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COMMUNICATIONS TECHNOLOGY

Coherent enterprise information modeling for 5G private network feasibility

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Abstract. In the era of Industry 4.0, the digital transformation of industrial systems necessitates advanced wireless communication solutions that are both agile and secure. Private 5G networks, characterized by their unparalleled bandwidth, reduced latency, and fortified security, have emerged as a beacon of innovation in this paradigm shift. This study explores the feasibility of deploying private 5G networks across diverse enterprises, underpinned by a robust methodological framework. Drawing from contemporary research, it is evident that while 5G promises transformative benefits for sectors like logistics, manufacturing, and autonomous vehicles, its adoption is riddled with challenges such as network oversaturation and frequency coordination. Analyzing 2006 companies, our findings reveal that only 103 enterprises align with the optimal criteria for private 5G network implementation, highlighting the intricate balance of spatial, economic, and regulatory considerations. This research not only offers a strategic roadmap for businesses and stakeholders but also positions private 5G networks as a pivotal tool for achieving operational excellence, enhanced data privacy, and seamless connectivity in the modern industrial landscape.

Keywords: 5G, private networks, economic feasibility, open data, spatial analysis.

INTRODUCTION

In the evolving landscape of wireless communication technologies, the imperative for robust, efficient, and high-speed communication networks is increasingly evident. As industries transition towards a more data-centric paradigm, the quest for a communication system that aligns with the bespoke requirements of modern enterprises is paramount. Private 5G networks have emerged at the forefront of this technological evolution, offering a suite of benefits tailored to address the multifaceted challenges of contemporary businesses. This paper explores the potential role of 5G private networks in industrial transformation, the inherent challenges they seek to mitigate, and the practicality of their deployment across varied sectors. Employing a methodological framework, the feasibility of these networks is assessed, drawing upon empirical data to furnish insights of significance for enterprises contemplating this technological transition.

State of the art

In contemporary industries, ranging from manufacturing to power utilities, operational tasks are intricately integrated and executed in real time, leading to a complex web of communication and computation. In expansive industrial zones, the sheer volume of data generated and exchanged has amplified these complexities. Numerous studies (Peters and Besley 2019; Aschenbrenner et al. 2022) have delved into these communication and computation intricacies, aiming to enhance the management efficiency of industrial parks. A private 5G network, as

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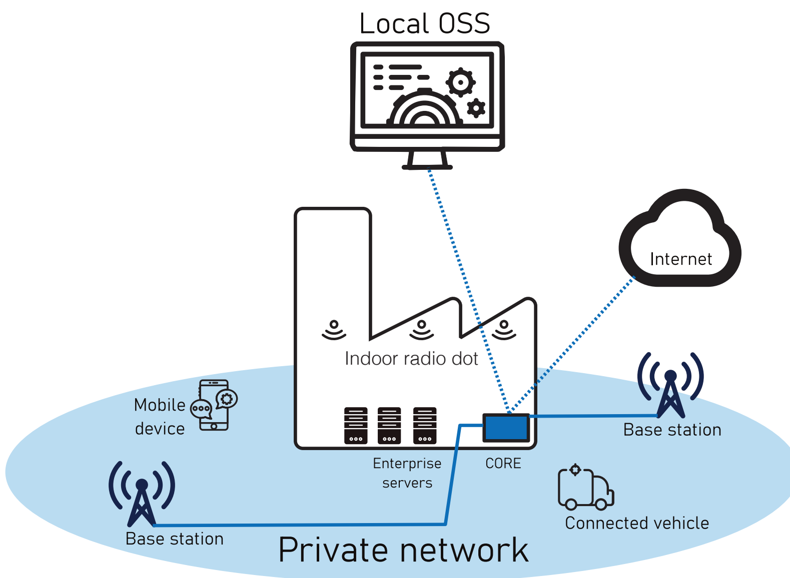

Fig. 1. Schematic representation of a private 5G network.

pictured in Fig. 1, is a reasonable solution for providing the communication required by the modern industrial technology.

