Economic assesment of cellular technologies deployment under carrier aggregation techniques for inter radio access technologies

Оцінка економічних аспектів впровадження мобільних технологій з використанням технік агрегації діапазонів для міжрадіочастотних технологій

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Purpose: The deployment of the fifth-generation (5G) of wireless communications that was launched worldwide in 2020 is entering its final stage in some countries. In this stage carriers apply new techniques that are boosting network performance without heavy investments of the initial build of the infrastructure. This techniques include but are not limited to carrier aggregation, 5G Non-standalone (NSA) and standalone(SA) NR modes, mmWave frequency range and higher bandwidth. Given considerable research in the area about economic and financial validation of the 5G, this work is an extension of a techno-economical assess of the cellular networks under these technologies.

Method: Computer simulations, theoretical derivations.

Findings: Major factors such as spectral efficiency, intercell interference and deployment cost are revisited, and updated to fit realities of the current technological progress. Finally, we use abovementioned theory and present simulation results from the city center of Kyiv city using recently developed pysim5G network simulator.

Paper type: Scientific and practical.

Key words next-generation networks, 5G NR, cellular Networks, economic assessment, carrier aggregation, 5G Standalone/Non-standalone, mmWave.

Мета роботи: Впровадження мобільного зв'язку п'ятого покоління (5G), розпочатий у 2020 році, наближається до завершального етапу в деяких країнах. На цьому етапі оператори використовують нові технології, які підвищують продуктивність мережі без великих інвестицій порівняно з базовим будівництвом інфраструктури. Ці технології включають в себе, але не обмежені, агрегацією робочих діапазонів, режими 5G Non-standalone (NSA) та Standalone (SA) NR, частотний діапазон мм-хвилі та ширококанальний зв'язок. З урахуванням значного дослідження в цій області з економічної та фінансової точки зору щодо валідації 5G, ця робота є розширенням техноекономічної оцінки мобільних мереж з використанням цих технологій.

Метод дослідження: Комп'ютерні симуляції, теоретичні вивчення.

Результати дослідження: Основні параметри, такі як спектральна ефективність, міжсотова інтерференція та вартість впровадження, переглядаються і оновлюються з урахуванням сучасних досягнень у технологічному прогресі. У заключенні наведені результати симуляцій зазначених аспектів, які були проведені в центральній частині міста Києва за допомогою новітнього емулятора мережі pysim5G.

Тип статті: Науково-практична.

Ключові слова: мережі нових поколінь, 5G NR, сотові мережі, економічна оцінка, агрегація діапазонів, 5G Standalone/Non-standalone, мм-хвилі.

Introduction

5G deployment is rapidly expanding across the globe, with over 229 commercial networks launched in 70 countries as of January 2023 [1]-[3]. This widespread adoption is driven by the increasing demand for mobile data, the need for faster and more reliable connectivity, and the emergence of new applications and services that leverage 5G's capabilities and overcoming its challenges [4]. According to a recent report by the GSMA [5], 5G subscriptions are expected to reach 1.3 billion by the end of 2023 and 5 billion by 2027. The report also found that 5G is expected to contribute $7 trillion to the global economy by 2030. The deployment of 5G is being driven by a number of factors, including the increasing demand for mobile data, the need for faster and more reliable connectivity, and the development of new applications and services that can take advantage of 5G's capabilities. Implementation of these capabilities in industry can greatly shift economical component in overall deployment. Main driving force behind bringing new wireless technologies in the industry are Mobile Network Operators (MNOs) and Network Equipment manufacturers. Based on theoretical studies, certain technology is prioritized in being implemented, as well as could be completely eliminated from the roadmap.

Currently, in research literature these studies are divided into two categories. In first one, performance of the deployed feature is evaluated. For example, mmWave communication, i.e., communication on radio frequencies in 28GHz and 38GHz range has offered new capabilities in terms of the peak data throughput. Studies in [6] has investigated the performance of two commercial 5G mmWave deployments in the United States. They find that the deployments differ in a number of aspects, including the number of beams used, the number of channels aggregated, and the density of deployments. These differences in deployment parameters have a significant impact on the performance of the networks. For example, the authors find that narrower beams experience a lower path-loss exponent than wider beams, which can lead to higher throughputs. Additionally, they find that up to eight frequency channels can be aggregated on up to eight beams, which can deliver peak throughputs of 1.2 Gbps at distances greater than 100 meters. Another example of feature, is NSA technology that allows to reuse existing LTE core network, while 5G is exploited mostly for data applications. Work in [7] presents a large-scale measurement study of a commercial mobile operator in the UK, focusing on the current status of 5G Non-Standalone (NSA) deployment and the network-level performance. The authors find that 5G NSA is already providing significant improvements in performance over 4G, particularly in terms of peak data rates and user-experienced data rates. However, they also identify a number of challenges that need to be addressed in order to fully realize the potential of 5G, including the need for more efficient spectrum utilization, improved device support, and better network management. Both works [6] and [7] provide strong technical analysis and good performance evaluation, while the financial component of the deployment is out of scope.

