user in an infinite network that has been determined in [12]. With this minimal ROI size, the two BEMSs, wraparound and interference region, will be compared in terms of accuracy of the model for a fixed BS density and different path loss exponents.

II. STATE OF ART

Wraparound methods have already been introduced two decades ago for hexagonal ring networks [13] and are utilized in multiple simulation environments [14], [15]. The wraparound strategy has been improved in several manners since its introduction. Geographical distance wrapping can be replaced by radio distance wrapping, where the signal strength is utilized to choose the wrapped BS instead of the euclidean distance between the two network elements. This leads to an increase of accuracy, but also of computational complexity [11]. The two strategies remain equivalent if direc-

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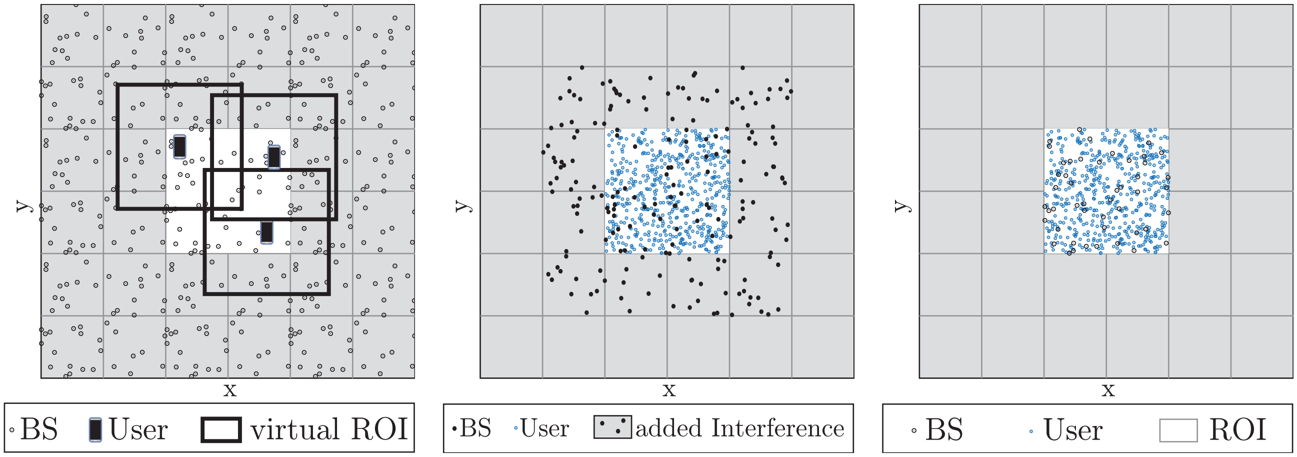


(a) Wraparound

(b) Interference Region

(c) None

Fig. 1: Examples of network realizations for the comparison of BEMSs. In Figure 1a, exemplary users are shown at the center of their wrapped network. The base station density is $\lambda_{BS} = 2$ BS/km^2 and the span of the ROI (in white) is 5 km in each example.

tion dependent propagation effects, such as antenna directivity, shadow fading and blockages, are not included.

Hexagonal wraparound has also been extended by a wrapped shadow fading model [16]. The wraparound of non-hexagonal network topologies has mostly been neglected, even though Poisson point process (PPP) networks are gaining in importance for network performance evaluation with the introduction of stochastic geometry.

An example of the interference region strategy is depicted in Figure 1b, the strategy is described in [17]. To reduce complexity and save simulation time, the BSs in the interference region are not fully simulated but utilize simplified scheduling and feedback. This does not affect the network performance since the scheduling decisions of interfering BSs do not influence the SINR statistics. In [4], an overestimation of the SINR in simulations without interference region is shown, proving the necessity of BEMSs. Despite the introduced simplifications, the additional interferers in the interference region lead to a substantial increase in simulation time.

The comparison of BEMSs in terms of accuracy and computational complexity has been neglected until now for all network topologies. Thus it remains unclear which BEMS, wraparound or interference region, is more accurate and how accuracy is traded off for simulation time for each strategy.

Stochastic geometry was introduced for the modeling of wireless networks as early as 1997 [18]. It offers powerful, mathematically tractable tools to evaluate the interference probability density function (pdf) in a network with transmitters placed according to a PPP or other point processes [19]. The diametrically opposed modeling approaches of stochastic networks and regular hexagonal grid networks, represent lower and upper performance bounds for wireless networks [12]. Thus, the modeling of the network topology in SL simulations is shifting from pure hexagonal grids to include networks with BSs placed through point processes. For random infinite network topologies the coverage probability is evaluated analytically in [12]. These results are utilized in this work to validate the required network size.