The challenges faced by these industries are multifaceted. Key among them are the requirements for seamless interconnections, especially with the proliferation of the Internet of Things (IoT), the integration of multiple factories, and the need for instantaneous responses, which are pivotal for both IoT and cloud computing applications (Aijaz 2020). As shown in Fig. 2, the 5G private network is a reasonable solution for multiple networks connected by a central infrastructure, providing internetwork communication. The Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS) project presents various scenarios for 5G deployment (Osseiran et al. 2014), emphasizing its potential benefits and challenges in diverse industrial settings.

However, as others (Birutis and Mykkeltveit 2022) have pointed out, the presence of neighboring networks can lead to oversaturation, resulting in increased latency and diminished reliability. This oversaturation can also be attributed to non-5G networks operating on similar wavelengths (Alkhansa et al. 2014). According to Skokowski et al. (2022), this can be mitigated by coordinating the frequencies, but that may not be a viable option for truly private networks. On the other hand, this effect can be used as an extra layer of security by denying bad actors the access to the network, as argued by Li et al. (2021). Enabling security and privacy using a private network is considered one of the key reasons for its adoption, as it secures data transfer, confidential data collection, device management, operational management, monitoring, access management, and prioritization.

The allure of 5G private networks is not solely based on their technical prowess but also on their potential economic impact. The promise of revenue augmentation, cost reduction, and expedited return on investment (ROI) makes the adoption of 5G private networks an enticing prospect for various industry stakeholders (Shi et al. 2021). Analytical results (Frank et al. 2022) further bolster this claim, revealing potential savings of up to 53% in total cost of ownership (TCO), signifying a marked reduction in both capital and operational expenditures.

With a private network in place, an operator can separate operational and public traffic among networks, essential for security, safety, and privacy reasons. Moving the bulk of the operational traffic to the private network also frees up more bandwidth for public Wi-Fi (Garg 2007). As a result, it provides operators with full visibility and control over their wireless infrastructure – from planning and deployment to operations and upgrades.

The inherent benefits of 5G, particularly its augmented bandwidth and reduced latency, pave the way for groundbreaking innovations in diverse sectors. Fields such as medicine (Navarro et al. 2022), autonomous vehicles (Chen et al. 2023), and industrial sensor communication (Condoluci et al. 2016) stand to gain immensely from these advancements. Even our whole concept of personal communication can be shifted with the arrival of tactile internet with haptic feedback (Simsek et al. 2016). However, the requisites of these sectors extend beyond mere capacity; they demand enhanced security layers. While public