Therefore, other categories of studies present the economic and financial evaluation for the network deployment. Work in [8] investigates the techno-economic feasibility of using 5G network slicing with multi-tenancy, also known as neutral host networks (NHN), to improve rural connectivity in India. The authors propose a generic model to analyze the techno-economic aspects of 5G NHN deployment, with a focus on rural areas where network operators are hesitant to provide services due to low return on investment. They apply this model to the Indian scenario, considering the existing infrastructure, competition, and statistics for Indian telecommunications. The study analyzes the relationship between coverage, network investment, subscriber base, investment time, demand, investment per user, and sensitivity analysis to assess the feasibility of the proposed solution for Indian villages with different conditions. A case study is conducted based on the proposed approach, along with coverage modeling for a few Indian villages with varying topologies. Finally, authors highlight the potential of 5G NHN with network slicing to bridge the digital divide in rural India by providing a cost-effective and scalable solution for extending 5G services to underserved areas. While [6]-[8] focus on networks countrywise, others focus on specific areas and complex scenarios. For example, studies in [9] present a business case analysis for three 5G use cases in an industrial sea port area, namely: 1) enhanced mobile broadband services, 2) automation of container handling in the port's container terminal, and 3) augmented reality for construction projects. The authors use a net present value (NPV) analysis to evaluate the financial viability of each use case. The first one, enhanced mobile broadband services has a very strong business case, with a payback period of less than one year. The second one, for automation of container handling in the port's container terminal also has a strong business case, with a payback period of less than one year.

The third one, case for augmented reality for construction projects has a weaker business case, with a payback period of five years. The authors find that this use case is more sensitive to changes in the cost of 5G technology and the willingness of users to pay for the service. In addition, it is concluded that 5G has the potential to significantly improve the efficiency and safety of operations in industrial sea port areas. They encourage mobile network operators to invest in 5G infrastructure in these areas and to develop and market innovative 5G services. Being restricted to particular area, scenario or technology, work in [10] took a big leap forward in developing open-access framework for 5G deployment, allowing to apply it to custom scenarios.

The framework is based on the Monte Carlo method and is designed to help network operators, policymakers, and researchers evaluate the costs and benefits of different 5G deployment strategies. The framework includes a number of features. First, includes a geospatial network planning tool that can be used to model the deployment of 5G networks in urban, suburban, and rural areas. Second, framework has a cost model that can be used to estimate the capital and operating expenses of 5G networks. Third, A performance model that can be used to estimate the performance of 5G networks, including user data rates, coverage, and capacity. Fourth, a multi-operator model that can be used to evaluate the impact of infrastructure sharing on the cost and performance of 5G networks.

Overall the authors use the framework to evaluate a number of different 5G deployment strategies: single-operator deployment, in which each operator builds its own 5G network; multi-operator deployment with passive site; sharing, in which operators share the cost of building and operating cell towers; multi-operator deployment with passive backhaul sharing, in which operators share the cost of building and operating the backhaul network; multi-operator deployment with a multi-operator radio access network (MORAN), in which operators share the cost of building and operating the radio access network. It is also noticeble that framework is open-sourced and open to local modifications and updates depending on scenario. In somehow updated form, this framework was applied in [11] and [12].

While being up to date in terms of mmWave technology, discussions in [10] do not include a carrier aggregation (CA) technique, which is significanly improved over last 5 years.

CA is a technology used in mobile networks to increase data rates by combining multiple frequency bands into a wider channel. This is similar to how a multi-lane highway can carry more traffic than a single-lane road. CA is a key technology for enabling the high data rates and low latency that are required for next-generation mobile applications, such as virtual reality, augmented reality, and autonomous vehicles.

This work extends theoretical coverage of [10] by including carrier aggregation technology into consideration, proposes deployment strategies based on carrier aggregation and re-evalutes abovementioned capacity metrics on exact 3gpp data rate formula. Next, proposed evaluated framework is added to pygsim5G simulator and used to evaluate network performance, cost of deployment and network capacity per area relation to the cost.