Since the assumption of infinite network size cannot be implemented in network simulations, [5] investigates the choice of the network size that achieves accurate results for networks with finite area. For this, the deviation of results of users affected by border effects from the results of users in the center of the ROI is evaluated. In sufficiently large networks, the average coverage probability of a user is constant in the central region of the ROI, but increases when approaching the border due to a lack of interfering BSs in proximity of the user. Moving the user even closer to the border leads to an increase of the distance to the serving BS, which lowers the expected value of the coverage probability.

In a simulation with the minimal ROI-size, the user in the center of the network is not significantly affected by border effects. By increasing the network size, more viable user results per simulation run are obtained and thus the simulation overhead per network realization is decreased. This suggests a trade-off between network size and the number of simulation runs. In practice, the network size is limited by the available memory of the simulation system while the number of simulation runs increases the simulation time. Here, the wraparound increases efficiency, by virtually placing every simulated user in the center of the network, rendering all user results valid.

III. MODEL AND METHODOLOGY

A. Analytical Model

The analytical evaluation utilized for comparison has been determined in [12]. There, the coverage probability p_c for a single user in a network with infinite area with BSs distributed according to a PPP of density λ_{BS} is given as:

$$p_c(T, \lambda_{BS}, \alpha) = \int_{r>0} e^{-\pi\lambda_{BS}r^2} \mathcal{L}_{I_r}(\mu T r^\alpha) 2\pi\lambda_{BS} r \mathrm{d}r \quad (1)$$

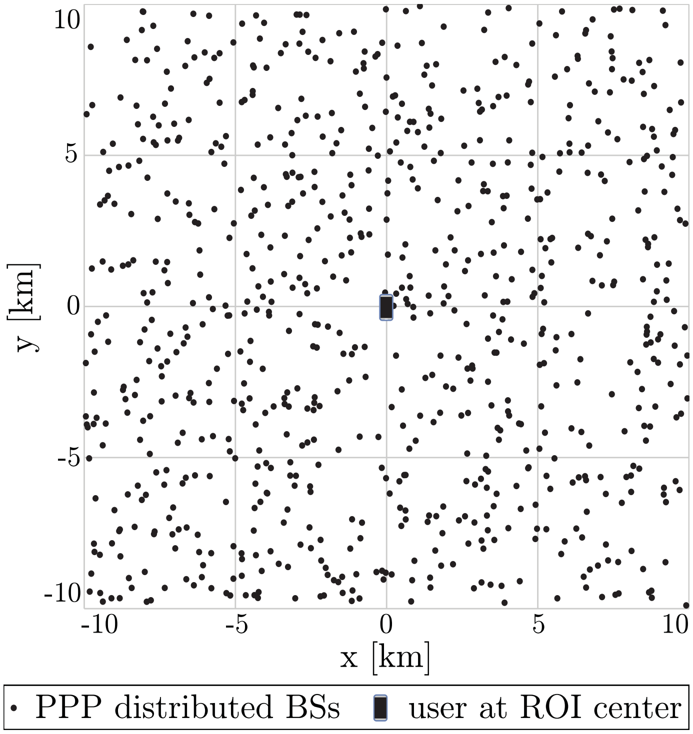


Fig. 2: Example of a network realization for the evaluation of the minimal ROI size with a single user placed at the center of the network.

with:

$$\mathcal{L}_{I_r} = \exp\left(-2\pi\lambda_{BS}\int_r^\infty \left(1-\frac{1}{1+Tr^\alpha v^{-\alpha}}\right) v\mathrm{d}v\right) \tag{2}$$

where T represents the signal to interference ratio (SIR)-threshold and α the path loss exponent. Same-cell interference and shadowing are neglected for this expression. It is shown in [12], that adding log-normal shadowing does not significantly affect the accuracy of this expression. Furthermore, it is assumed that the interfering signals experience Rayleigh fading and a single input single output (SISO) transmission scheme is used. The geographically closest BS is considered to be the serving BS. A free space path loss model is utilized, where the path loss L_{PL} is defined by

$$L_{PL} = \left(\frac{4\pi df}{c_0}\right)^\alpha \tag{3}$$

where d is the distance between transmitter and receiver in meters, i.e. the distance between user and BS, f is the carrier frequency in Hz and c_0 is the speed of light in vacuum in m/s. The expression in (1) becomes independent of λ_{BS} for $\alpha > 2$. However, the independence of the base station density λ_{BS} does not uphold for more complex scenarios [20].