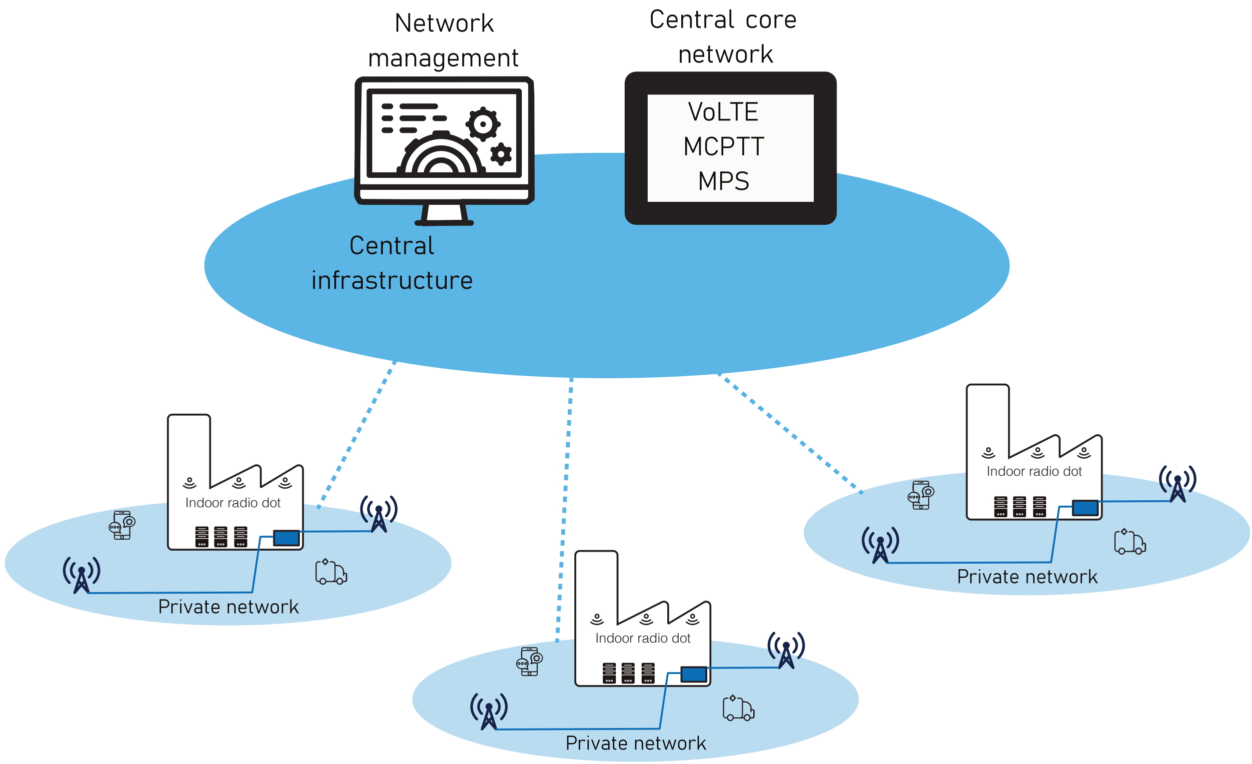

Fig. 2. Schematic representation of multiple 5G networks connected to a central infrastructure.

4G and 5G networks cater to the demands of high-quality video streaming and cloud gaming services (Carrascosa and Bellalta 2022), the unique requirements of modern industries necessitate the deployment of private 5G networks. These networks not only ensure uninterrupted data transmission but also safeguard against potential threats, such as corporate espionage – a concern prevalent across both large corporations and SMEs (Härting et al. 2022).

METHODOLOGY

The objective of this study was to develop a robust model to assess the feasibility of implementing private 5G networks within enterprises. To provide a model for decision making for private 5G network implementation feasibility, a data analysis was performed with publicly available open data provided by government agencies. These datasets were used for model development as a base for estimating major limitations and opportunities for private 5G networks. For validation, we selected a random sample from the dataset for evaluation. Data processing was done with the open-source relational database PostgreSQL 13, utilizing the spatial extension PostGIS 3. Additional scripts for data transformation were written in Python 3.9 with the pandas 1.5.2 library (Pandas). The concept was developed with transferability in mind, so that the resulting model would be applicable to other regions with comparable source data, requiring only minimal modifications.

Data collection and pre-processing

Primary data for this study was sourced from the Estonian Business Register. To ensure the relevance and accuracy of the data, several filtering criteria were applied. Only active companies were considered, and entities with fewer than 10 employees or revenue below 100 000 euros were excluded. Further, companies were categorized based on their reported nomenclature of economic activities (NACE) codes, leading to the exclusion of firms not engaged in physical activity or production, as these entities inherently lack the need for 5G private networks.

Spatial data, encompassing cadastral units, fiber networks, and building structures, was procured from the Estonian Land Board. These data were pivotal in identifying economically active areas associated with each company and understanding the current infrastructure landscape.

Model development

The primary objective of the model was to evaluate the feasibility of 5G private networks for each company based on spatial and economic parameters. The spatial characteristics of each company were analyzed using a convex hull method to estimate the number of 5G service stations required for coverage. A hexagonal grid, simulating the circular coverage area of a 100-milliwatt 5G transmitter with a 50-meter radius, was employed. Hexagons were used as they allow the area to be divided without any gaps. Given the criticality of an uninterrupted service for applications such as autonomous vehicles, a denser placement strategy was adopted, effectively halving the coverage radius. For structures that could potentially obstruct signals, such as reinforced concrete buildings, additional stations were factored in.

