On Techno-Economic Optimization of Non-Public Networks for Industrial 5G Applications

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Abstract**—Non-Public Networks (NPN), or Private Networks, are gaining traction in commercial deployments as they provide benefits to many verticals. The technical base of the NPN is being developed in 3rd Generation Partnership Project (3GPP), and the currently available models can already be deployed providing ecosystem multiple options to set up the services basing on various mobile communication generations. This paper discusses the current state of the art of the standardized NPN solutions focusing on Fifth Generation of mobile communications (5G), and evaluates their applicability to industrial applications. This paper also discusses the ecosystem needs and respective gaps in the models considering selected industrial use cases. Through available references on experiences and deployment scenarios, this paper evaluates some of the key aspects that can impact NPN model selection related to Industrial IoT scenarios, and proposes ways to assess NPN techno-economic aspects.**

Keywords—NPN; private network; 5G deployment modeling; NPN optimization; network planning

I. Introduction

A Non-Public Network (NPN), referred also to as Private Network, provides network services in isolated environment. It can base on cellular networks or other wireless technologies, and it does not depend on numbering of regulated Public Land Mobile Networks (PLMN). 5G NPN refers to a 3GPP cellular system to deliver its capabilities for NPN use cases, such as businesses and municipalities. The 5G NPN can reside partially or completely in physical premises of an organization using it, e.g., within a factory or campus area, so that an external entity separate from a Mobile Network Operator (MNO) assumes the responsibilities of the isolated part offering its services to a limited group. NPN does not typically allow inbound roamers, although the NPN users may have roaming capabilities to use other PLMNs. The benefits of NPN deployment include the possibility to control the Quality of Service (QoS) and protection by isolation. NPN service can include voice connectivity in defined geographical area, or it can focus on Internet of Things (IoT) and respective industrial applications; today, there are many test projects and commercial setups involving industrial devices [1].

This paper explores the applicability of NPNs for Industrial 5G applications. Industrial 5G refers to Industrial Internet of Things (IIoT) with real-time data of networked sensors, assets, objects, and people, 5G network and edge computing enabling ultra-reliable, low-latency, and high-bandwidth communication.

The presented model is aimed to provide means to evaluate the feasibility of available private network deployment models considering key requirements of use cases of interest. The model supports high-level techno-economic assessment, although its limitation is that it considers rather generic parameters. Along with practical experiences, the model and its use can be developed further to better reflect the realities.

This paper introduces the standardization of private network landscape in Section II, and summarizes the key architectures of the available 3GPP models in Section III. Section IV discusses private network deployment models including 3GPP and other relevant options highlighting their key aspects. Section V summarizes the most important pros and cons of the presented private network variants, comparing their suitability in different scenarios. Section VI presents how techno-economic modeling can be applied in the selection of the most feasible variants, and Section VII summarizes the findings.

II. Standardization

Private networks can be formed by a variety of technologies. To cope with the increased interest and demand, 3GPP has formed a set of standardized solutions based on mobile network technology, and industry bodies are considering guidelines for the actual deployment.

A. 3GPP

The 3rd Generation Partnership Project (3GPP) has designed 4G and 5G NPN specifications in Release 16 providing enablers for also Industrial 5G IoT. The areas include Time Sensitive Networking (TSN), NPN, and Local Area Network (LAN) type services. Release 17 and beyond evolve these aspects further. The 3GPP defines NPN in the Technical Specifications TS 23.251 (architecture and functional description of network sharing), TS 22.104 (service requirements for cyber-physical control applications in vertical domains), and TS 23.501 (5G System architecture).

B. Industry bodies

The 5G-ACIA (5G Alliance for Connected Industries and Automation) summarizes industrial IoT deployment scenarios for 5G NPNs basing on 3GPP-defined 5G NPN [2]. It presents deployment models to complement their architectural design.

Also, GSMA (GSM Association) considers NPN, and their guidelines provide overview to deploy 5G industry campus NPN by 3GPP definition, which is one of the key 5G concepts to support “to business” models (2B) [3].

 ISBN: 978-1-68558-068-1

III. 5G NPN STANDARD ARCHITECTURES

As per the 3GPP Release 16 definitions, an NPN enables deployment of 5G System (5GS) for private use. The NPN can be deployed as a Stand-alone Non-Public Network (SNPN) or Public Network Integrated NPN (PNI-NPN). An NPN operator manages SNPN without relying on the functions of a PLMN, whereas PNI-NPN deployment depends on those [4].