B. Scenario for Minimal ROI Size Evaluation

An infinite network size cannot be replicated in a simulation utilizing finite resources. Thus, a minimal ROI size, for which the simulated coverage probability is sufficiently accurate for a user at the center of the ROI, has to be determined. To find this minimal ROI size, a simulation scenario replicating the assumptions of the analytical model described in section III-A, is utilized. The network size of the simulated network is increased stepwise until the analytical coverage probability is sufficiently approximated. An exemplary network realization is shown in Figure 2.

In a wraparound simulation, each user is virtually placed in the center of the network. This concept is exemplified in Figure 1a. Thus, in a simulation with wraparound, the results of all users can be utilized if the network size is equal to, or exceeds, the minimal ROI size.

C. Scenario for BEMS Comparison

To evaluate the effectiveness of different BEMSs, the empirical cumulative distribution functions (ecdfs) of the SIR for simulations with equivalent conditions are compared for two different path loss exponents. In total, three scenarios are compared: a wraparound scenario, a scenario with an additional interference region and a scenario without any BEMS. Exemplary scenario realizations are shown in Figure 1.

The ROI size is chosen such that the border effects are limited for a user in the center of the ROI. The size of the interference region is chosen such that the maximum deviation from the results of an infinite network are comparable to the deviation in the wraparound network. To achieve this, the size of the interference region is chosen such that a user at the border of the ROI is surrounded by at least the same area of interfering BSs, as a user in the wraparound scenario. For ROI-sizes exceeding the minimal ROI-size, the interference region can be limited to this minimal network size.

A scenario without additional interference is utilized as a baseline scenario, to show the necessity of the BEMSs. In this scenario the ROI size and all other simulation parameters are maintained, but no additional interferers are placed in or around the network.

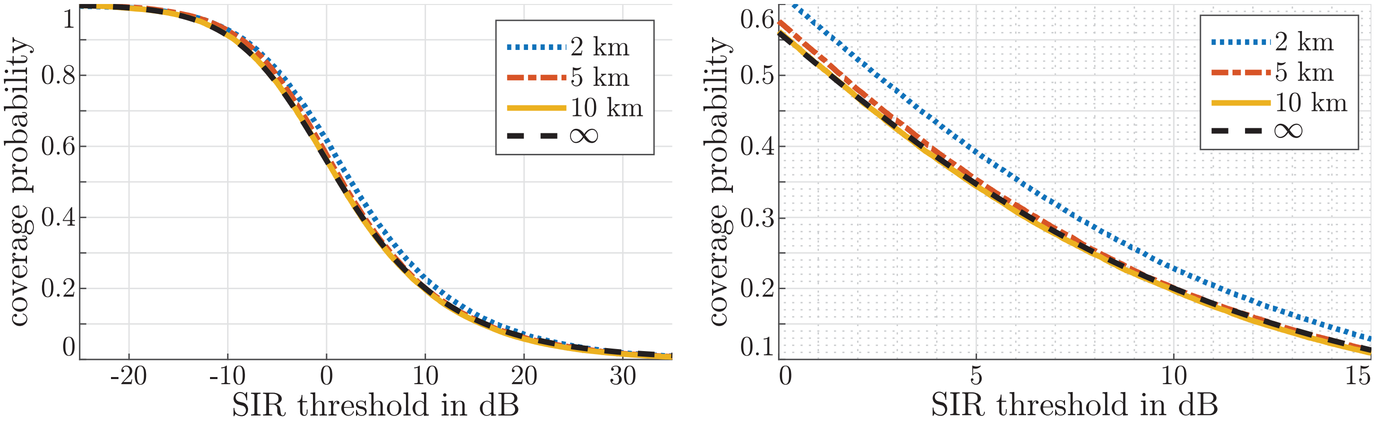
D. Simulation Environment

For the evaluation of the minimal ROI size, the simulation of networks with more than 20.000 network elements is necessary. The *lite* version of the VCCS 5G SLS offers the capabilities to perform fast simulations of networks without MAC layer procedures. With an extension for network wraparound, the VCCS 5G SLS allows the simulation of the two BEMSs considered in this work and the simulation of networks without BEMS.