Based on the spatial data, all enterprise data were enhanced with various characteristics. First, the shape was analyzed as a convex hull to find out the number of 5G service stations needed to cover it. This was achieved by using a hexagonal grid as a substitute for the circular area of coverage with a radius of 50 meters (equivalent of 100-milliwatt 5G transmitter range). However, since autonomous vehicles should not be affected by network outage at any point, redundancy should be achieved by a denser placement. Thus, all radiuses should be divided in half. For buildings acting as Faraday cages (such as reinforced concrete), separate stations were added. This did not include the optimal placement of the devices and did not consider the natural effects, such as elevation and vegetation. The model yielded two primary outputs:

1. Area effect of 5G private networks: this metric identified regions where 5G private networks might be infeasible due to regulatory or technical constraints.
2. Required infrastructure per company: this provided an estimate of the infrastructure needed for each company to implement a private 5G network.

Analytical framework

For each company, a comprehensive dataset was compiled, encompassing parameters such as the number of base stations required, coverage area ratios, total wattage, proximity to fiber backbone networks, and potential overlaps with competing networks.

Based on the compiled data, certain criteria were established to determine the immediate feasibility of a private 5G network for each company. These criteria included potential overlaps with other networks, minimal infrastructure requirements, proximity to fiber networks, and compliance with legal wattage limits.

To further refine the feasibility assessment, economic metrics were introduced. Revenue per base station and coverage area ratios were analyzed, and thresholds were established based on their respective distributions. Companies meeting these economic and spatial criteria were deemed suitable for a private 5G network implementation.

Testing and validation

A validation exercise was undertaken to ensure the model's accuracy and reliability. Companies from each feasibility category (feasible and infeasible) were randomly selected and subjected to a detailed review. The objective was to ascertain the correctness of the model's predictions and identify potential false positives or negatives. The validation process was instrumental in reinforcing the model's credibility and ensuring its applicability in real-world scenarios. The companies receiving a negative result were investigated to verify the result was not a false negative. Similarly, companies with positive results were checked for possible false positive outcomes. The following scenarios were considered:

- result is correct,
- result is erroneous due to an issue with underlying data,
- result is erroneous due to a fault with the model.

The validation sample was chosen randomly by using the PostgreSQL built-in RANDOM() function. Each company was assigned a random number, and rows with the ten lowest values for each category were selected for validation.

RESULTS

The application of the developed model yielded a comprehensive set of results, providing insights into the feasibility of private 5G networks for various companies. This section delineates the numerical findings and their implications. The spatial characteristics of each company were analyzed. The convex hull method estimated the number of 5G service stations required for optimal coverage. Using a hexagonal grid to simulate the coverage area, it was determined that:

- the average coverage radius for a 100-milliwatt 5G transmitter was approximately 50 meters;
- given the necessity for uninterrupted service, especially for applications like autonomous vehicles, a denser placement strategy was adopted, effectively halving the coverage radius to 25 meters;
- structures that could potentially obstruct signals, such as reinforced concrete buildings, necessitated additional stations.

Based on the compiled data, several criteria were established to determine the immediate feasibility of a private 5G network for each company:

Fig. 3. Spatial representation of the dataset with overlapping networks.

- Overlap with other networks: a significant portion of companies faced potential overlaps with other networks. The overlap was identified as the primary constraint for 163 areas, rendering them unsuitable for private 5G network implementation. As illustrated by Fig. 3, network coverage bleeds into neighboring areas, even reaching the property of other eligible companies. This shows the conflict areas in which the private network is destined to run into issues.
- Minimal infrastructure requirements: companies requiring fewer than three base stations were deemed unsuitable for private 5G networks.
- Proximity to fiber networks: companies with foreign relations and a distance greater than 500 meters to the fiber backbone network were considered infeasible for private 5G network implementation.
- Compliance with legal wattage limits: companies whose total wattage exceeded legal limits were also deemed unsuitable.

Applying these criteria, the initial sample size of 2006 companies was significantly reduced. Only 548 companies were identified where private 5G networks were considered feasible. However, it is noteworthy that companies eliminated in the initial stage could still potentially implement their own 5G private networks, provided they address and mitigate the identified challenges.

The next stage in the model determined the lower limit of economic activity (revenue) per base station and the maximum acceptable ratio of coverage outside the cadastral unit. Revenue per base station followed the log-normal distribution with the two-sided Kolmogorov–Smirnov statistic (the maximum absolute difference) D (548) = 0.037, Lilliefors p-value = 0.076. The ratio of coverage was also log-normal, with the asymptotic z-value of 0.948 and p-value = 0.343. Based on these results, the limits were set at logarithmic means. The limit for outside coverage was 1.99 and for revenue per base station, 275 000 euros. Thus, 103 companies were in such an economic state and location that 5G private networks are feasible solutions.

