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Coverage and Link Quality Improvement of Cellular IoT Networks with Multi-Operator and Multi-Link Strategies

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Abstract—**While the rollout of the fifth generation of mobile communications is already being discussed, existing networks are still suffering from major coverage gaps even years after their introduction. For the implementation of most IoT applications, however, a mobile network with comprehensive availability is a mandatory prerequisite. Therefore, this paper addresses the problem of coverage gaps and investigates the potential for improvement through multi-operator strategies for LTE and cellular IoT (cIoT) networks in the urban environment of the Smart City Dortmund. Additionally, the potential of data rate improvement through multi-link strategies is evaluated, enabling sufficient data rates of cIoT even in extreme coupling loss conditions. It is shown that in outdoor scenarios both LTE and cIoT can provide 100% coverage, but in indoor and deep indoor scenarios, the Mobile Network Operators (MNO) can not provide full network coverage. When considering multi-operator strategies, the LTE deep indoor coverage can be increased by up to 40%. cIoT can provide full coverage at a Maximum Coupling Loss (MCL) of 164 dB even in deep indoor scenarios using only a single operator, but with very low data rates. Even though cIoT enables sufficient coverage, multi-link communication enabling multi-operator strategies can increase the downlink data rates by a factor of 2.8.**

I. Introduction

The aim of Smart Cities is to be overall connected. Smart Power, Water or Gas Meter, typically installed in basements, and E-Mobility Charging spots in car parks or courtyards highly depend on the availability and performance of communication networks to be able to provide sufficient service quality. Thus a comprehensive coverage of communication networks is necessary. With Long Term Evolution (LTE), a promising cellular network technology was introduced in 2009. Though 9 years after the start of the LTE rollout, a recent study on the LTE coverage has shown that in Germany the three Mobile Network Operators (MNO) only provide an LTE coverage of 46.8% up to 75.1%, making the deployment of IoT devices in challenging coupling loss environments difficult [1]. The authors in [1] recommend local roaming for areas where one MNO already provides sufficient LTE coverage. In addition, the authors in [2] present results of mobile network coverage measurements using global SIM cards and thus being able to use all available networks. Considering a multi-operator strategy, the indoor coverage of LTE networks was increased by 29% to a maximum of 99%.

While LTE can provide data rates up to hundreds of Mbps, most IoT applications have relaxed data rate and latency requirements by transmitting only a small amount of generally non-critical data. Paving the way to massive Machine Type Communication in 5G, Narrowband IoT (NB-IoT) and enhanced Machine Type Communication (eMTC), in the following referred to as cellular IoT (cIoT), were introduced with extended coverage and limited bandwidth, enabling a Maximum Coupling Loss (MCL) of 164 dB with data rates between 167 bps and 375 kbps [3]. Even though these data rates are sufficient for most IoT scenarios, several extended use cases exist where higher data rates are beneficial or mandatory. Firmware updates frequently challenge MNOs as well as IoT node manufacturers. Downloading large updates using only a very low data rate is inefficient in several ways: on the one hand, the download takes a long time and keeps the device for a longer period in a high power state. In the long run, it reduces significantly battery duration [4]. On the other hand, IoT nodes placed in areas with worse network coverage consume more resources in terms of network capacity as they require to use a more robust modulation and coding scheme as well as more repetitions [3] [5].

In summary, Fig. 1 presents the challenges in Smart City and Grid environments that are addressed in this paper.

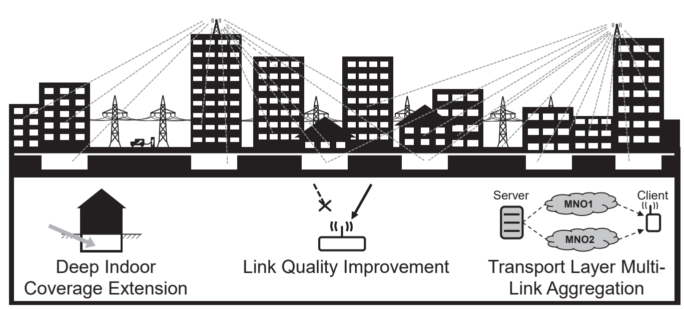


Fig. 1: Connectivity challenges in Smart Cities / Grids

In order to evaluate the coverage and data rate, the authors focus on three main scenarios: outdoor, indoor and deep indoor. To increase the overall coverage, multiple MNOs can be used at once. In addition, the link quality can be improved by switching to the network that provides the best signal quality. Finally, the download time can be reduced by leveraging transport layer multi-link aggregation.

