Network-in-a-box to provide health services in remote areas

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List of Abbreviations

AoI	Age of information
AWGN	Additive white Gaussian noise
BB	Broadband
BCD	Block coordinate descent
BLER	Block error rate
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CDF	Cumulative distribution function
COTS	Commercial off-the-shelf
DL	Downlink
E2E	End-to-end
ECG	Electrocardiogram
EEG	Electroencephalogram
eNB	Evolved node B
gNB	Next generation node B
HAPS	High altitude platform station
ICT	Information and communication technology
IoT	Internet-of-things
LoRa	Long range
LTE	Long term evolution
MANET	Mobile ad-hoc networks
MEC	Mobile edge computing
MTC	Machine type communications
NFV	Network function virtualization
NIB	Network-in-a-box
OPEX	Operation expenditure
PMR	Professional mobile radio
SCA	Successive convex approximation
SDG	Sustainable development goal
SDN	Software defined networking
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
SPC	Short packet communications
SWaP	Size, weight, and power
UAV	Unmanned aerial vehicle
UL	Uplink
UN	United Nation

1. Executive Summary

The COVID-19 pandemic has dramatically changed our lives. Social distancing is widely applied in the society. Remote working and distance learning have become the new norm of our lives to reinforce social distances, supported by the development of new technologies, such as metaverse platform which is a network of virtual world embodying extended reality and e-commerce interoperability. However, people living in the rural and low-income urban/suburban areas, cannot benefit from these developments due to insufficient return on investment on the network infrastructure in such areas. Thus, it is of great interest to develop cost-effective networking in low-density areas to support the post-pandemic recovery. In addition, many use cases for on-demand networking exist. For example, many countries operate temporary testing sites for COVID-19 at designated places or offer COVID-19 drive-through testing near roads. The collected medical information needs to be updated in real-time via on-demand networking from these temporary locations to reduce delays in policymaking. During a medical emergency situation where remote medical treatment is required, the ambulance itself can be mobilized. In addition, the healthcare information from wearables and implants may be remotely diagnosed in almost real-time in hospitals.

In order to meet the requirements of the use cases described above, the potential network should be flexible and fast to deploy. The network-in-a-box (NIB) is a promising technology to provide solutions to the above use cases targeting ubiquitous network connectivity in remote areas and on-demand access in temporary sites since it is light to carry, easy to deploy, and cost-effective. The NIB is the portable solution which integrates hardware and software modules for multiple network service provisioning and backhauling into a box. Here, we consider two categories of network service, mobile broadband for general access to the Internet and short packet health internet-of-things (IoT) services. The efficient operation of NIB relies on careful coverage planning to determine the NIB positions and the best means to transport the NIBs to the determined positions, which will be optimized in this research.

2. Introduction

After COVID-19 pandemic affects the whole world, social distancing has been widely adopted and became the “New Normal”. This caused many industrial application verticals to adopt online platforms, accelerated online multiverse with extended reality, and boosted e-commerce and the growth of FinTech. Consequently, a drastic increase of data traffic for on-demand services has been seen [1], [2]. This necessitates the provision of resilient and ubiquitous networking. As such, the International Telecommunication Union (ITU)’s Connect2Recover initiative focuses to reinforce the digital infrastructure and ecosystems of countries so that they can leverage the information and communications technologies (ICTs) to support COVID-19 pandemic recovery and preparedness for New Normal and remain resilient in times of hazards. In addition, Connect2Recover Research Competition was organized to encourage research to contribute towards digital resiliency and digital inclusion to yield positive outcomes in education, healthcare, or job creation. This report is one of the 15 winning proposals selected by the Research Competition.

During the early COVID-19, we witnessed how important managing the bed rate in the hospital is and remote medical health is now mandated to control it in an appropriate level for critical patients. The health service is not only performed at the hospital site but also online and remotely. Massive number of health sensors and internet-of-things (IoT) devices can help in self-monitoring and early diagnosis. Figure 1 shows how healthcare IoT service works in a network. The wearable and implant IoT sensor can periodically send the measurement data regarding the health information such as heart rate, respiration rate, blood information, medication, body composition analysis data, brain wave profile, etc. Multiple end users can simultaneously access to the anonymous networks connected to a cloud server providing the necessary information to hospitals, disease control center, and personal healthcare monitoring units. By doing so, it enables us to benefit from efficient health monitoring, early diagnosis, emergency response, and contagious disease control.

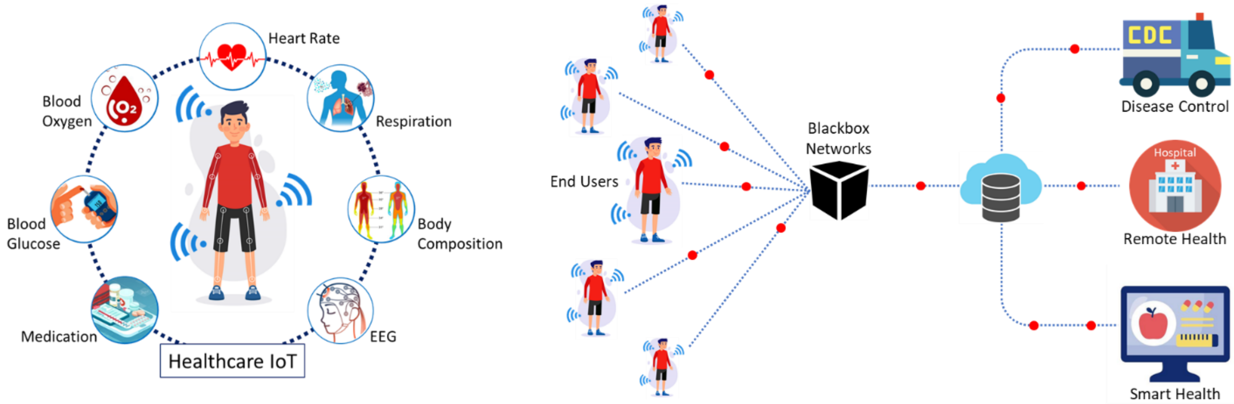


Figure 1. Concept of healthcare IoT with wearables and implants and network configuration. Source: L. Linkous et. Al [3]