The validation exercise provided further insights into the model's predictions. Out of the companies deemed suitable for private 5G networks, all ten randomly selected companies were validated as correct. Similarly, for com-

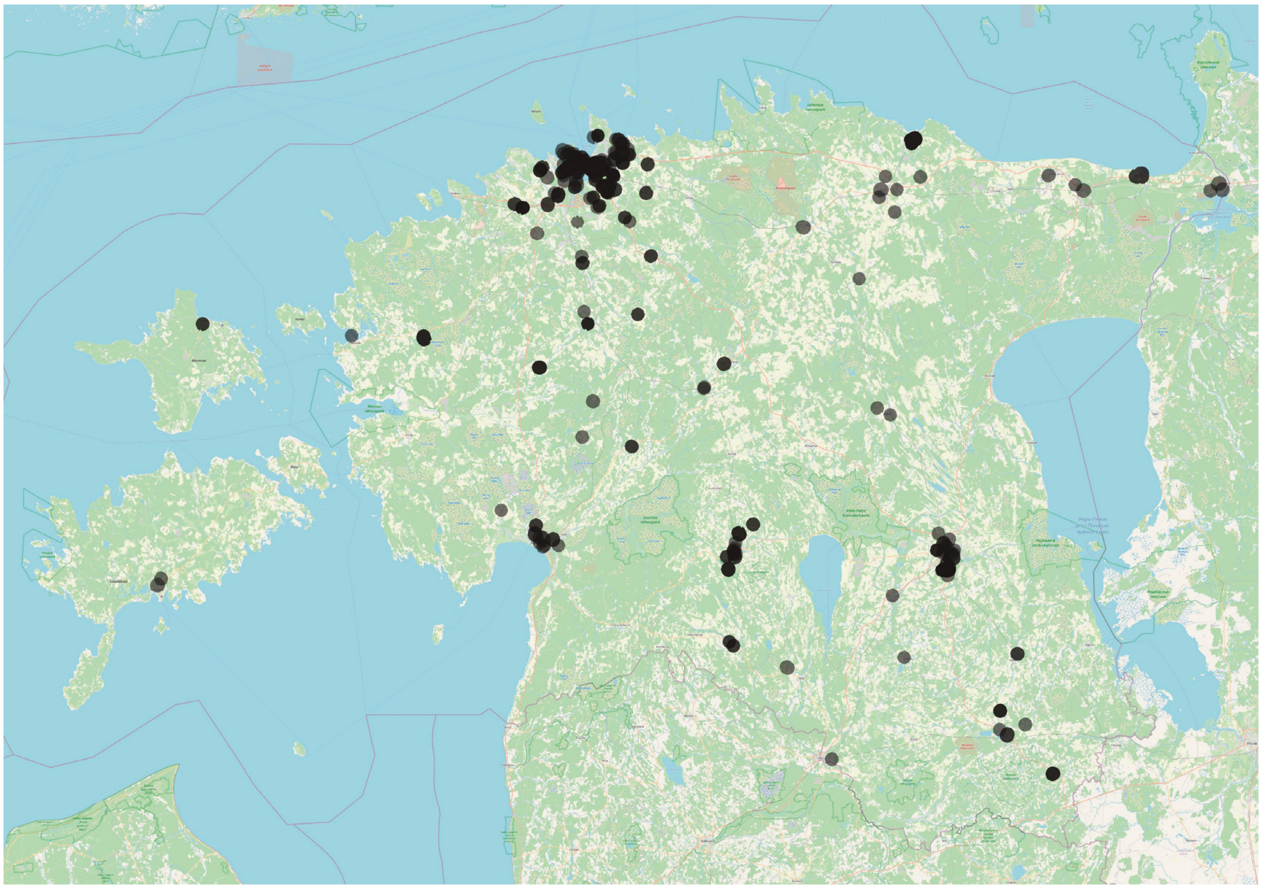

Fig. 4. Areas in Estonia not recommended for private 5G networks on OpenStreetMap base map (OpenStreetMap).

panies deemed unsuitable, all ten randomly selected companies were validated as correct. The main reason for not being eligible for private 5G networks was small size, followed by conflict with another network. While conflicting networks are not inherently prohibitive, it will eventually lead to problems. In total, 163 such areas were identified where installing private networks is not feasible with the current land use and ownership.