The VCCS 5G SLS is based on Monte Carlo simulations with temporal channel realizations and spatial network position realizations.

IV. COMPARISON OF RESULTS

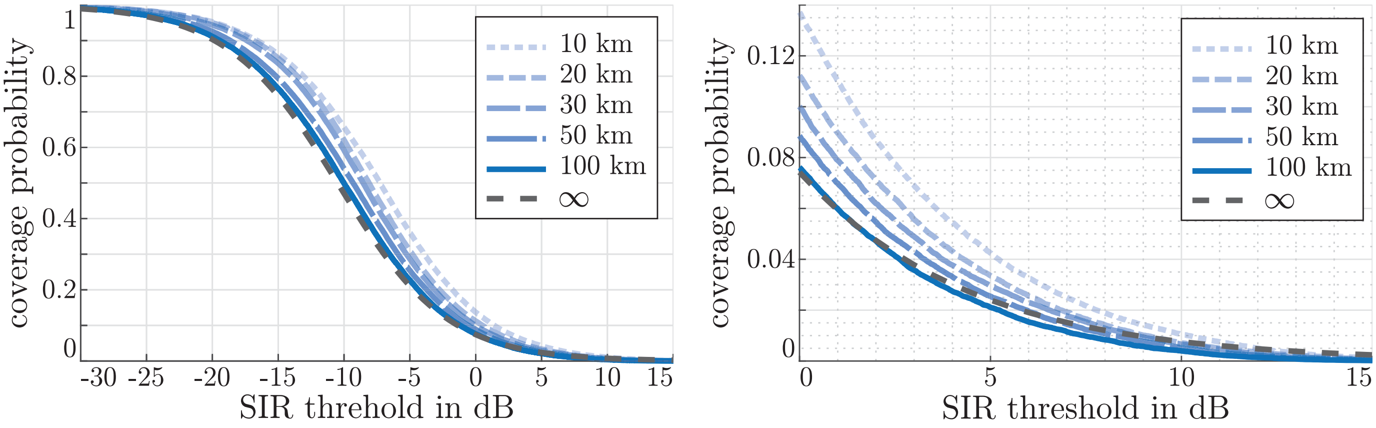
In this section, a minimal ROI size is established for two different path loss exponents and this minimal ROI size is then utilized to compare the performance of different BEMSs. For the following simulations, a carrier frequency of 2 GHz is chosen, such that the simulated scenarios represent a general long term evolution advanced (LTE-A) configuration, and a BS density of $\lambda_{BS} = 2$ BS/km^2 is utilized.



(a) $\alpha = 4$

(b) $\alpha = 4$

Fig. 3: Coverage probability for different network sizes. The network sizes designate the span of the network in x-axis and y-axis. Figure 3b shows the SIR range from 0 dB to 15 dB in detail.



(a) $\alpha = 2$

(b) $\alpha = 2$

Fig. 4: Coverage probability for different network sizes. The network sizes designate the span of the network in x-axis and y-axis. Figure 4b shows the SIR range from 0 dB to 15 dB in detail.

A. *Evaluation of Minimal ROI Size*

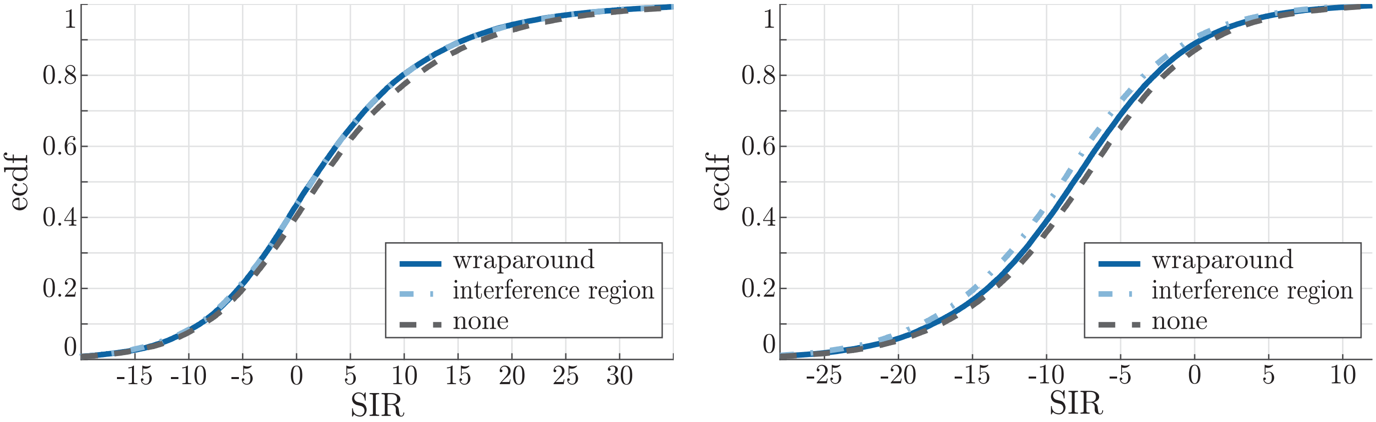
To achieve sufficiently reliable results, the simulation for ROI size evaluation is repeated over 50.000 spatial realizations, with independent channel realizations.