Theoretical Background

1.1 5G Standalone and Non-standalone

5G Standalone (SA) and 5G Non-Standalone (NSA) are two different deployment modes for 5G networks.

SA is a fully independent 5G network that does not rely on any existing LTE infrastructure. It uses a new core network and new radio access network (RAN) technologies. This allows for the full range of 5G capabilities, including ultra-low latency, high bandwidth, and massive capacity.

5G NSA is a transitional deployment mode that uses the existing LTE core network and a new 5G RAN. This allows for a faster rollout of 5G services, as it does not require the deployment of a new core network. However, 5G NSA does not support all of the full capabilities of 5G SA, such as VoNR or conrol plane optimizations.

1.2 Carrier Aggregation Technology

As was mentioned above, CA is a technology used in mobile networks to increase data rates by combining multiple frequency bands into a wider channel. CA is used in both 4G (LTE) and 5G networks, SA and NSA. In 4G, CA can combine up to five frequency bands, each up to 20 MHz wide, for a maximum bandwidth of 100 MHz. In 5G, CA can combine up to eight frequency bands, each up to 100 MHz wide, for a maximum bandwidth of 800 MHz. Among the benefits of CA, are increased data rates, improved coverage and reduced latency. The increased data rates comes from the fact that multiple frequency bands can be used to transmit data simultaneously, i.e., higher aggregated bandwidth. The improved coverage achieved as the wider channels used by CA can reach farther and penetrate buildings more effectively than narrower channels. Lastly, reduced latency, which is the time it takes for a signal to travel from a device to a network and back, is obtained as the device has higher chance to scan band earlier compared to the case of single band or even worse, switching between bands. Reduced latency is important for applications that require real-time communication, such as gaming and video conferencing.

Despite all of its advantages, CA is a complex technology, and there are a number of challenges that need to be addressed in order to deploy it effectively. These challenges include spectrum availability, device support and network management. First, the availability of spectrum is a major challenge for CA. In many countries, there is not enough spectrum available to support the use of multiple frequency bands. Second, not all mobile devices support CA. This means that operators need to ensure that their networks are compatible with a wide range of devices. Third, managing a network with multiple frequency bands is a complex task. Operators need to ensure that the different frequency bands are used efficiently and that there is no interference between them.

Despite these challenges, CA is a promising technology that is revolutionizing mobile networks. As the technology matures, we can expect to see CA deployed more widely and to see even more benefits for mobile users.

1.3 Pysim5g Simulator

Python simulator for integrated modelling of 5G, or pysim5G is an open-source techno-economic assessment framework designed for evaluating the deployment of 5G networks. It utilizes the Monte Carlo method to comprehensively assess both engineering and economic cost metrics within a unified and systematic framework. This powerful tool incorporates statistical analysis of radio interference to evaluate the system-level performance of 4G and 5G frequency band coexistence, including millimeter wave bands. Additionally, it quantifies the costs associated with ultra-dense 5G networks. Among key Features of pysim5g, following can be outlined:

- *Integrated techno-economic assessment:* pysim5g enables the simultaneous evaluation of both engineering and economic aspects of 5G deployment, providing a holistic understanding of the network's costs and performance.
- *Statistical analysis of radio interference:* The simulator incorporates statistical analysis of radio interference to assess the system-level performance of 4G and 5G frequency band coexistence, ensuring efficient spectrum utilization and minimizing interference.

- *Cost quantification for ultra-dense 5G networks:* pysim5g accurately quantifies the costs associated with ultra-dense 5G networks, considering factors such as small cell deployment, backhaul infrastructure, and network management.

1.4 Revisited system capacity model

The main objective of the pysim5G simulator is to estimate network spectral efficiency, $\bar{\eta}_{area}$ (bps/Hz/km^2). In [10] it is estimated using a stochastic geometry approach to provide an average value representing the number of bits per second per Hz (bps/Hz), given a certain traffic load and current radio channel and interference conditions.

$$\bar{\eta}_{area} = \rho_{sites} \cdot \bar{\eta}_{cells}$$

This approach is more practical compared to static interference assumption [14], [15] as it is a generalization of the performance estimation, rather that best/worst case scenario. The quantity of cells per site ($\bar{\eta}_{cells}$) and density of co-channel sites (ρ_{sites}) using the same spectrum frequency affects the Inter-Site Distance (ISD), one of the major parameters in cellular system architectures. Increasing it, reduces intercell interference, however, also makes more users be located farther from the serving cell. Affect of ISD on cellular networks spectrum efficiency was studied in [13], and is not investigated herein, which allows ρ_{sites} to be treated as a constant value. Therefore, system spectral efficiency can be narrowed down to spectral efficiency of a single cell.