Accordingly, the market of healthcare IoT is growing fast. Figure 2 shows the projected size of the IoT devices in global healthcare market from 2016 to 2025. Healthcare IoT revenues of 24 billion USD are expected to increase up to 135 billion USD by 2025 at the compound annual growth rate (CAGR) of nearly 20 % during 2016 and 2021 and the expected CAGR of 22.3 during 2022 and 2025. Temporary PCR testing or vaccination sites built on the designated places for quarantine are connected to the online database and require temporary bandwidth support due to their unusually high user density. Important medical information, alert, and guide such as number of cases, contact tracing, location of testing and quarantine sites is necessary to be well distributed in public without the internet. Ultra-low latency and ultra-high reliability will be the key driver indicators of the potential network solutions to provide good quality of physical experience in the private network sectors based on the extended reality and nearly zero delay interaction in remote rescue and medical operation regarding human health [5].

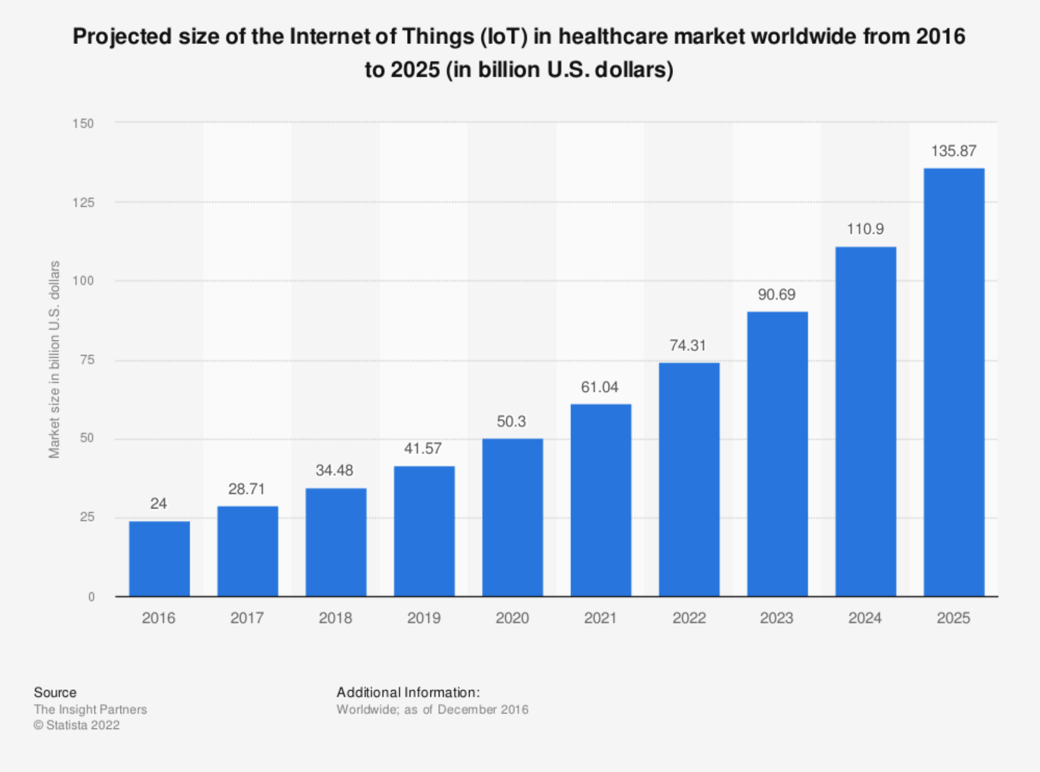


Figure 2. Projected size of IoT in global healthcare market.
Source: The Insight Partners [4]

During the pandemic, remote working and distance learning are intermittently transiting on demand. The workers and students are required to access to the private networks from wherever they are located. Meanwhile, people in rural and remote areas with underutilized network face greater difficulty to experience remote working under secure and resilient network connectivity [6], [7].

Therefore, in recovering from the New Normal, potential network solutions would be required to support certain features to enable the following new use. First, the potential networks can support service on demand. If the temporary medical investigation sites are established or the private network for remote working and education is required, the portable and easily deployable network connectivity should be established at the concerned locations during the determined network operating time. Second, ultra-reliable and ultra-low latency medical information should be ubiquitously connected into a network to provide super-accurate medical assistance in any required location. These use cases in post-COVID recovery have the same unique characteristic that their traffic is spontaneous but critical. To support such traffic, we should deploy one-off network solution which can be temporarily built and removed at any location. This one-off network which is easy and fast to deploy is more beneficial than time-consuming and costly conventional fixed network where the base stations are fixed at one location. Network-in-a-box (NIB) is an example of one-off network solutions, which are mobile and easily deployable and the installation for these solutions can be done almost within half an hour [8].

2.1. Research Background

Ultra-low latency and ultra-high reliability will be the key indicators of the potential network solutions to provide good quality of physical experience in the private network sectors based on the extended reality and nearly zero delay interaction in remoting rescue and medical operation regarding human health. Therefore, potential network solutions must operate under at least 5G standards or even 6G initiatives which enable the following new use cases characterizing the aforementioned network features in recovering from the New Normal.

- Access on demand: Temporary medical sites and intermittent remote working and education require network connectivity only during the concerned time or at the concerned locations.
- Ultra-reliable ultra-low latency portable network: Smart ambulance can be ubiquitously connected to the network and provide super-accurate medical assistance in any locations.

These use cases have the same unique characteristic that their traffic is spontaneous but critical. To support such traffic, the potential solution must be flexible and fast to be deployed. Thus, one-off infrastructure is far more advantageous than time-consuming and costly permanent fixed infrastructure. Also, it is time-consuming and inefficient to deploy permanent fixed infrastructure during temporary events.

NIB provides an excellent pop-out network solution integrating hardware/software modules in a form of portable device. It is designed as a one-off network infrastructure. The NIB with limited and user- friendly hardware and software capability significantly saves capital and operation expenditure in a mobile network. NIB perfectly fits supporting use cases above owing to ease of deployment, mobility, network flexibility and reconfigurability in varying environments.