Figure 1 depicts NPN variants as interpreted from [3], [2].

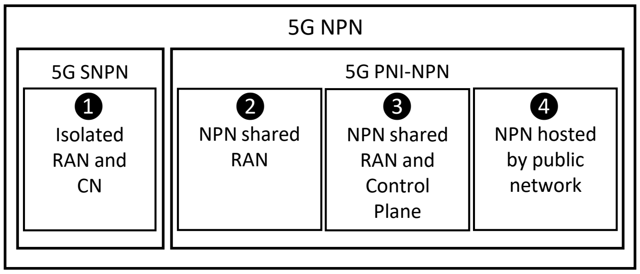

Figure 1. 3GPP and 5G-ACIA NPN variants.

A. SNPN

The SNPN uses combined PLMN Identifier (PLMN ID) and Network Identifier (NID). 5G User Equipment (UE) supporting SNPN can attach to it based on 5G Subscriber's Permanent Identifier (SUPI) and credentials. The Radio Access Network (RAN) of SNPN broadcasts the combined PLMN ID and NID in the System Broadcast Information and supports network selection and re-selection, load and access control, and barring. The NIDs can be self-assigned individually to the SNPN NIDs upon its deployment. The active NIDs may not be unique, but they use different numbering space than the other scenario, coordinated NID-assignment, that can have either 1) globally unique NID-assignment independent of the respective PLMN ID; or 2) globally unique NID/PLMN ID combination.

B. PNI-NPN

The PNI-NPN uses PLMN ID whereas Closed Access Group Identity (CAG ID) indicates the CAG -enabled 5G radio cells. Within a PLMN, a CAG cell can broadcast one or more CAG IDs, in which case PLMN ID is the base for the network selection and reselection whereas the network uses CAG ID for the cell selection and re-selection, as well as for the control for letting only CAG-enabled UEs access the network.

C. Implementation aspects

As depicted in Figure 1, these two options result in practical scenarios of isolated deployment of standalone non-public network (1) or non-public network in conjunction with public networks. The latter breaks down into three scenarios including the Industrial and IoT environment: Shared radio access network (2); Shared radio access network and control plane (3); and NPN hosted by the public network (4) [2].

- SNPN: the NPN is separated from the public network and all network functions reside inside the organization's premises. The possible communication between the NPN and the public network takes place via a firewall, e.g., through Non-3GPP Interworking Function (N3IWF).
- Shared radio access network: the NPN and public network share part of the radio access network as per the 3GPP TS 23.251. The communication stays within NPN.
- Shared radio access network and control plane: the NPN and the public network share the RAN for the defined premises while the public network does the network control tasks, the NPN traffic remaining within the premises. Network slicing or 3GPP Access Point Name (APN) can realize this case.
- PLMN-hosted NPN: the enterprise is served by a Network Slice (NS).

IV. NPN DEPLOYMENT MODELS

A. Standalone NPN

Figure 2 depicts the principle of SNPN as interpreted from [2], [5]. In this scenario, the User Plane Function (UPF) works as a data router to connect Multi-access Edge Cloud (MEC) and possible LAN. The RAN manages the connectivity of 5G gNB (next generation Node B) and UE of the SNPN users on licensed or unlicensed band. 5G Core (5GC) houses the NFs including UDM (Unified Data Management for user credentials).

In this model, the Network Functions (NF) reside within the operational area of related entity, such as factory, the SNPN being an isolated network from the PLMN. This allows communication between the PLMN and NPN through an optional firewall which isolates the NPN so that Operational Technology (OT) company can operate the NPN and its services, including the NPN IDs to have additional PLMN services in the NPN coverage area, NPN-subscribers to roam the public networks, and public networks' subscribers to roam the NPN depending on roaming agreement. NPN users may also have dual subscription for the PLMN use.

An example of the NPN 5G deployment on IIoT scenarios is the interconnection with TSN as per 3GPP TS 24.519. TSN is a set of new open standards that provide deterministic, reliable, high-bandwidth, low-latency communication [6].