1.5 Spectral efficiency: Coverage, SINR, and Channel Capacity

In mobile networks, coverage is defined as the ability of a receiver(Rx) to decode signal sent from transmitter and guarantee certain QoS. Coverage depends on the received signal power, also known as link budget, which in return depends on both transmit power, interference, Tx and Rx antenna gains, and path loss. Generally, link budget can be calculated as

$$\begin{aligned} Link\ budget_{Rx\ power} = Tx\ power + Antenna\ gain_{Tx} + Antenna\ gain_{Rx} - \\ Path\ Loss - Slow\ fading\ margin - Interf.margin - Noise\ margin - \\ Oxygen\ absorption - \ \ Penetration\ Loss. \end{aligned} \quad (1)$$

Next, this number is compared with receiver sensitivity, and if it exceeds a threshold, then the successful transmission is possible.

SINR is a quantity used to give theoretical upper bounds on channel capacity in wireless communication systems such as networks and defined as

$$SINR = \frac{Rx\ power}{Interference\ power + noise\ power}. \quad (2)$$

Herein, we assume that Rx or user equipment (UE) is attached to the Tx or basestation (BS) that results in strongest received signal power, and therefore signals from other BSs are treated as interference. Given SINR, the upper bound channel capacity C can be calculated with Shannon's equation

$$C = B \times \log_2(1 + SINR), \quad (3)$$

where B denotes signal bandwidth. While the equation above is a popular way to estimate channel capacity, it is does not respesent actual data rates. In order to provide precise financial-economical assessment, a precise data rate equation should be used, which captures parameters of RAT technology, MIMO and signaling overhead. Data rate at UE can be calculated as

$$R = \sum_{j=1}^{J} \nu_{layers}^{(j)} Q_m^{(j)} f^{(j)} R_{max} \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^{\mu}} (1 - OH^{(j)}), \tag{4}$$

where J – number of cells with j as a cell index. Notice, that (4) is sum of rates of all serving cells, which accounts for carrier aggregation, i.e. when UE is connected to more than one cell;

$\nu^{(j)}$ – number of spatial streams for jth cell. For simplicity, we assume here that it is equal to number MIMO antennas, i.e. channel matrix has full rank;

$Q_m^{(j)}$ – modulation coding scheme(MCS) index for jth cell. This index is decided upon BS depending on channel conditions and described in more details in simulation section;

R_{max} – maximum coding ratio, depends on modulation and slot configurations for time division duplex (TDD) cells;

$N_{PRB}^{BW(j),\mu}$ – number of physical resource blocks per bandwidth of the jth cell and numerology μ;

T_s^{μ} – average OFDM symbol duration in seconds for numerology μ;

$OH^{(j)}$ – signal overhead (control) data for jth cell.

Notice that Q_m and corresponding R_m are dictated by Rx SINR.

1.6 Carrier aggregation strategies and deployment scenarios

In order to achieve carrier aggregation for a UE, it has to be located in certain proximity to both of the cells. Given that deployment of carrier aggregation can be viewed as the densification of the network, it is logically to assume that new cells will be placed in the "blind spots" of the network coverage as is shown in Figure 1. Generally, we assume that MNOs will mostly upgrade network with 5G cells, NSA and SA. NSA cells are able to be integrated within existing 4G core network, Evolved Packets Core or EPC. SA in return is more difficult to deploy as it requires a 5G Core or 5GC, which offers new services and functionalities, e.g., VoNR.

Depending on the type of the cell, it will be improving overall coverage and spectrum efficiency by either: being aggregated with other cells or acting as independent serving cell. Among recent development of the cellular technologies we can segregate three scenarios:

- *LTE carrier aggregation*. Multiple LTE cells are synchronyzed in a way, that instead of interfering, are able to simultaneously serve a UE with additional downlink connection, only. Currently, overall aggregated bandwidth cannot exceed 100MHz, i.e. 5 cells with 20MHz bandwidth.
- *5G SA carrier aggregation.* In some way, it is similar to LTE CA, however, 5G CA allows uplink aggregation and overall maximum bandwidth up to 800MHz.
- *5G NSA for Sub 6 GHz and mmWave.* This scenario allows to reuse existing LTE core network infrastructure, while archive significant gain in spectral efficiency using 5G NSA stations.