2.2. Research Scope

Bearing in mind the advantages of NIB, one consideration is the manner in which NIB can be used to support some of 6G use cases. In that regard, NIB can either work on a stand-alone basis or with other NIBs and incumbent network components to provision end-user services as well as backhauling through multiple air and wired interfaces. Moreover, for sustaining the ubiquitous network connectivity, the network has to be resilient to the circumstances externally confronting the defect and challenges to the ordinary operation of networks such as the malfunction due to the natural disaster or temporary blackout. This research aims to study the use of NIB to support potential use cases that require on-demand access for ubiquitous networking. As the foundation of the research, we consider how the optimal deployment of dynamically reconfigurable NIBs for on-demand access is determined.

NIB deployment is the first step and also the first challenge to be solved for its use in on-demand ubiquitous access. Given a fixed designated area, such as a temporary medical testing area or a large rural area for distance learning, we determine how many NIBs should be deployed and where in the 3D space these NIBs should be placed to provide sufficient coverage for this area.

However, the traditional planning methods for fixed ground infrastructure are not suitable for one-off infrastructure, such as NIB. Compared with the traditional planning, we will face several new challenges. First, an increase in the number of base stations may give larger coverage areas but also cause stronger co-channel interference. Thus, an optimum number of base stations will need to be determined. Second, the area to be covered may be disjointed or irregular. Finally, NIB can support users in multiple networks. Thus, the position of NIB needs to be jointly considered for all networks.

For our proposed work, deterministic planning is the most suitable method, as the areas in the use cases concerned are often fixed. The deployment time was minimized to provide fast coverage. The effect of the shape of the area on coverage provision can be analyzed in terms of signal-to-interference ratio affected by positions of NIBs.

2.3. Research Objectives/Aim

The objective of optimal deployment is to solve the NIB coverage and positioning problem, which is essentially a trade-off between coverage area and interference. For the use cases considered, we can tackle several coverage scenarios: i) maximizing interference-free coverage or throughput, ii) maximizing coverage or throughput under inter-NIB interference, and iii) minimizing deployment time. Inter-NIB interference can be accounted for maintaining the quality-of-service in the coverage area, while optimizing the positions of NIB access points for maximum coverage area within an arbitrary service area of interest.

Using omni-directional antennas, the coverage of NIB is considered as a circle. And geometric distribution of service users will be modeled to analyze the areal performance of each NIB under fixed positions. Low latency communication will be applied to satisfy the delay-limited data in the service area. The use of multi-NIB deployment is required to meet the signal-to-interference-plus-noise ratio (SINR) requirements when we formulate the optimization problem from the perspective of communications theory. In the second step, we will use convex optimization under signal-to-noise ratio (SNR) or SINR constraints. In the optimization, small-scale fading will be averaged out in the planning. When NIBs support multiple networks, there is also a network association problem, that is, which NIB supports what network and where it should be placed to support users from different networks.

Once the number and positions of NIBs are determined, the next problem is how to transport these NIBs to the determined locations. The NIB could be carried by a person in a backpack, a ground/aerial vehicle, or even aerial platforms. This will affect the deployment time with their dynamics of mobility and environmental conditions. The best means of transport can be determined by comparing different means of transport.

3. Literature Review

3.1. On-demand Network-in-a-Box

Network-in-a-box (NIB) is based on the concept of all-in-one pop-up network [8]. It is a single portable device consisting of all software, firmware, and hardware modules typically operating in a cellular network; and the original intention was to provide an emergency network for network resilience. As shown in Figure 3, NIB is lightweight to be carried by either a human-being or in vehicles and provides ubiquitous wireless connectivity for a group of end users, while backhauling with a data server network. The NIB can solely serve the network connectivity by operating both end user service provisioning and backhauling together at the same time. Or, it can play a role to provide connectivity for some network components or functions in the core network. Multiple NIBs are evolved to configure mobile ad-hoc networks (MANETs). The mobility of NIBs allows the network operator to deploy and move the network anywhere and anytime on demand which is also called “bring your own coverage” [10]. Some cases such as disaster recovery network and private/tactical network forces non-professional operators to build the network and maintain its operation for specific duration. NIBs should have a user-friendly interface platform in order to “do it yourself”. This means that the medical emergency rescue team can operate the NIB network with minimal effort to learn the basic skills on network configuration. For further information of NIB beyond of scope in this research, the readers can see the details of NIB on the concepts, functions, and technologies in the tutorial provided by M. Pozza et. al. [8].