Several approaches for multi-link aggregation exist. The most commonly used approach is *Multipath Transmission Control Protocol (MPTCP)* [6], on which this paper focuses. MPTCP provides an extension to the Transmission Control Protocol (TCP) by establishing multiple TCP subflows. Hereby, MPTCP achieves higher throughput, more reliability as well as lower latency. Alternate approaches like *Multipath Quic* [7] and *Scalable Network Coding* [8] are based on the stateless *User Datagram Protocol (UDP)*. However, latter protocols require significantly more resources due to their higher complexity and are currently not applicable as part of IoT nodes.

This paper is structured as follows: Section II proposes two methods to analyse and evaluate the complementarity of mobile communication networks. Section III presents the results of the complementarity analysis and the potential using multi-operator and multi-link strategies, which are concluded in section IV.

II. Proposed Methods for Connectivity Enhancements of IoT

To evaluate the potential of coverage and link quality improvement through multi-operator and multi-link strategies, different scenarios with one MNO as well as collaborating MNOs are examined. In this context, Fig. 2 shows a scenario with an exemplary constellation of 2 MNOs. The device on the left is out of range for the base stations of its own MNO. When MNO1 collaborates with MNO2, the coverage gap is closed and the device can connect to a cellular network. In this case, a high complementarity of both networks would be desirable to close more coverage gaps. Even though the device on the right in Fig. 2 is in range of its own network, the connection to the nearer base station of MNO2 can reduce the coupling loss from 103 dB to 98 dB, thus improving the link quality. Furthermore, the device can connect to base stations of both MNOs and perform a multi-link operation to improve its overall data rate. While a large complementarity is desired in the case of closing coverage gaps, for multi-link operations a low complementarity with large overlapping between the MNOs leads to a better data rate performance in general, which will be shown in the following sections.

A. Case Study: Smart City Dortmund

The analysis methods presented below are applied to the Smart City Dortmund, Germany. Dortmund is well-suited as a case study for an analysis of the coverage and link quality improvement of cellular networks considering multi-operator and multi-link strategies. Information of the area of Dortmund is obtained by *openstreetmap.org*. These data include the borderline of Dortmund along with detailed information about building areas following indoor analyses. The new digital strategy of Dortmund aims to open up data and information to the public, including information about cellular networks. Unlike most other cities in Germany, Dortmund provides detailed information about the base station locations as well as the associated MNOs and cellular network technologies [9]. For a detailed analysis frequencies of all base stations are added by using the database from [10].

B. Connectivity Analysis

For a detailed analysis of a given area, the area is divided into a grid with predefined grid spacing. In our analysis we determined that a grid spacing of 25 m is sufficient. Reducing the grid space below 25 m produces equal results, but requires much longer computation times. Considering a map of 30 km x 30 km, the grid is divided in 1.44 million grid points. When the position and frequency of the base stations are known, the nearest base station for each MNO and grid point is searched and the path loss to these base stations is calculated with the COST Hata radio propagation model [11]. For indoor and deep indoor scenarios the COST Hata coupling loss is supplemented with additional building entry losses derived from [2] (Table I). Note that for indoor and deep indoor scenarios a coupling loss quantile of 90% and 75%, respectively, is assumed.