For a path loss exponent of $\alpha = 4$, the signal attenuation increases quickly over distances. Thus, BSs, that are positioned far away from the user, add an insignificantly small contribution to the total amount of interference. This allows small ROIs to yield results comparable to an infinite ROI. As it can be seen in Figure 3, the coverage probability of infinite ROIs is approximated by ROI spans starting from 5 km. For a ROI-span of 5 km, the coverage probability does not deviate more than 1% from the coverage probability of the infinite network. With an even stronger path loss, such as would be the case for millimeter wave (mmWave) scenarios, even smaller ROIs can yield viable results, potentially even making BEMSs obsolete.

The comparison with an infinite ROI for a path loss exponent of $\alpha = 2$ in Figure 4 shows that substantial ROI sizes are necessary to approximate the behavior of an infinite network. For SIR thresholds larger than 0 dB, the evaluated coverage probability deviates up to 3% from the analytical result for ROI spans of 30 km and the infinite network is only approximated for ROI-spans larger than 100 km. A ROI of this size with a BS density of $\lambda_{BS} = 2$ BS/km^2 contains 20.000 BSs, a full simulation with more than one user and scheduling of this size has high memory requirements and an unfeasibly large amount of computational complexity. For a path loss exponent of $\alpha = 2$, a trade-off between accuracy and ROI-size has to be made. Our system requirements limit the ROI-span to 20 km, thus an average of 8.000 BSs and 80.000 users, which leaves a maximum coverage probability deviation of 4% in the SIR range above 0 dB, as shown in Figure 4.

In Figures 3 and 4, an absence of high SIR values in the simulated results can be observed. This is due to the limitation of path loss values to positive values in the simulation, which is not considered in the analytical results, where the path loss can enhance the received signal, if the desired BS is in close proximity of the user.

The free space path loss model chosen for this work is a model for line of sight (LOS) links. The extension of the path loss model with a non line of sight (NLOS) path



(a) $\alpha = 4$

(b) $\alpha = 2$

Fig. 5: SIR ecdf for different path loss exponents and BEMSs.

loss for large distances might reduce the minimal ROI-size. Especially for small path loss exponents, where the modeling of LOS-connections over several kilometers might not be a valid assumption.

B. BEMS Comparison

For the comparison of different BEMSs, a user density of $\lambda_{UE} = 10\lambda_{BS} = 20$ User/km^2 is considered. The comparison is performed for two different path loss exponents, $\alpha = 2$ and $\alpha = 4$. The minimal ROI-size for a path loss exponent $\alpha = 2$ is a ROI with a span of more than 100 km. As discussed in section IV-A, this exceeds the computational complexity limitations and a ROI-span of 20 km is chosen. For a path loss exponent $\alpha = 4$ the minimal ROI size of 5 km can be simulated.

For ROIs smaller than the minimal ROI, the interference region scenario simulates more additional interference than the wraparound scenario and it is expected, that the SIR ecdf of the interference region scenario is shifted towards lower SIR values than the wraparound SIR ecdf. If the simulated ROI-size is equal or exceeds the minimal ROI-size, the wraparound and the interference region scenario yield identical results.

To achieve the same number of results in a scenario with an additional interference region as in a wraparound scenario, the interference region's radius has to add the minimal network radius to the network size. In this case, the span of the interference region is twice the span of the ROI, as can be seen in figure 1b. This interference region span assures that users at the border of the ROI have at least the same amount of interference as the users in the wraparound scenario.