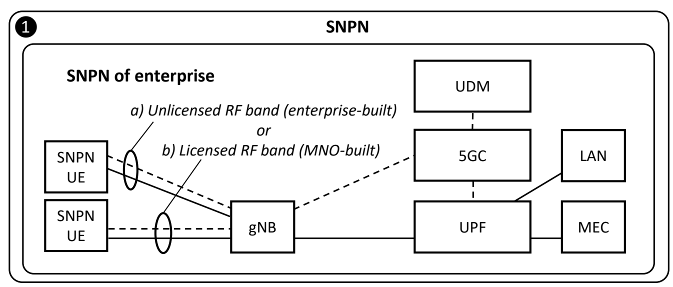

Figure 2. Principle of a SNPN.

The standalone private network can be built in various ways: by dedicated Service Level Assurance (SLA), local PLMN, PLMN by dedicated proportion of operator's licensed spectrum, or by SNPN using unlicensed or private spectrum.

Each deployment model has their pros and cons. As an example, licensed spectrum is one of the most expensive single items in the commercial network. Feasible way to set up this type of network is to construct mm-Wave radio access points in a limited enterprise area and virtualized cloud core functions in nearby edge, one option being a broker managing the NPN [7].

B. Shared RAN

Shared RAN involves NPN and PLMN with certain part of its RAN for joint use whereas other network functions remain separated. Figure 3 depicts the principle of this model showing the connectivity of the NPN RAN to PLMN core while the own core network of the NPN is isolated from the external world as interpreted from [2], [3], [8]. In this deployment model, NPN traffic stays internal and within the logical, defined area, such as factory premises.

The 3GPP TS 23.251 details the network sharing model in its architectural and functional description and scenarios for network sharing usable also in NPN environment, which are Gateway Core Network (GWCN) and Multi-Operator Core Network (MOCN) [9].

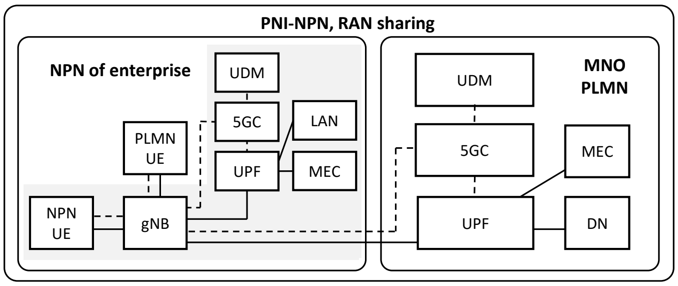

Figure 3. Shared RAN NPN deployment. The grey area indicates the private network slice that forms the NPN.

C. Shared RAN and Control Plane

As depicted in Figure 4, interpreted from [2], [3], [8], in this deployment, both NPN and PLMN share the RAN within defined business area premises and PLMN takes care of the control plane so that the internal NPN traffic stays always within the logical network related to the business. Network Slicing is one way to set up this scenario as it creates logically independent networks within a shared physical infrastructure. The isolation of the private network portion is possible by using unique NS identifiers.

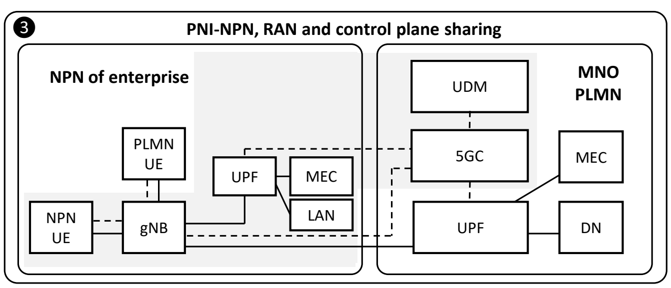

Figure 4. Deployment for shared RAN with control plane. The grey area indicates the private network slice that forms the NPN.

Using APN, as defined by 3GPP, is another way to implement this scenario. In this case, the APN indicates the target network with opportunity to differentiate traffic.

In the shared RAN scenario with shared control plane, the PLMN hosts the NPN so that the devices are a subset of PLMN subscribers. This arrangement eases the contractual aspects of PLMN and NPN operators, and the NPN devices can connect, apart from the NPN itself, also to the PLMN services and roaming. The NPN services may connect to PLMN services, which requires optional interface between the NPN and PLMN services, so NPN devices can connect to NPN services via the PLMN if the device is located outside of the NPN coverage and still within the PLMN. Logically, if the NPN devices can access the PLMN services, this interface is not needed.