As displayed in Fig. 4, conflict areas are concentrated in economically more active areas. However, these areas cover only a small part of all land parcels zoned for enterprise use in any given administrative area. Therefore, it will not inhibit adoption of innovative technologies but will require certain companies to rethink their location and strategy.

CONCLUSIONS

The digital transformation of industrial systems, underpinned by the tenets of Industry 4.0, necessitates robust, high-performance wireless communication solutions. Private 5G networks have emerged as a promising solution, offering a blend of mobility, bandwidth, and security tailored to the unique needs of modern enterprises. This study embarked on a comprehensive exploration of the feasibility of implementing these networks across various companies, leveraging a robust methodological framework.

Our findings underscore the nuanced landscape of private 5G network implementation. While the technological advantages of 5G, such as increased bandwidth and reduced latency, are undeniable, their practical deployment is contingent on a myriad of spatial, economic, and regulatory factors. The spatial analysis revealed critical considerations related to infrastructure requirements, potential overlaps with other networks, and proximity to essential services, such as fiber backbone networks. On the economic front, metrics such as revenue per base station and coverage area ratios emerged as pivotal determinants of feasibility.

Of the initial sample of 2006 companies, only 103 were identified as prime candidates for private 5G network implementation, underscoring the selective nature of this technological transition. However, it is imperative to note that this does not diminish the potential of 5G. Instead, it highlights the need for strategic planning, informed decision-making, and potential collaboration to harness its full potential. While the model was developed based on Estonian datasets, the technical implementation is transferrable and thus can be used to analyze any other region with minimal modifications.

In conclusion, while private 5G networks hold immense promise for the future of industrial communication, their implementation is a complex endeavor, shaped by a confluence of factors. This study provides a foundational framework for businesses, policymakers, and stakeholders to navigate this transformative journey, ensuring that the leap to 5G is both strategic and sustainable.

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Ettevõtlusandmetel põhinev 5G privaatvõrkude tasuvuse hindamise mudel

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Tootmise digitaliseerimist nimetatakse neljandaks tööstusrevolutsiooniks, kusjuures kasutatakse ka nimetust Tööstus 4.0. Üleminek digitaliseeritud tootmisele eeldab tänapäevaseid ja võimekaid sidelahendusi, mis oleksid turvalised, kiired ja juhtmevabad. 5G privaatvõrgud on selle paradigma muutuse esirinnas, pakkudes suuremat läbilaskevõimet, väiksemaid viiteaegu ja tõhusamat turvalisust. Artiklis uuritakse 5G privaatvõrkude rajamise majanduslikku tasuvust ja mõttekust erinevate ettevõtete jaoks reaalsete andmete põhjal loodud mudeli alusel. Varasemate uuringute najal on selge, et üleminek nii 5G sidelahendustele üldiselt kui ka spetsiifilisemalt privaatvõrkudele pole väljakutseteta. Ehkki logistikasektor, tootmisettevõtted ja isejuhtivad sõidukid võidavad ülemineku eelistest palju, ei saa mööda vaadata ribalaiuse ületäitumise ja sagedusvahemike jaotumise probleemidest. Kasutades geoinformaatika võimalusi ning maa-ameti ja äriregistri avalikke andmeid, määrati sobiva võrgu ulatus, vajalike seadmete arv ja võimalikud konfliktid teiste võrkudega. Uuritud 2006 ettevõttest ilmnes vaid 103 puhul kokkulangevus optimaalsete mõõdikutega 5G privaatvõrkude rakendamiseks, kuna piirangud tulenevad nii majanduslikest kui ka ruumilistest teguritest. Samuti tuvastati piirkonnad, kus ei ole otstarbekas rajada üht ettevõtet teenindavaid privaatvõrke, kuna maakasutus erinevate ettevõtete vahel on liiga killustatud.