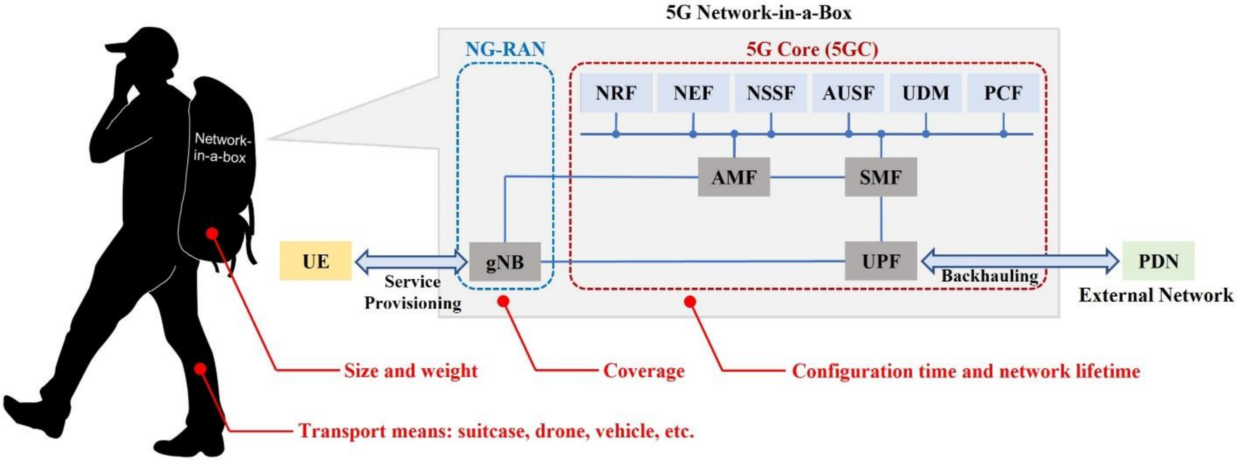
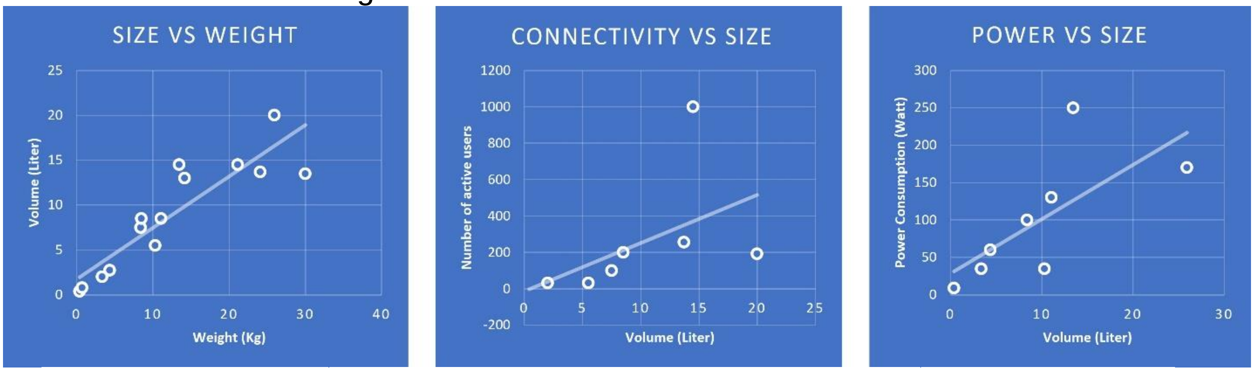


Figure 3. Structure and key factor of 5G NIB. NIB can perform two main functions, next generation radio access network (NG-RAN) gNB or 5G core[1]. Source: K. Park

The commercial off-the-shelf (COTS) NIBs are available for purchase in the current market. However, there is a need to consider and choose the appropriate COTS NIB based on their functionality and specification to fit with the purpose of the target network. The mobility and flexibility of NIBs highly depend on their physical properties and power. We illustrate the relation between them in Figure 2. Roughly speaking, the relation among NIB's size, weight, and power (SWaP) are linearly proportional as well as the user connectivity is also increasing with the volume of NIB. Transport means is another key factor to select right NIB to be deployed. For example, vehicle installed NIB can consume more power than other NIB, while providing more networking performance such as higher downlink (DL) and uplink (UL) maximum throughput and increased user connectivity. On the other hand, the size and weight of NIB deploying unmanned aerial vehicle (UAV) is highly limited due to the UAV's battery lifetime and, for example, a commercial UAV-enabled NIB weighs 2 Kg and 3.37 Liter, which is one of the smallest NIBs in Figure 4.



(a) (b) (c)

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[1] For the readers who are further interested in the functionalities in 5G core, the definition of acronyms in this figure can be found in the 3GPP standard document [9].

Figure 4. Off-the-shelf NIB products in the market: (a) Volume vs. weight on the left, (b) Number of connected users vs. size in the middle, and (c) Power consumption vs. size on the right. Source: K. Park

These NIBs are leveraging several technologies, which are typically used in three targeted scenarios in which a NIB communicate with. First, a NIB provides the wireless connectivity to the mobile users. A NIB is usually plugging multiple radio interfaces such as WiFi, 3G, 4G long term evolution (LTE) evolved node B (eNB), and 5G next generation node B (gNB) to support these technologies at the same time [11]. For public safety purpose, a NIB has utilized the mobile radio standard developed to meet the needs of traditional Professional Mobile Radio (PMR) user organizations such as first-aid operators, police, and firefighter, e.g., P25, TETRA, or TETRAPOL. Second, a NIB can connect the mobile users to any external data networks with backhaul links. The backhaul links that a NIB utilizes can be established by either a wired cable (Ethernet, fiber, or coaxial) or wireless technology (satellite or microwave). Wireless backhaul can give a NIB network a greater degree of freedom in mobility and flexibility while extra equipment such as satellite dish antenna should be equipped with a NIB. Third, multiple NIB can inter-operate with each other as well as other network components. A NIB may support the technologies regarding this interoperability with other network components for several reasons: 1) a single NIB cannot build a full-fledged network, and 2) operating with existing network infrastructure is the best option for networking. The roles of NIBs in a network can be dynamically and flexibly adapted according to the network environment [12]. For example, in a remote area, where one of the network components in a pre-existing network becomes missing, instead of the time and effort taken to reinstall the missing network component, NIB may be rapidly configured.

The NIB can leverage on mobile edge computing (MEC) technology which decentralizes services on the network edge to avoid the massive traffic connected by backhaul link to the central server [13]. MEC is a concept of cellular network architecture that allows the running of applications and processing of jobs in the edge cloud computing servers, which are close to the end users. MEC can help to reduce network congestion and enhance the tolerance of network malfunctioning and overload by reducing the dependency in the core network. Moreover, the services are processed locally and the data flow to the core network is reduced. The network transmission and processing delay remains low. Another important technological issue to be implemented in a NIB is to develop a user-friendly operating and management platform which interfaces with the network operators and to design based on self-organizing network principles in NIBs to allow autonomous decision-making for their network functioning [14]. The private NIB-based network might be managed by the non-professional network operators such as first-aid rescue team or firefighters. Therefore, self-organizing, self-reconfigurable, and eventually self-sustainable capability is a critical and important issue to increase the efficiency of NIB. This feature will leverage on the network flexibility of NIBs to quickly respond to the varying network environments.

In summary, a NIB realizes the network connectivity in an on-demand fashion and dynamically reconfigures the deployment of network functions according to the need of different types of network services. The network flexibility and mobility of NIBs enable the network operator to deploy and configure for various types of use cases on demand. We confirmed the advantages of NIBs in connectivity, e.g., network flexibility and low SWaP for remote areas such as cost-effectiveness for sparsely populated areas, multiple networking options for service provisioning and backhauling. In addition, the advantages of NIBs in connectivity, e.g., portability and reconfigurability can boost the efficiency of one-off health network services[2] using massive Internet-of-things (IoT) health devices. Therefore, we embodied the general concept of NIB in health services in remote areas.