D. PLMN-Hosted NPN

In this case, as depicted in Figure 5 and interpreted from [2], [3], [8], thanks to the network virtualization and cloudification, both the PLMN and NPN traffic are external to the business area. This means that these traffic flows are served by different networks, and the NPN subscribers are in fact public network subscribers. The NPN-PLMN roaming implementation is straightforward as the traffic routes via the PLMN.

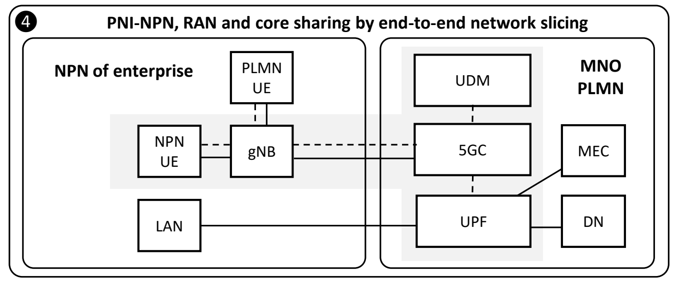

Figure 5. PLMN-hosted NPN. The grey area indicates the private network slice that forms the NPN.

E. Private network on Network Slice

Although the differentiation between certain user types is possible in 4G networks, it is limited to techniques, such as the isolation of services in a common infrastructure; the means for this include APN Routing, MOCN, and Dedicated Core Network (DECOR) [10]. Built upon Service Based Architecture (SBA), which enables the use of common hardware that executes the Network Functions as instances, 5G has been designed to support also network slicing with respective QoS assurance. In this manner, the Network Slice Provider (NSP) can offer suitable characteristics within their different NSs fulfilling variety of different requirements for their subscribed verticals, also in NPN environment. NS provides means to differentiate the network resources and performance figures that can create also new business models. As an example, the operator can offer their customers gold, silver, and bronze categories, each having their personalized NS price and QoS levels [11]. The NSP can be either MNO or 3rd party. Technically, the NSP could be also enterprise taken their skillset suffices to manage slices.

In NS-based NPN, it is important to adequately interpret the end-user requirements. GSMA provides guidelines for NS setup based on requirements [12], and clarifies how the requirements can be captured from the vertical field [11].

NSs are not yet used widely in commercial Standalone (SA) 5G networks, despite of the forecast indicating about 25% use base in 5G by 2025 [13], [14]. Furthermore, the optimal NS functionality in practice, especially in the end-to-end scenarios, might require still further development to cope with the impacts of real-world non-idealities in synchronization, near real-time orchestration, and overall management of the slices.

F. Open RAN as a Private Network

Open RAN refers to the overall movement of the telecom industry to disaggregate hardware and software to create respective open interfaces in between [15]. O-RAN Alliance publishes RAN specifications, releases open software for the

 ISBN: 978-1-68558-068-1

RAN, and supports O-RAN Alliance members in integration and implementation testing. O-RAN Alliance works on open, interoperable interfaces, RAN virtualization, and big data enabled RAN intelligence [15], [16]. Open RAN may offer feasible possibility to form small-scale, isolated shared RAN networks also in a form of NPN. The concept is still evolving, though, and may not provide optimal techno-economic solutions soon; nevertheless, as the technology matures, Open RAN may offer competitive 4G and 5G NPN variants.

G. Legacy network as a service

Increasing number of incumbent MNOs have switched off their 2G and/or 3G legacy mobile communications networks, or are aiming to sunset them soon. Nevertheless, there will remain scenarios involving IoT and voice services via legacy systems especially in developing markets. According to GSMA statistics, the 2G and 3G systems represent combined still more than 20% of the global footprint in 2025 [14]. This can be a niche opportunity to manage part of this lessening infrastructure on the remaining spectrum, maintaining a minimum feasible infrastructure for IoT and other 2G/3G services via private networks for verticals needing only low capacity.