TABLE I: Additional Coupling Loss for Indoor and Deep Indoor scenarios [4]

Frequency / Scenario	800 MHz / 900 MHz	1800 MHz
Indoor	15.4 dB	15.8 dB
Deep Indoor	20.9 dB	25.0 dB

C. Coverage Extension

The previous step results in three matrices of coupling losses. To investigate the coverage, the coupling losses are filtered according to the MCL of each technology. For LTE the MCL is defined as 142 dB [12]. Thus, for LTE all calculated coupling losses over 142 dB are marked as out of range, resulting in an availability map of the given area. If multiple operators are to be considered in a multi-operator strategy, the lowest coupling loss of all MNOs is determined.

D. Link Quality Improvement

When both MNOs can provide sufficient connectivity to a device, the use of both networks can provide a gain on the signal quality compared to a single operator strategy (ref. Fig. 2). When taking the difference between the coupling loss matrix of the original MNO and the matrices of collaborating MNOs into account, the coupling gains and losses of this collaborations are obtained. Since a device will not use a collaborating network when the signal quality would decrease, negative entries in these difference matrices are ignored.

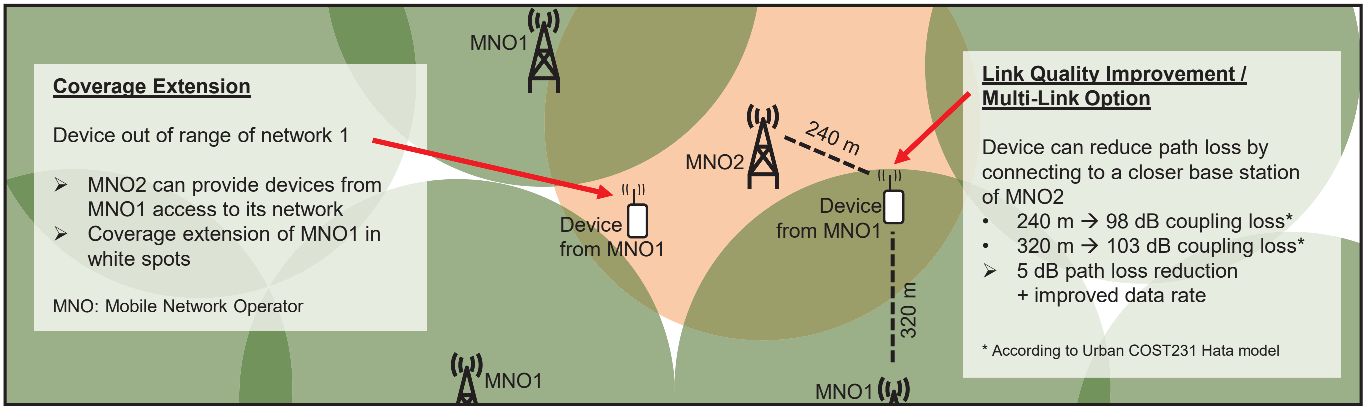


Fig. 2: Nearest server analysis based on proposed grid search method for different Mobile Network Operators (MNO) enables coverage extensions as well as link quality improvement and multi-link options.

E. Multi-Link Enabled Data Rate Improvement

For data rate constrained devices using the cIoT network, the potential of data rate improvement using multiple links simultaneously is investigated.

1) Empirical Throughput Model: First, a model for the available throughput, measured on the Radio Link Control (RLC) layer, in dependency of the Signal to Noise Ratio (SNR) is derived. As no suitable model in literature exists, this paper proposes an empirical model. Fig. 3 shows measured throughput samples as well as the resulting model both for up- and downlink. The model was derived from the samples by applying a moving average filter.

The measurement has been conducted in the area of the German City Dortmund using a ublox SARA-N211 device in a public NB-IoT network deployment. The device supports single-tone transmissions. For a future wide-spread deployment the data rates may be k-fold higher in dependency of the number of tones.

2) Signal Quality Model: In the next step the signal quality in dependency of the position was retrieved. The model makes use of the relationship $SNR = P_{tx} + G_i - L - P_n$ in order to determine the SNR. Herein, P_{tx} represents the transmission power, G_i all antenna gains, P_n the noise floor. L represents the coupling loss, which has been described in the earlier sections. The values for each parameter are given in Tab. II.