3.2. Rural Connectivity

The United Nations (UN) sustainable development goals (SDGs) were agreed by world leaders to overcome global challenges and address the inequality on economics, education, health, etc. worldwide by 2030 [15]. The ICTs which link the globe together and equally are very important and indispensable to achieve the UN SDGs as shown in Figure 5.

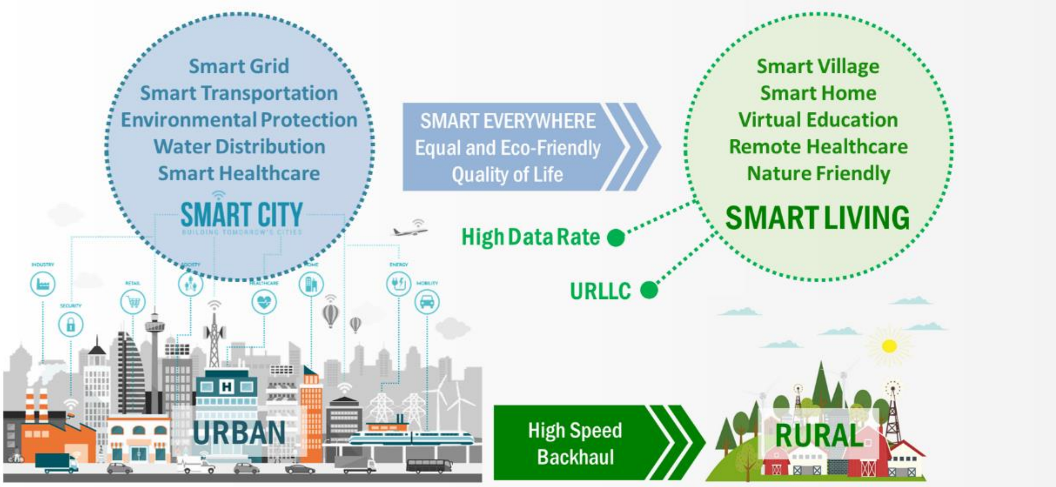

Figure 5. Rural connectivity and Role of ICTs - Overcoming digital divide. Source: K. Park

Unfortunately, almost 4 billion living in developing, rural, and/or remote areas are still hard to be connected or even “off-line” [16]. The lack of sufficient digital connectivity results in the weak development and growth in the economy. The poor economic conditions limit the investment of services in ICT causing insufficient connectivity. Hence, the rural and remote areas are likely to be trapped on this vicious cycle of digital divide.

The main barriers to this digital divide come from 1) low income, 2) low population density, 3) user capabilities, and 4) public infrastructure which make the implementation of ICT networks difficult [17], [18]. It is very challenging to deploy ICT networks in rural areas and under-developed countries due to several reasons. First, it is hard to build a successful business model for the Internet service provider [6]. Second, spatial sparsity and user density increase capital expenditure (CAPEX) of installing new access points or backhaul infrastructure [19]. Third, insufficient energy supply increases operating expenditure (OPEX) [20]. Fourth, there are few skillful technicians to maintain the network infrastructure in these region which also increases OPEX [21], [22]. Again, these challenges highlight the importance to build rural-customized network where it is cost-effective, mobile, off-grid compatible, and self-

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[2] We define the one-off health network service as the temporary access network, where the purpose is for the dissemination and collection of health information. For example, setting up the temporary testing sites and provision of mobile health service through the use of vehicles.

reconfigurable. From this perspective, we here note that NIB can be one of promising candidate networks for rural connectivity.

Table 1. Key connectivity factors and technologies for rural connectivity.

Connectivity	Potential Technology
Fronthaul Connectivity	Cellular networks
	Free space optics
	Satellite access
	WiFi/WiMAX/Multihop/Mesh networks
	Power line communications
	TV white space
	Spectrum sharing
	Community network
	Long Range (LoRa)
Backhaul Connectivity	Fiber optics
	Microwave
	Free space optics
	Aerial Platforms (HAPs, UAVs, Airships, and Balloons)
	Satellite
	Integrated access and backhaul
Power Grid Connectivity	On-grid
	Off-grid (Solar, wind turbine, and diesel generator)
	Hybrid grid

Source: E. Yaccoub et. Al [24]

From the perspective of rural connectivity, providing the broadband internet connection to rural areas has a higher priority than other use cases in 5G networks such as ultra-reliable and low latency communications and massive machine type communications [23]. Therefore, the studies on the rural connectivity concentrate on how to build fronthaul and backhaul links in rural area and optimizing affordable broadband internet service. In Table 1, key fronthaul and backhaul technologies under the consideration of power-grid are addressed, which the details of each technology can be found in the literature [25]-[27].

The people in rural areas experience low quality of healthcare due to the insufficient primary central hospitals, inefficient patient transfer information, and over-loaded out-patients. Telemedicine and remote consulting might work to improve the quality of healthcare in rural areas through WiMAX [28] and WiFi [29]. By taking advantage of wearables and health IoT, health information including electroencephalogram (EEG) and electrocardiogram (ECG) data and information is collected, transmitted to mobile phones via low energy Bluetooth, and stored in the cloud [30]-[32]. Means of transportation such as a motorcycle can be implemented with health sensors for monitoring purposes while collecting the health data as well as transferring them to the cloud server via WiFi/WiMAX [33]. This necessitates the embedding of the lightweight fronthaul/backhaul ICT unit such as NIB onto the vehicle. These are some preliminary studies towards supporting the innovative medical smart care expected in 5G such as remote surgery and diagnostics using haptic technology, robotics, and machine learning [34].