H. Local and Fixed Wireless Access (FWA)

The LTE-WLAN Aggregation (LWA) as per 3GPP Release 13 allows mobile device configuring on simultaneous LTE and Wi-Fi links [17]. 5G can work also in parallel with non-3GPP accesses to comply with a light-weight private networks' need. 3GPP Release 15 defines Non-3GPP Interworking Function (N3IWF) allowing Wi-Fi access points delivered via 5G infrastructure as Wi-Fi hotspots or Fixed Wireless Access (FWA). The Release 16 defines further Residential Gateways (RG) to interconnect end-users' devices via trusted access points. These gateways complement the N3IWF.

FWA can provide solution to variety of use cases, such as tethering and Mobile Broadband (MBB), best effort FWA, and speed-based QoS [18]. Reflecting these use cases, the FWA could serve as a small-scale home office solution, too, with quick and economic deployment without need for optic fiber.

I. Non-3GPP wireless private network

Technically, it is possible to set up a simple private network using any wireless access beyond the 3GPP specifications on unlicensed, shared spectrum. An example of this is a Wi-Fi hotspot network using common applications within the network providing Over the Top (OTT) voice and messaging. Also, Low Power Wide Area Networks (LPWAN) can provide a feasible communications channel to many IIoT use cases.

V. Considerations of Scenarios

The feasibility of each NPN deployment depends on the foreseen use cases. As an example, the roaming requirements impact the needed coverage and mobility of the end-users of the NPN. This is one of the examples that can dictate the selection between Standalone and PLMN-assisted scenarios.

A. SNSP deployment

The main aspects of the previously presented deployment models for SNPN scenarios are summarized in the following list, with statements on their suitability for selected use cases.

<u>5G SNPN</u>. OT operates the NPN and its services behind a firewall independently. Provides good security isolation, e.g., to IIoT applications as data is not exposed externally. Optional PLMN interconnectivity via firewall. The operation and management of SNPN requires sufficient skillset from OT company. Provides the opportunity to build a very secure environment, but can be more expensive than only partially owned, or completely outsourced network.

<u>5G SNPN with SLA</u>. The agreed SLA level impacts the business case; the higher the SLA, more costly the CAPEX and OPEX due to, e.g., active-active network mode and reliability of, e.g., 99.999% as per 3GPP Rel 15 URLLC performance, or up to 99.9999% as per Release 16 performance for, e.g., TSN interconnectivity to serve critical IIoT applications.

<u>PLMN with local infrastructure</u>. This is a special case of PLMN that isolates part of the infrastructure and spectrum to a sole use of private network devices in limited geographical area. It can be set up technically, e.g., by barring the access from others than specifically defined set of subscribers.

<u>PLMN on part of MNO's licensed spectrum</u>. Spectrum is typically very expensive investment for the license holder, so dedicating part of it needs to be designed carefully applying techno-economic optimization, in order to adequately balance the cost and expected quality.

<u>SA NPN on unlicensed spectrum</u>. The radio deployment and RAN business case are light as there is no license fee involved. Nevertheless, the QoS cannot be ensured due to load of shared spectrum with possible other users.

B. PNI-NPN deployment

The following list summarizes key aspects of this model.

<u>NPN shared RAN</u>. NPN and PLMN share part of the RAN, but the NPN communications stay within the defined premises. 3GPP defines well the technical RAN sharing options that can be applied in this model.

<u>NPN shared RAN and CP</u>. NPN and PLMN share the RAN for the defined premises while the PLMN has network control; the NPN traffic remains within the defined premises. Network slicing serves this model as per 3GPP specifications, complemented by industry forums' guidelines for slice template setup. Alternatively, the setup can be based on APN.

<u>NPN hosted by public network</u>. PLMN and NPN traffic are external to the business area so that these traffic flows are served by different networks, and the NPN subscribers are effectively public network subscribers.

C. Pros and Cons of deployment models

a) SNPN

- Pros: access for customization, independent controlling; high security by full isolation; RAN functions are within reduced geographical area favoring low-latency applications.
- Cons: deployment cost; expertise required for deployment. Dedicated network for sole enterprise includes the cost of the whole system in the geographic area.

b) Shared RAN

- Pros: optimizes RAN infrastructure costs while the internal data remains within the NPN infrastructure providing good protection; PLMN RAN connectivity serves for delivering the data meant for outside of the NPN as per need. Within the NPN, part of the base stations can be connected to PLMN according to the RAN sharing agreement between the PLMN and NPN operators while the rest can be kept internal. Licensed spectrum copes interferences; deployment less expensive compared to SNPN; uses typically local functions favoring low-latency applications.