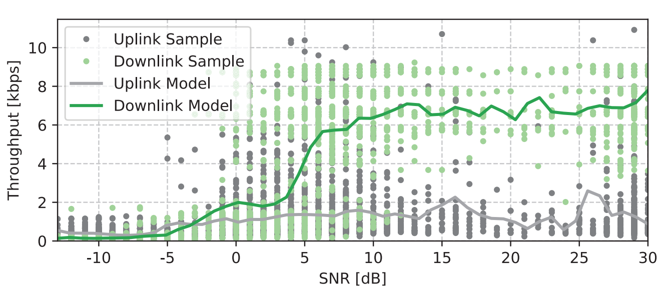


Fig. 3: Achievable throughput in public NB-IoT Networks (Throughput was recorded on Radio Link Control layer)

F. Limitations due to border effects

With the known positions and frequencies of base stations, a detailed connectivity area is derived. Though for positions near the areal border, base stations with unknown positions outside the examined area have to be considered, since in reality devices will connect to the base station with the strongest signals. To prevent corruption in the results from these "border effects", positions, in which the coupling loss to the border and thus a potentially unknown base station may be lower than to the next known base station inside the examined area, are excluded from the analysis.

III. Evaluation of Coverage and Link Quality Improvement

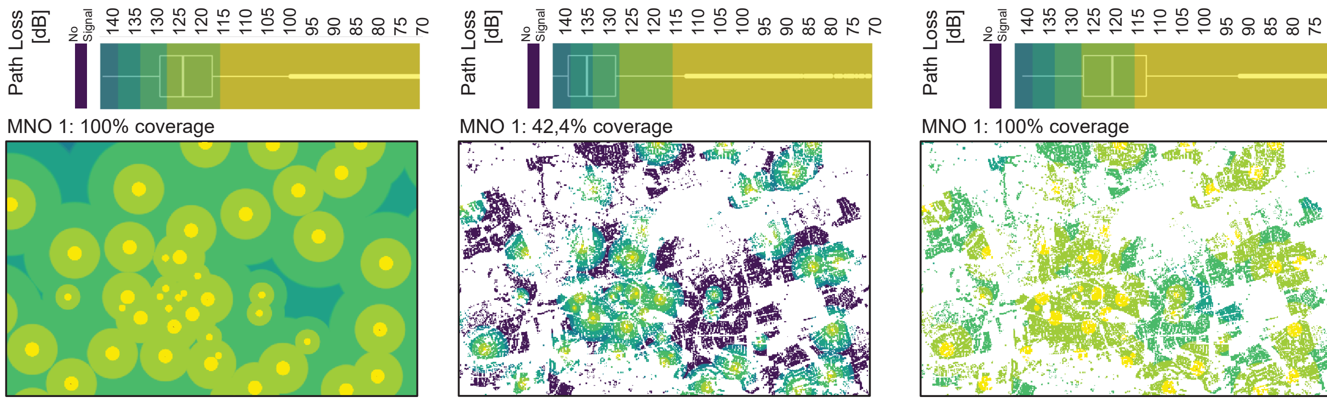
After gathering all information including areal characteristics of Dortmund such as borders and building areas, base station locations, installed technologies and frequencies as well as deriving an empirical data rate model for NB-IoT networks in Dortmund, a detailed analysis on the coverage extension, link quality improvement and transport layer multi-link aggregation is performed. The outdoor analysis covers the full area of Dortmund, while the analysis of the indoor and deep indoor scenarios is limited to the areas of the buildings.

A. Coverage extension

Fig. 4 shows an extract from the coverage analysis. While LTE can provide 100% coverage in outdoor scenarios (Fig. 4 a), only 42% of deep indoor areas can be reached due to a significant higher coupling loss (Fig. 4 b). With a 22 dB higher MCL, NB-IoT can provide 100% coverage even in deep indoor scenarios (Fig. 4 c).