Notice that according to DUT automatic gain control algorithms, in order to achieve carrier aggregation, cells received signal power should not be different more than certain value, and hence more likely to happen at cell edge.

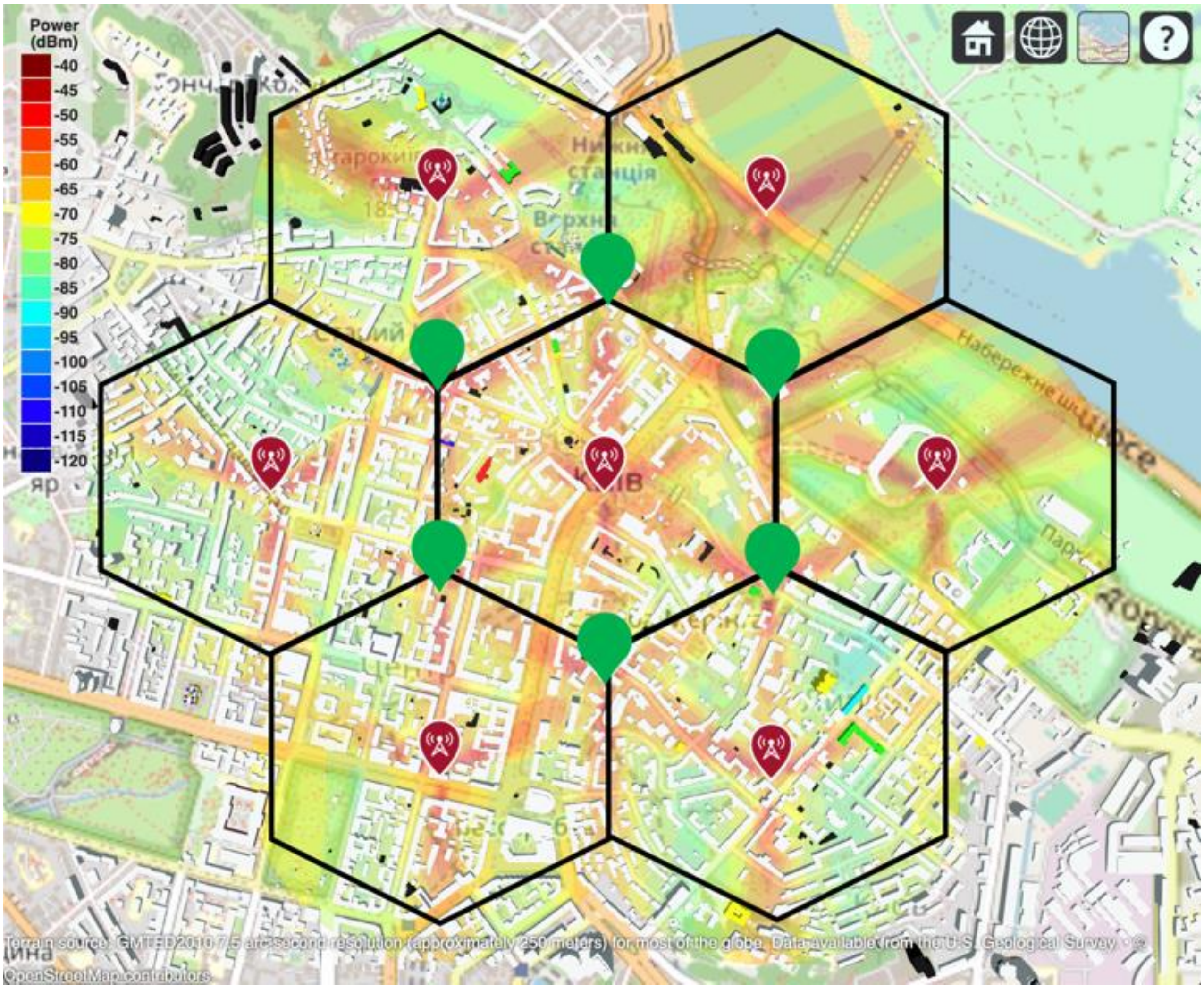

Figure 1 – Deployment scenario for the Kyiv city center. Existing network (red pins, ISD = 500m) is densified with new stations (green pins)

Results and Discussions

2.1 Deployment scenarios

Based on discussion above, there are three scenarios that can be deployed in order to densify current network, and achieve overall performance gain: deploy LTE, 5G NSA FR1/FR2 and 5G SA cell. For the simulated location environment is the city center of Kyiv, Ukraine, and is depicted in Fig. 1. 7 BS sites are considered to be already deployed LTE cells. Another 6 cells (green pins) of the one of the four types are deployed within the existing areas in the locations that are on the edge of the cell. Notice while it appears, that there are 13 cells, it is actually 39 sites, as every BS consists of three sectors. For the existing BSs, we assume LTE cell using band B1 being deployed with bandwith of 20MHz. For the newly deployed BSs, for the LTE, we assume cell using band B3 with bandwidth 20MHz. For 5G NSA/SA, we simulate band n78 with bandwidth 40MHz and NSA mmWave band n260 with aggregated bandwidth of 800MHz. All the scenarios are summarized in the table below.