With a user density of 20 User/km^2, the scenario with a 20 km ROI-span yields an average of 8.000 SIR values per network realization. Thus, a low number of network realizations is sufficient to obtain a large number of spatial user realizations. In contrast, the minimal ROI-size for a path loss exponent of $\alpha = 4$ is smaller and one network realization yields 500 SIR-values on average. Thus, more network realizations have to be simulated for the scenario with the smaller ROI. The simulations for $\alpha = 2$ and $\alpha = 4$ are repeated over 10 and 100 spatial network realizations respectively to obtain the a sufficient amount of SIR realizations in both cases.

In figure 5b, the SIR ecdfs for $\alpha = 2$ show the expected results for the three scenarios: the scenario without BEMS yields the highest ecdf values, while the wraparound strategy corrects some border effects and the interference region adds the most interference. The interference region SIR ecdf is shifted towards lower SIRs compared to the wraparound SIR ecdf, because the simulation region is smaller than the minimal ROI-size. The virtual ROI in the wraparound scenario is not big enough to imitate an infinite network and interference is underrepresented. In the interference region scenario, users are subject to more interference than a user in the wraparound scenario and thus the link quality suffers in the interference region scenario.

In figure 5a, the SIR distribution for $\alpha = 4$ is shown. Here, the minimal network size is utilized, which leads to the wraparound and interference region strategy to be equivalent. As for $\alpha = 2$, the users in the interference region scenario are surrounded by more interferers, but the interferers that are further away from the user, than the radius of the minimal ROI, add a negligible amount of interference and thus have no influence on the SIR.

C. Discussion

In this work, direction dependent propagation effects such as directive antennas and blockages have been neglected. As [11] suggests, radio distance wraparound, that considers these direction dependent propagation effects, is more accurate than geographical distance wraparound. Using for example a simplified SINR, as used for cell association in the VCCS 5G SL, the effectiveness of the wraparound strategy, but also the computational costs would be increased.

An approach to decrease the computational costs of the wraparound strategy, would be to limit wraparound candidates. In Figure 1a, it can be inferred that a large part of the wraparound candidates will not be selected by geographical distance wraparound: all BSs in the outer squares do not have to be considered as wraparound candidates. The outer BSs are also unlikely to be selected by radio distance wraparound. From this arises the conclusion that it is sufficient to choose only parts of the network as wraparound candidates. In the case where the network is larger than the minimal required ROI-size, the wraparound candidates could be chosen according to the minimal ROI-size. In extension, the interferers for each user could be chosen according to distance or according to a minimal preliminary SINR to decrease the computational cost.

To apply wraparound to networks with blockages, the geometry of the blockages has to be considered. Randomly distributed blockages can be wrapped by replicating them in the same manner as the BSs. For Manhattan cities on the other hand, the Manhattan grid should be extended into the wraparound region.

For moving users in a wraparound scenario, the movement pattern should favor wrapping the users in the network to reflecting the users at the border of the ROI. This would keep the movement pattern consistent and the issue of users disappearing and re-appearing in the network would not occur.

The assumption of interference limited networks, for which the wraparound strategy is utilized, is applicable to state of the art LTE-A networks. For 5G wireless networks, this assumption might however no longer be appropriate for transmissions in the mmWave domain. Another open problem is the use of a wraparound strategy in networks with beamforming and high antenna gains. The additional antenna gains render it difficult to determine the minimal ROI-size for both BEMSs. The results are in general not applicable to noise limited networks, in which the introduction of additional interference should not have a significant effect.

V. CONCLUSIONS

In this work we investigated the minimal ROI-size for which a simulation with BEMS yields results comparable to infinite networks. The minimal ROI-size has been determined for two sets of parameters and was shown to be a span of 5 km for a high path loss exponent and larger than 100 km for a small path loss exponent. For a small path loss exponent, we analyzed the deviation from the infinite ROI for different network sizes to determine the loss in accuracy for the simulation of ROIs smaller than the minimal network size.

We then compared the effects of the different BEMSs. We showed that the performance of the wraparound and the interference region strategy are equivalent for the simulation of networks reaching the minimal ROI size. If the simulated network size does not reach the minimal ROI size, the performance of the interference region is closer to the infinite network, at the cost of increased computational complexity compared to the wraparound strategy.

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