TABLE II: Parametrization

Throughput Map Model	Value
Transmission Power	23 dBm
Antenna Gain (BS / UE)	$9/1dBi$
Noise Floor	$-110\ dBm$
Throughput Model	cf. Fig. 3
Device	ublox SARA-N211



(a) LTE Outdoor Area (b) LTE Deep Indoor (buildings only) (c) NB-IoT Deep Indoor (buildings only)

Fig. 4: Extract from coverage maps of Dortmund for Outdoor and Deep Indoor scenarios

Fig. 5 gives an overview of the results of all analyzed scenarios. In outdoor scenarios, all MNOs and technologies can provide 100% coverage. Thus multi-operator strategies can not enable an outdoor coverage gain. When considering indoor scenarios, the coverage of LTE increases significantly to at least 66% for LTE and MNO1. According to indoor scenarios, MNO3 can provide the best coverage. When considering two operator collaborations, the overall coverage gain is up to 26%, showing the high potential of multi-operator. The additional third MNO further extends the coverage by at-most 9%. Therefore, depending on the coverage requirements of service providers, two collaborating MNOs may be sufficient. In deep indoor scenarios the multi-operator strategy with three MNOs can add up to 40% coverage and thus is highly recommended. Furthermore the results show that NB-IoT can provide 100% coverage with 164 dB MCL for all scenarios, enabling up to 58% coverage gain in respect to LTE networks without even considering multi-operator strategies. Though the uplink is limited to 343 bps for devices with 164 dB coupling loss [3]. For service providers requiring higher data rates, the analysis was additionally performed for MCL limitations to 154 dB and 144 dB, resulting in data rates of 2.6 kbps and 18.7 kbps, respectively. Fig. 5 presents that NB-IoT with an MCL of 154 dB can provide 99.9% coverage using all three MNO networks. In case of 144 dB, the coverage of a single MNO decreases down to a minimum of 50%, but with all three MNO networks, a coverage of 89% can be provided. In conclusion, multi-operator strategies can provide significant gains of coverage for LTE and NB-IoT with advanced requirements of the data rate.