3.3. Short Packet Communications

Machine-type communication (MTC) is the key enabler of future autonomous systems. Massive amount of MTC users including health IoT sensors require low latency and ultra-reliable conditions. MTC traffic usually consist of short data packets which are delay-limited, highly reliable, and energy-efficient. Transmitters are often idle since MTC traffic is not required to send the data continuously but rather periodically. Traditionally, Shannon capacity formula is a fundamental performance metric to evaluate the channel capacity [35]. However, if the packet is short, Shannon capacity formula is no longer accurate since optimal coding in a traditional way is much longer than packet length. In the finite block-length communication, packet error probability is not asymptotically approaching zero and significantly related to the coding rate. An accurate approximation of packet error probability has been obtained [36]. The short packet communications (SPC) over block fading channels have been studied in some studies [37], [38]. Health IoT information which requires minimal delay and has short packet length fit well with the characteristics of MTC traffic mentioned above. It requires periodic sensing over multiple wearables, implants, and IoT on human body or wireless sensing through off-body monitoring units. The length of sensing data is very short, which is reliable and latency-limited. Therefore, the health IoT information in rural area should be considered in the analytical framework of SPC systems.

4. Methodology

4.1. Network and System modeling

Taking into consideration the advantages of NIB, it is important to consider how NIB can be used to support networking cases for post-COVID recovery. It can either work on a stand-alone basis or with other NIBs and incumbent network components to provision end-user services as well as backhauling through multiple air and wired interfaces. This research aims to study the use of NIB in post-COVID recovery to support several use cases that require on-demand and ubiquitous networking. As the foundation of the research, we focus on how to optimally deploy and reconfigure NIBs for health services in rural area. The traditional planning methods for fixed ground infrastructure are not cost-effective for sparsely populated rural area. In rural areas, the user density is sparsely clustered and far from each other, i.e., the distance between villages is far away and the user density in a village is low and concentrated in the center of the village [39].

We consider the following network scenario in Figure 3 where multiple health IoT devices are distributed with a certain point process on 2-dimensional space. The locations and centers of villages can be geometrically modeled, and the user density of each village is estimated based on the census. Multiple N NIBs support two type of data in a network, e.g., short packet data from health IoT devices and broadband data from mobile users. We define the location of NIBs as $\boldsymbol{q_n} \in R^{\mathbb{2}}$ for $n = 1,2, \dots , N$.

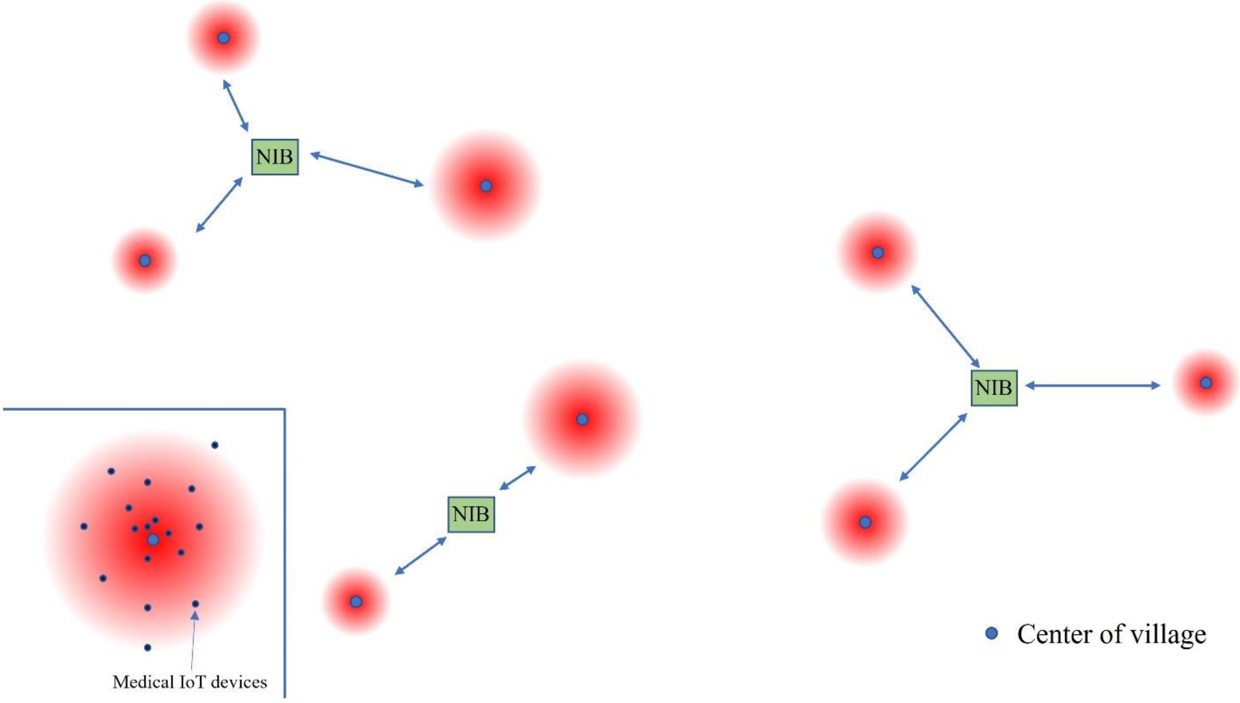
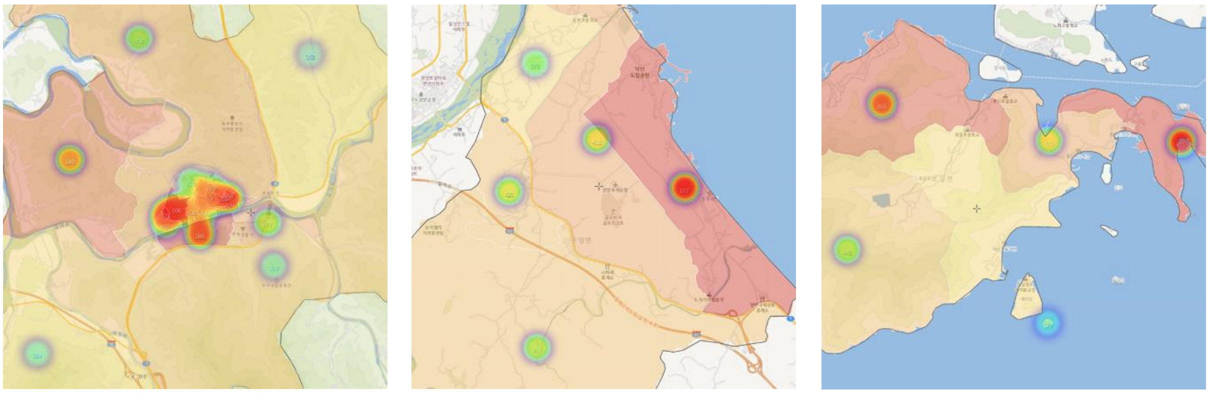