Table 1 – Aggregation scenarios

Scenario	S1: LTE CA	S2: NR SA	S3: NR NSA FR1	S4: NR NSA FR2
Cell band	B1, B12, B3	N78	N78	N260
Cell bandwidth	10MHz	40MHz	40MHz	100MHz
Network Combo	B1(2A), B12(2A), B3(2A) B1A-B3A	CA_N78(2A)	DC_B1A-N78A	DC_B1A-N260A

For sake of consistency with [10], corresponding cental frequencies are used in simulations in the next section.

2.2 Simulation results

Simulation results below illustrate how carrier aggregation affects total network efficiency in terms of system capacity, cost of deployment and other network metrics. In addition, comparison between various MNO infrastructure sharing strategies are shown as well. Simulations were conducted using pysim5g simulator, with additional library implemented to account for the carrier aggregation. For clarity of comparison simulation results were used the same as in [10] and summarized in the table below for readers convenience.

Table 2 – Simulation parameters

Parameter	Value	Unit
Interference stochastic approximation	100	Samples per user
Spectrum bands	0.7, 0.8, 1.8, 2.6, 3.5, 26	GHz
Respective banwidth	10, 10, 10, 10, 40, 100	MHz
ISD	0.1 – 3	km
Tx power	40	dBm
Transmitter antenna type	Directional	
Transmitter antenna gain	16	dbi
Sectors	3	Sectors
Transmitter height	30	Meters
UE antenna gain	4	dBi
UE losses	4	dB
UE miscellaneous losses	4	dB
Propagation model	ETSI 138901	
Shadow fading log normal distribution	$(\mu, \sigma) = (0, \sigma)$	dB
Building Penetration loss log normal distribution	$(\mu, \sigma) = (12, 8)$	dB
Frequency reuse	1	Factor
Shadow fading	Log normal	dB
Indoor probability	50	%

Parameter	Value	Unit
Line of sight	<250m	Meters
Transmission method	SISO (Single-input-single-output)	

In the Figure 2, simulation results for network performance metrics are shown. From the results, relative performance for different frequencies can be observed. As a key contributors of this, path loss and cell bandwidth can be recognized. For, example FR2 cells have the highest bandwidth while also the highest path loss rate, which affects both received signal power (negatively for UE) and interference power (positively for UE). Notice that in terms of SINR and network capacity, there is an optimal point in terms of intersite-distance, which aligns with [13]. Another key observation that can be made from the simulations shown in the Fig 2 is the improvement that carrier aggregation brings to the system. Indeed, improvements in terms of the interference and as a result to SINR and network capacity can be seen. This is due to the fact that in some the occasion of carrier aggregation, a neighbor cell will participate in the aggregation, hence not play a role as an interference cell. Specifically, gain of 1 Mbps/Hz can be seen for mmWave frequency and up to 1.5 mbps/Hz for 700Mhz and 800MHz frequencies. As a sidenote, it worth to mention that while in current work only two cell aggregation is considered, while current 3gpp specifications consider aggregation up to 10 cells (e.g. b2(2A)_n260M) and therefore currently presented results just show a lowerbound for the performance gain.