- Cons: external interferences can be higher than in SNPN, and the overall control of the network is less independent; need for local expertise, although less than in SNSP.

c) Shared RAN and CP

- Pros: licensed spectrum for controlled interferences; lower deployment expenses compared to SNPN and PNI-NPN; SLA can be applied between the NPN and public network.
- Cons: less independent from public networks; latency typically higher than in SNSP and PNI-NPN deployments; some local expertise required.

d) Hosted solution (Network Slicing by NSP/MNO)

- Pros: facilitated by NSP, no need for local expertise; fast to set up and adjust based on expressed requirements.
- Cons: less control for adjustments as the NS is managed by the NSP; technology not yet final, practical deployments require SA 5G network that are not yet many in markets.

e) Open RAN as an NPN service

- Pros: the cost can be low; easy to set up by provider; can be hosted as "light-weight" 5G SNPN or NPI-NSN.
- Cons: technology is still evolving and the realistic products for Open RAN -based NPN can take time.

f) 5G FWA (home office use case)

- Pros: Customer Premises Equipment (CPE) easy to install; replaces fixed cabling.
- Cons: use case adequate in a home office environment, but limited for larger enterprise NPN use.

g) Non-5G-based solutions (Wi-Fi hotspots)

- Pros: Wi-Fi hotspot deployment is rather straightforward within an enterprise area. The radio coverage does not require license, and it can also be extended to reach any Wi-Fi device external to the enterprise premises.
- Cons: low security, limited mobility, and lack of QoS.

h) LPWAN

- Pros: many options available basing on both cellular and non-cellular radio technologies. Cellular-based LPWANs are services integrated to system, easy to deploy.
- Cons: non-3GPP-based LPWANs have varying security and protection levels, and they require a separate infrastructure.

VI. TECHNO-ECONOMIC OPTIMIZATION MODELING ASPECTS

A. Current deployment models

Each NPN deployment model has their advantages and disadvantages. Understanding the requirements of the use cases, and applying tecno-economic optimization assessment that considers the key variables, the selection of the most adequate deployment model will benefit favorable business.

In the selection of the deployment model, the task is to understand the realistic needs of the final users of the NPN access, performance, security aspects, mobility, capacity, QoS, and other key factors, and how they can be served by applying cost-efficient technical solutions. It is important to understand also the changing requirements in the foreseen future because along with the evolution of the environment, originally selected, initially optimal model, can turn out to be less optimal in longer term.

As described in [11], related to NS scenarios, the collection of the verticals' requirements can be done via practical means to interpret the needs of the end-users. From the operators' perspective, this can be somewhat challenging task as the verticals may often express their requirements using non-standard terminology, or are not able to formulate the actual requirements. The methodology in [11], despite its original focus on NS, can be useful to be extended to cover additional aspects the other NPN deployment models. This methodology suits to interpret practical vertical needs based on the foreseen use cases, and to form technical requirements that can be finally be mapped to represent input parameters for the NPN modeling, whether it is about tailored 5G NS template for which the GSMA PRD NG.116 serves as a base, more "traditional" standalone NPN setup, or shared network model. The aim of the requirement list is to ensure the common understanding of the environment, and set the expectations also for service level.

B. On further techno-economic optimization

The assumption of the modeling is that the NPN is a business between an entity capable of deploying adequate wireless network (such as MNO, NSP, network equipment vendor, or system integrator) and an enterprise desiring to facilitate the mobile communications for their end-users in their communications via Industry IoT applications (such as port or energy company monitoring and controlling their workflow via intelligent sensor network).

The model for the selection of the most adequate NPN deployment option can build upon modular elements, which are:

- *Interpretation* of the enterprise and end-user needs (e.g., via survey) to form technical requirements statement as a base for the input parameters; e.g., capacity (number of expected users/devices), coverage, QoS, need for roaming/local-only utilization; and services (IoT, voice, other).
- *Business aspects* assessment (understanding possibility for investment in terms of CAPEX and OPEX; flexibility for initial and longer-term investments).
- *Forecast* of today's, near-future, and longer-term outlook for the possible need for expansion of the network, capacity, and evolving QoS (which is important to avoid investing to multiple types of NPN as the requirements evolve).
- Any other relevant information on the deployment aspects.