Figure 6. Considered network model in multi-NIB network for sparsely populated clustered area. Source: K. Park

We will face several new challenges. First, deploying more NIBs in the same frequency band may give a larger coverage and better channel quality while causing stronger co-channel interference to the adjacent NIBs. Thus, we need to determine how many NIBs should be deployed. Second, the user distribution in the area to be covered is disjointed and irregular. Thus, we carefully estimate the performance metric that each NIB can provide at one position. Finally, NIB is capable of supporting multiple networks but users in different networks will not overlap. This means that the NIB can support low-rate massive IoT network while serving wide broadband service. Thus, the resource allocation and position of NIB needs to be jointly considered for all networks. The conditions that we take into consideration in our considered model are in the following sections.

4.1.1. User Distribution and Density

The end users in rural areas are sparsely located over a wide area and it is not accurate to model the network with the traditional method used in a conventional cellular network. The network topology is likely to be irregular and therefore the user distribution should be modeled by reflecting the geometrically statistical distribution of real user distribution. Then, we can simplify to model the network with multiple user clusters with statistical distribution and user density. Figure 7 shows three typical user distribution patterns in rural areas where the users are located in rural, coastal, and island area, which can be obtained from the national governmental website on geographical statistics information.



(a) (b)

(c)

Figure 7. Geographic representation of user distribution in three rural areas in South Korea: (a) rural example on the left, (b) coastal example in the middle, and (c) island example on the right. *Source: Statistical Geographic Information Services (SGIS) [40]*

Two kinds of representation regarding user density and distribution can be observed: 1) the fully colored segmented areas (the more red-colored, indicates greater the population), 2) the heat map in segmented areas (the more red-colored thermo graphic, indicates greater the population). In the first example of rural area, we can confirm that multiple user clusters with lower population surround the dense user cluster which means it is a town center. Second, the coastal scenario shows that the dense user cluster is located at the coast and the less populated user clusters are located around it. It seems to be asymmetric scenario. In the third example of island scenario, depending on the location of sea ports, multiple dense user clusters are located at the coast, while less-populated user clusters are located between dense user clusters. Depending on the geographical information of environment where we try to implement a NIB-based network, the correct network profiles with user clusters and density can be obtained.

We assume that, in the region of interest, K clusters of users exist like small and scattered villages in rural area. The clusters for IoT devices and mobile users are assumed to be identical. The center of user distribution in each cluster is deterministic based on geometric information from a location-based system which is defined as $\boldsymbol{\mu}_k^{\mathrm{x}} \in R^{2}$ for $k = 1,2,\dots,K$ and x ∈ {iot,bb}. As the heat map has shown in Figure 7, user distribution for each cluster is approximately modeled as 2-dimensional Gaussian distribution is given by ElSawy et. al. [41]

$$f_k^{\mathrm{x}}(\boldsymbol{x}) = \frac{1}{2\pi\sigma_{k,\mathrm{x}}^2}\exp\left(-\frac{|\boldsymbol{x}-\boldsymbol{\mu}_k^{\mathrm{x}}|^2}{2\sigma_{k,\mathrm{x}}^2}\right),\ \ \forall k,\ \mathrm{x} \in \{\text{iot,bb}\} \tag{1}$$

where $\sigma_{k,\mathrm{x}}^2$ is the variance of the k th user cluster in one dimension which characterizes the strength of dispersion for user distribution for IoT devices or mobile users in a cluster. The dispersion of IoT devices and mobile users in a cluster can be different from each other. Or, by approximating to fully colored user distribution model in Figure 7, we can consider a disc with uniform distribution which is given by

$$f_k^{\mathrm{x}}(x) = \frac{1}{\pi R_{k,\mathrm{x}}^2},\ |\boldsymbol{x}-\boldsymbol{\mu}_k^{\mathrm{x}}| \le R_{k,\mathrm{x}},\ \ \forall k \tag{2}$$

where $R_{k,\mathrm{x}}$ is the radius of a cluster disc which is a measure of user dispersion. User density of each village is different from each other and, typically, the villages located at the center which is surrounded by other villages can be modeled as higher user density villages known as central towns administrating other villages. In each village, the traffic load for medical information and broadband service cannot be reflected by the same user density. Therefore, we define the user densities for IoT devices and mobile broadband users as ρ_k^{iot} and ρ_k^{bb} $\left[\text{m}^{-2}\right]$ for $k = 1,2,\dots,K$.

4.1.2. Information for Health Services

We assume that the information in health services should be very reliable and delay-limited, which requires very low error probability and latency. On the other hand, most of the information collection from health IoT devices might not be data-intensive and therefore requires short length of packets which might be much shorter than packets in a conventional broadband cellular network [42]. In the health services for massive health IoT devices, we assume short packet communications (SPC) which characterizes the throughput based on the block error rate (BLER), and latency for a given data block size in a SPC system. Assuming that each block is of length l_n data symbols carrying B_n information bits, the coding rate in bits per channel uses of the link between the nth NIB and an IoT device ($link_n$) is $r_n = B_n/l_n$ for $n = 1,2,\dots,N$. The delay of the IoT information can be adjusted by the block length l_n. For sufficiently large block length l_n ($l_n > 100$), the BLER of $link_n$ for quasi-static fading channel with coding rate r_n can be tightly approximated as stated in the article by Hu et. al. [42]

$$\overline{\varepsilon_n}(x) = E\left[Q\left(\frac{\mathcal{C}(\gamma_n) - r_n}{\sqrt{\mathcal{V}(\gamma_n)/l_n}}\right)\right], \tag{3}$$