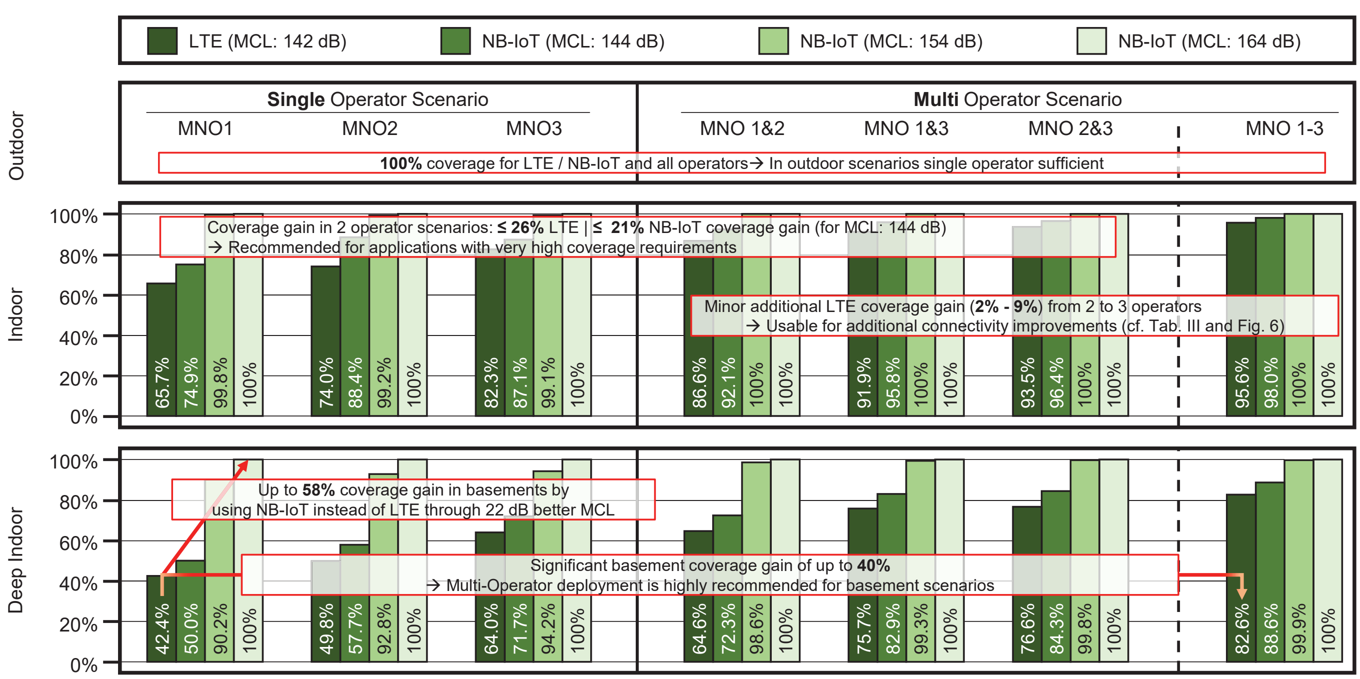


Fig. 5: Results of the coverage analysis for outdoor, indoor and deep indoor scenarios and different cellular communication technologies in urban environment

Average Signal Power Gain for LTE and NB-IoT	MNO 1&2		MNO 1&3		MNO 2&3		MNO 1-3 (National Roaming)		
	MNO 1	MNO 2	MNO 1	MNO 3	MNO 2	MNO 3	MNO 1	MNO 2	MNO 3
Outdoor	9.5 dB	8.0 dB	10.2 dB	8.3 dB	9.0 dB	7.8 dB	11.4 dB	10.0 dB	9.0 dB
Indoor	11.2 dB	9.1 dB	12.3 dB	10.1 dB	10.2 dB	9.0 dB	13.6 dB	11.0 dB	10.6 dB
Deep Indoor	10.4 dB	8.9 dB	11.0 dB	9.1 dB	9.6 dB	8.4 dB	12.6 dB	10.9 dB	10.0 dB

TABLE III: Results of the coupling loss reduction potential for different coupling loss scenarios and cellular communication technologies

B. Link Quality Improvement

Table III presents the average coupling loss reduction potential to improve the overall link quality. As shown in Fig. 5 MNO1 provides the weakest coverage of all MNOs, thus having the highest potential to improve its network. When a mobile device is receiving a signal from another MNO except its own, it can gain its link quality up to 13.6 dB on average, which is a significant improvement and therefore highly recommended. Although economy is not the scope of this work, it should be noted, that the collaboration of MNOs comes with different potential of improvement for each MNO and thus requires a fair pricing model. The results still show a notable improvement for all MNOs.

C. Multi-Link Data Rate Improvement

To evaluate the data rate improvement using a multi-link strategy, the empirical NB-IoT throughput and signal quality models presented in section II are united to a throughput map. Fig. 6 shows the maps for individual MNOs (a-c) as well as the multi-link aggregated MNO model (d). It is evident that each MNO suffers from very low throughputs in the areas at the city border, where the density of base stations decreases. However, these shortcomings can be compensated as MNOs are complementary to each other in those areas.

Fig. 7 shows the cumulative distribution function (CDF) for the deep indoor scenarios of all single MNOs as well as of the collaboration of all three MNOs. In the latter scenario, the download time can be drastically decreased. For 95% of all examined IoT device positions, the firmware is downloaded within 4.9 hours. When using a single network, the download time for 95% is 63 hours.

Since the download time drastically decreases for firmware updates, this work highly recommends the consideration of multi-operator strategies, speeding up the overall update process as well as consuming less resources in terms of network capacity.