The assessment of the feasibility of the deployment options relevant to the scenario under evaluation can be carried out based on these results in a comparative manner. The base for the economic assessment is the cost for enterprise in terms of the CAPEX (initial deployment and forecasted posterior need for new infrastructure investments) and OPEX (yearly cost in order to operate NPN). The cost estimate of each scenario presented in the NPN Deployment Models Section considers the key attributes, such as area of deployment, device number (total expense x_d), and radio performance indicators, which together result in the required bandwidth and number of radio cells, and finally in the total cost of cells x_{gnb}. As an example, in very high data rate scenario requiring large indoor and outdoor NPN, the number of mm-Wave small cells, each resulting in, e.g., 80-100 m cell range, can be in order of dozens per km^2. Other attributes consider the cost of transmission network x_{tn}, and spectrum x_s.

 ISBN: 978-1-68558-068-1

For the core network, the cost includes the licenses and other cost items to activate the needed network functions NF x_{nf}. Cost of the needed applications / services x_a refers to the support of, e.g., voice service (that requires either own or outsourced IMS core for integrated Voice over New Radio) and IoT service license, and Location Based Services (LBS) deployment. Roaming and interconnectivity cost x_r is related to the agreements with national and international networks.

The cost x_v of other variable items can include, e.g., the actual installation of RAN, Transmission Network (TN), and Core Network (CN) equipment or cloud environment, including antenna systems, base station shields, cabling, and any other expense that is required to set up the NPN for enterprise.

For the estimate of yearly operating costs y, the same main components as presented in CAPEX analysis generate expenses, such as licensing fees and electricity consumption, whereas an additional item to be considered in operations is the maintenance cost y_m. The resulting Equations for the initial costs (1) and operating costs (2) are thus

$$CAPEX = x_{gnb} + x_{tn} + x_s + x_a + x_d + x_v + x_r + \sum_{nf1}^{nfn} x_{nf} \quad (1)$$

$$OPEX = y_m + y_{gnb} + y_{tn} + y_s + y_a + y_d + y_v + y_r + \sum_{nf1}^{nfn} y_{nf} \quad (2)$$

It should be noted that the variables in Equations (1) and (2) can have non-linear inter-dependencies; as an example, the volume discount of the number of radio cells can also lower the relative cost of core software and cloud feature licensing.

The assessment results in a statement of the suitability of deployment scenarios to indicate their level of compliance with the requirements. This method can be visualized in terms of the total cost per area as a function of time, considering attributes of interest, such as maximum supported device number or maximum data rate. The method serves thus to estimate the initial and longer-term cost of each deployment model under evaluation; it is possible, that the initially most cost-efficient option might turn out to be less optimal in longer run.

C. Return on Investment

The described modeling can be extended to estimate Return on Investment (RoI) of private network, including the business of MNO, enterprise, or 3rd party. The RoI depends on the deployment and operational costs, share of ownership of private network components (hardware, software) versus outsourced items (e.g., 5G core that runs in virtualized environment served by cloud provider) in different deployment scenarios of interest, the generated savings compared to reference deployment scenario (as an example, enterprise can compare MNO-operated scenario against completely or partially enterprise-owned network), as well as potential earnings for different stakeholders. As an example, enterprise managing completely or partially owned private network, either on shared or own spectrum, could allow also additional users to roam into that network for a fee that depends on the data consumption or time.

Although the pricing of network components is business between the vendors and customers and thus largely non-public information, it can be assumed that large entities investing to either own network infrastructure or outsourced solutions to provide the private network services to the end-users, may benefit from lower costs due to scale of economies compared to smaller entities. Nevertheless, the private network ecosystem is expected to grow significantly at present, so it can thus also be assumed that small and medium sized entities could reach fortified position for own network component price negotiation in their private network market, which also can impact positively on the pricing models.

D. Expectations of the modeling

As can be seen from Equations 1 and 2, the selected items result in a linear presentation for initial and operating costs. That said, the Equations represent snapshots of scenarios, and each parameter value may have either linear or non-linear behavior as a function of time, number of components, etc. As an example, the expense related to gNB can be either fixed per the number of gNBs, or there could be a volume-based discount granted by the vendor as a function of the number of gNBs.