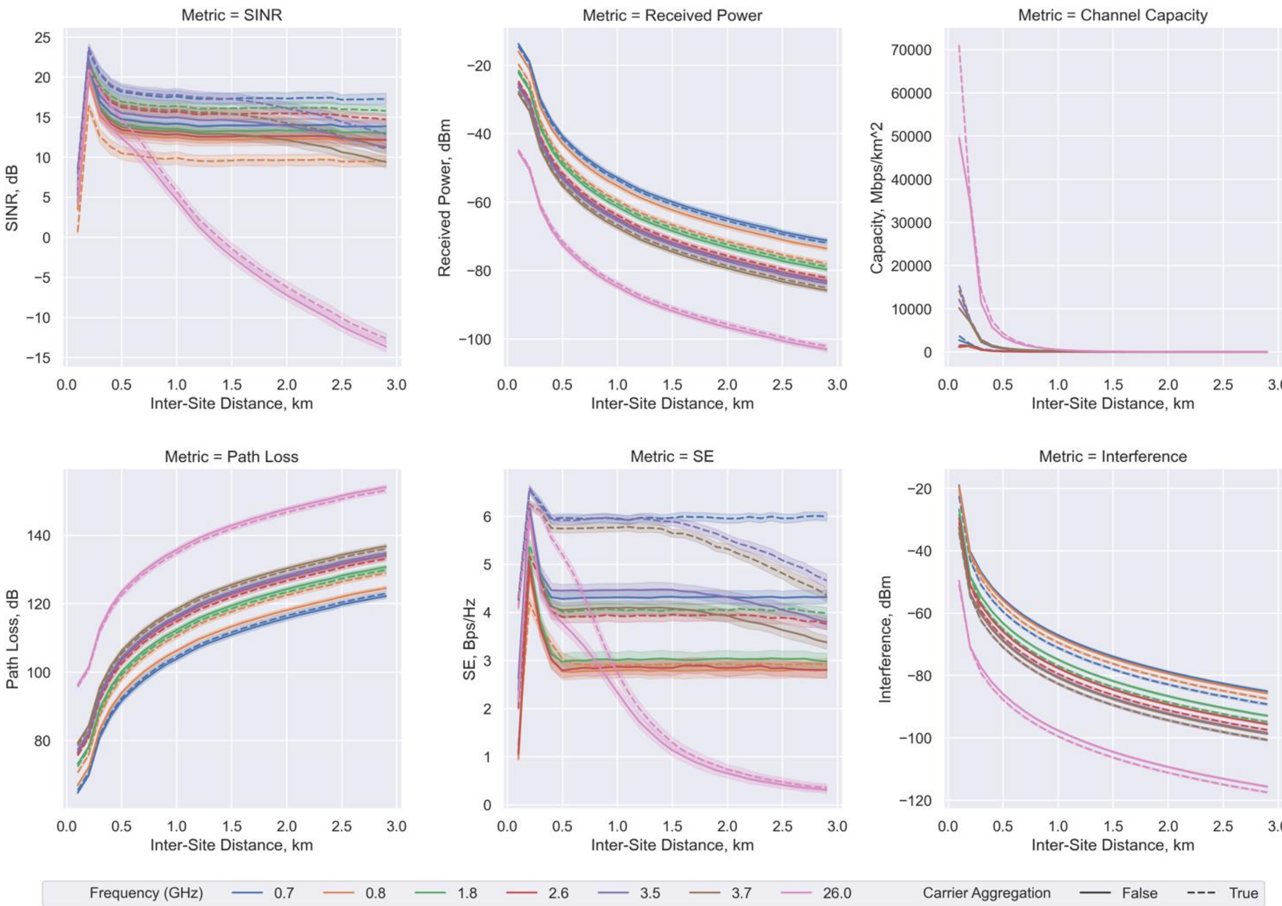

Figure 2 – Network system performance metrics by Inter-Site Distance (ISD) and frequencies comparison between single serving cell connection and carrier aggregation (CA)