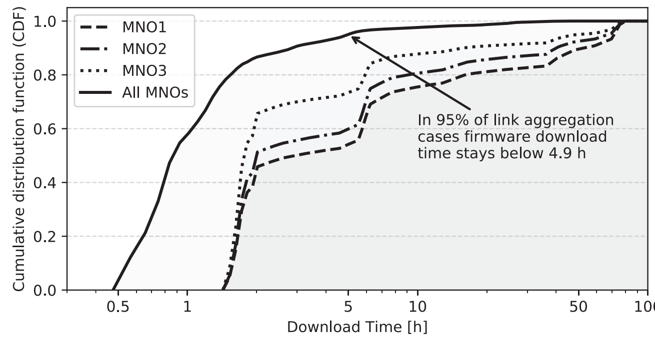


Fig. 7: The cumulative distribution function shows a significant decrease of the firmware update download time in case of a multi-operator strategy.

IV. Conclusion

Availability of communication networks is the key to an overall connected Smart City. Sensors and actuators can only be smart if they can communicate with each other and central instances, providing data and executing tasks. Therefore, the network performance of LTE is compared to the cellular IoT network technologies such as NB-IoT. Since eMTC has the same MCL as NB-IoT, the results of the coverage and link quality improvements can be assumed for eMTC as well.

The analytical results show that three MNOs provide at least 99.9% coverage in outdoor scenarios. Additional signal attenuation by building entry losses decreases the network coverage by 58%. In order to provide network access in these white spots, MNOs may collaborate and grant other MNOs access to their networks. In case of multi-operator strategies, where each MNO can access all available cellular networks, the coverage can be increased by 30% and 40% for indoor and deep indoor scenarios, respectively, showing the high potential of collaboration between MNOs. Compared to LTE,

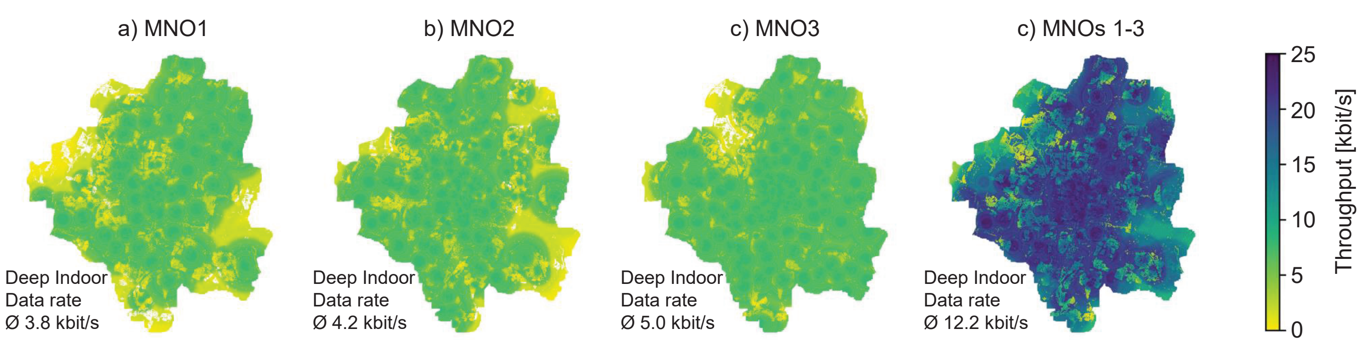


Fig. 6: Throughput maps for combined indoor and outdoor scenarios for separate MNOs (a-c) and multi-operator-options (d)

the cIoT technologies NB-IoT and eMTC come with superior network coverage by providing 164 dB MCL. Considering this MCL, cIoT can provide 100% coverage outdoor, indoor and even in deep indoor with a single MNO. Therefore cIoT is well suited for distributed IoT devices, but is limited to very small data rates and long latencies. For a better performance of cIoT networks, devices either may use the potential of link quality improvement through nearer base stations of other operators, or perform multi-link transmissions over the network of multiple MNOs. In that case, devices are able to improve their data rate by a factor of 2.8 to an average of 12 kbps in deep indoor scenarios.

In summary, multi-operator and multi-link strategies have shown a high potential for improving mobile networks. Existing gaps of coverage can be reduced as the overall performance can be improved, making the usage of multiple networks a good opportunity for future IoT applications.

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