As can be expected, the values of the cost items in Equations 1 and 2 depend on the markets, vendor pricing strategies, competitive landscape, and many more variables, so the further analysis of scenarios would be merely speculative without the availability of concrete parameter values. Nevertheless, an example of the potential possible behavior can be presented by testing different scenarios and cost estimates of the parameters to understand the business impact in short, mid, and long-term operation of a private network.

The scenarios can be divided into following categories for the assessment of the total cost of a network, that a) is completely owned, partially owned, or completely outsourced ownership; b) uses licensed, shared, or unlicensed spectrum; c) has no roaming (completely isolated), or has inbound roaming, outbound roaming, or bilateral roaming. To complement the evaluation, additional criteria can be assessed, too, for validating the level of compliance for end-user requirements such as QoS, latency, maximum and average data rate, reliability, etc. The level of compliance of different scenarios can be compared by using numeric values and their weights of importance.

Let us assume an enterprise desires to compare the techno-economic feasibility of a) completely own and isolated small-scale (10 mm-Wave gNBs), 5G network (SNPN) that is based on unlicensed 5 GHz spectrum and 5GC NFs on cloud, with b) MNO-operated private network that is based on an NS dedicated to the enterprise with gNBs that are already partially deployed for PLMN users in the area complemented by new, 5 additional indoor mm-Wave small cells in the enterprise's operational premises. Figure 6 depicts an imaginary example of the relevant key expense behavior over time using the parameters of Equation 1 and 2 and certain estimated values so that they are normalized having the SNPN CAPEX as the reference at year 0.

As can be seen from Figure 6, the initial cost of enterprise's completely own network can be considerably higher than a subscription to an MNO's NS-based service to form a private network due to required investments on the infrastructure. In this scenario, also the OPEX of the SNPN cumulates faster compared to the dedicated MNO NS due to maintenance and licensing expenses of the own network.

This method provides the enterprise with a tool to estimate the cost difference of deployment models of interest over time and to assess whether certain model is acceptable for deployment regardless of projected, potentially higher cost to balance the key requirements of the enterprise considering, e.g., the level of independent network control and security.

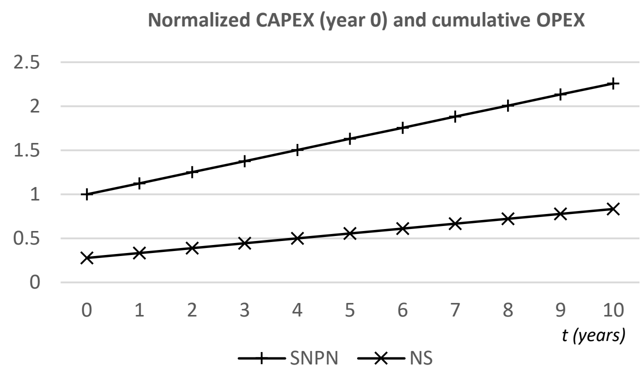

Figure 6. Example of the model's outcome comparing SNPN (reference) and NS deployment scenarios.

VII. Summary and Future Work Opportunities

NPN can serve many verticals and their use cases in a more optimal way than PLMN may be able to, to comply with special requirements for, e.g., hardened security by isolation, or high flexibility for network settings adjustment, for which the pros and cons of enterprise-owned vs. operators' components need to be evaluated. There are variety of deployment and ownership models, so the assessment of the scenarios prior to business decisions for the most feasible deployment and ownership model is beneficial.

This paper presents means for the assessment of the techno-economic feasibility of NPN models and an imaginary example on the evaluation. For the model to perform adequately, insights on realistic OPEX and CAPEX values of the model's parameters are important. Thus, feedback from NPN proof of concepts and trials serves to calibrate this modeling and helps identify and focus on the evaluation of the most essential cost items.

The private networks are becoming reality, and they provide a functional base for many verticals and use cases to cope with special requirements. Stakeholders considering deployment and use of private networks benefit from adequate platform. As this study shows, even a relatively simple model can support the ecosystem to better understand the differences of the business cases related to a variety of private network models.

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