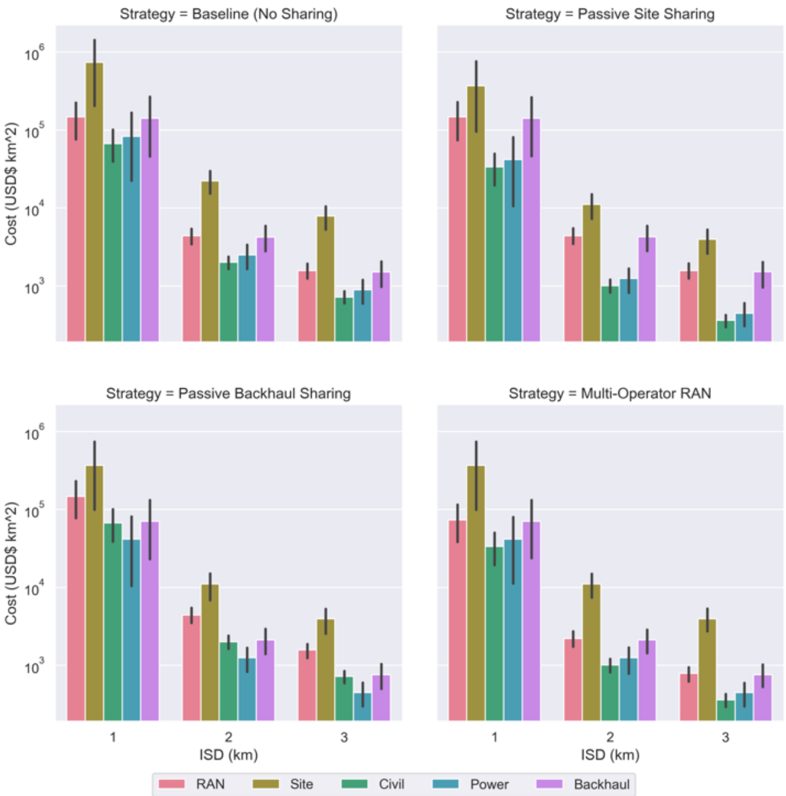

Figure 3 – Cost results per operator by ISD and infrastructure sharing strategy for simulated scenarios

Next, simulations for the deployment cost for different MNOs strategies that includes carrier aggregation are shown in Figure 3. Essentially, carrier aggregation does not include additional expenses in the deployment cost, as current network already satisfy synchronization requirements imposed by the technology. Nonetheless, additional operational cost shall persist due to the data overhead introduces by base station synchronization.

Finally, results for the network capacity per area are presented in Figure 4. Results depicted herein present cost requirement to achieve a certain network throughput in the network. From the figure it is apparent that for the MNOs shared infrastructure and re-use cost decreases. Additionally, carrier aggregation allows to achieve higher capacity, for the same cost. For every cell frequency band, certain saturation can be observed, i.e. increased investment does not increase network throughput. This reflects that network densification has its limits; therefore putting more basestations in the field would not only result in increased signal power for target user but also interference toward others. This results in the SINR limit, hence throughput, capacity and spectral efficiency limits.

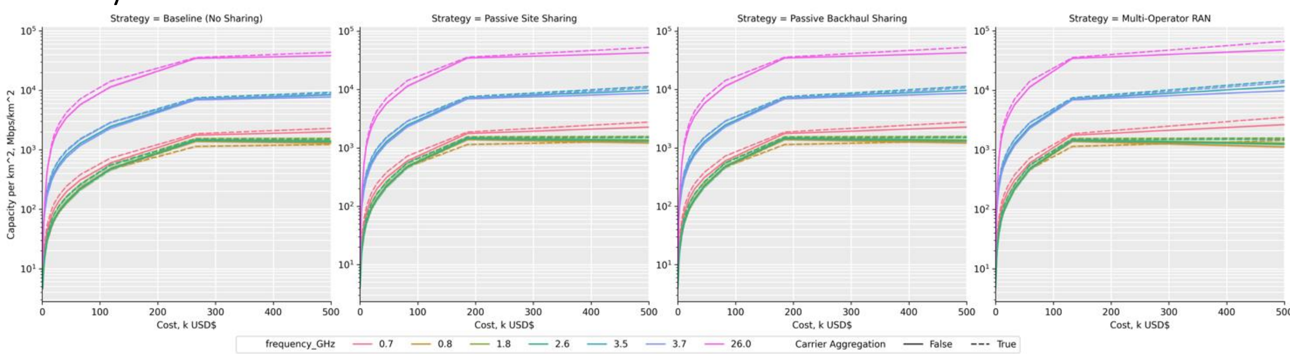

Figure 4 – Capacity per area performance comparison for different cell frequency bands and carrier aggregation

Conclusions

The study expands upon the theoretical foundation laid out in [10] by incorporating carrier aggregation technology, introducing deployment strategies grounded in carrier aggregation principles, and re-examining capacity metrics through the lens of practical channel quality indicator metrics including carrier aggregation. The developed framework is seamlessly integrated into the pygsim5G simulator, enabling a comprehensive evaluation of network performance, deployment costs, and the relationship between network capacity and cost per unit area. This research not only contributes to the advancement of theoretical models but also provides a practical implementation for assessing the real-world implications of deploying carrier aggregation in 5G networks.

Simulation results reveal the relative network performance of for different network deployment techniques and network parameters, such as RAT, frequencies, bandwidth and effect of the carrier aggregation. Carrier aggregation enhances the system by mitigating interference, leading to improvements in SINR and network capacity, which make this technology more common in the deployments worldwide. Deployment cost simulations demonstrate that carrier aggregation incurs no additional expenses however introduces operational costs. Finally, network capacity per area results indicate diminishing returns with increased network densification, emphasizing the limits of SINR, throughput, capacity, and spectral efficiency.

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Competing interests

The authors declare that they have no competing interests.

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