where $Q(\cdot)$ denotes standard Q-function. γ_n is the received signal-to-noise ratio (SNR) of $link_n$ which is given by $\gamma_n = \frac{|h_n|^2 d_n^{-2}\beta_0}{\sigma_n^2}$, where h_n is the Rayleigh fading coefficient in block fading channel, $d_n = |\boldsymbol{x} - \boldsymbol{q}_n|$ is the communication distance of $link_n$, β_0 is the received power at the reference distance, and σ_n^2 is the variance of additive white Gaussian noise (AWGN) at the receiver. $\mathcal{C}(\gamma_n) = \log_2(1+\gamma_n)$ is the Shannon capacity function with respect to SNR and $\mathcal{V}(\gamma_n) = \left(1 - \frac{1}{(1+\gamma_n)^2}\right)(\log_2 e)^2$ is the channel dispersion of a complex Gaussian channel. The instantaneous BLER in a form of Q-function can be linearly approximated as

$$Q\left(\frac{\mathcal{C}(\gamma_n) - r_n}{\sqrt{\mathcal{V}(\gamma_n)/l_n}}\right) \approx \begin{cases} 1, & \gamma_n \le \gamma_n^{\text{low}} \\ \frac{1}{2} - v_n\sqrt{l_n}(\gamma_n - \theta_n), & \gamma_n^{\text{low}} < \gamma_n < \gamma_n^{\text{high}} \\ 0, & \gamma_n \ge \gamma_n^{\text{high}} \end{cases} \tag{4}$$

where $v_n = \frac{1}{\sqrt{2\pi(2^{2r_n}-1)}}$, $\theta_n = 2^{r_n} - 1$, $\gamma_n^{\text{low}} = \theta_n - \frac{1}{2v_n\sqrt{l_n}}$, and $\gamma_n^{\text{high}} = \theta_n + \frac{1}{2v_n\sqrt{l_n}}$. Substituting (4) into (3), the BLER of $link_n$ can be calculated as

$$\begin{aligned} \overline{\varepsilon_n}(\boldsymbol{x}) &= v_n\sqrt{l_n}\int_{\gamma_n^{\text{low}}}^{\gamma_n^{\text{high}}} F_{\gamma_n}(\gamma)\,d\gamma \\ &= 1 + v_{n\sqrt{l_n}\overline{\gamma_n}}\left(e^{-\frac{\gamma_n^{\text{high}}}{\overline{\gamma_n}}} - e^{-\frac{\gamma_n^{\text{low}}}{\overline{\gamma_n}}}\right) \end{aligned}$$

$$= v_n\sqrt{l_n}\sum_{m=1}^{\infty}\frac{(-1)^{m+1}\left(\left(\gamma_n^{\text{high}}\right)^{m+1}-\left(\gamma_n^{\text{low}}\right)^{m+1}\right)}{(m+1)!\,\overline{\gamma_n^m}} \tag{5}$$

where $F_{\gamma_n}(\gamma)$ is the cumulative distribution function (CDF) of γ_n which is given by $F_{\gamma_n}(\gamma) = 1 - e^{-\frac{\gamma}{\overline{\gamma_n}}}$ with $\overline{\gamma_n} = \frac{d_n^{-2}\beta_0}{\sigma_n^2}$. The BLER over user distribution in the kth cluster can be computed as

$$\overline{\varepsilon_{n,k}} = \int_{\boldsymbol{x}} \overline{\varepsilon_n}(\boldsymbol{x}) f_k^{\text{iot}}(\boldsymbol{x})\, d\boldsymbol{x}$$

$$= v_n\sqrt{l_n}\sum_{m=1}^{\infty}\frac{(-1)^{m+1}\left(\left(\gamma_n^{\text{high}}\right)^{m+1}-\left(\gamma_n^{\text{low}}\right)^{m+1}\right)}{(m+1)!}\left(\frac{\sigma_n^2}{\beta_0}\right)^m \sigma_{k,\text{iot}}^{2m}\mathcal{M}_m\left(2, |\boldsymbol{q}_n - \boldsymbol{\mu}_k^{\text{iot}}|^2\right) \tag{6}$$

where $\mathcal{M}_m(k,\lambda)$ is the mth moment of non-central chi-squared distribution which is given by

$$\mathcal{M}_m(k,\lambda) = 2^{m-1}(m-1)!\,(k+m\lambda) + \sum_{j=1}^{m-1}\frac{(m-1)!\,2^{j-1}}{(m-j)!}(k+j\lambda)\mu'_{m-j}\,. \tag{7}$$

The end-to-end (E2E) latency is characterized by average processing delay and transmission delay given by $\tau_n = l_n + \mathcal{L}(l_n)$, where $\mathcal{L}(l_n) = c_d l_n$ with the decoding processing delay factor c_d [43]. As a result, the E2E spectral efficiency from health IoT devices in the kth cluster to the nth NIB in SPC systems can be represented as

$$\overline{\eta_{n,k}^{\text{iot}}} = \frac{B_n\left(1-\overline{\varepsilon_{n,k}}\right)}{\tau_n} \quad \text{[bps/Hz]}. \tag{8}$$

The spectral efficiency based on Eq. (6) is too complex to optimize and we instead consider the lower bound of spectral efficiency by considering the first term $m = 1$ in Eq. (5), which is given by

$$\overline{\eta_{n,k}^{\text{iot}}} \geq \overline{\eta_{n,k}^{\text{iot,LB}}} = \frac{B_n\left(1-\frac{\theta_n}{\overline{\gamma_0}}\left(2\sigma_{k,\text{iot}}^2 + |\boldsymbol{q}_n - \boldsymbol{\mu}_k^{\text{iot}}|^2\right)\right)}{\tau_n} \quad \text{[bps/Hz]} \tag{9}$$

where $\overline{\gamma_0} = \frac{\beta_0}{\sigma_n^2}$ denotes the reference SNR at the reference distance. Eq. (9) gives us some insight on the spectral efficiency: i) if the user distribution becomes broader with increasing $\sigma_{k,\text{iot}}^2$, the spectral efficiency decreases, ii) if the NIB becomes far away from a user cluster, it also decreases the spectral efficiency, and iii) when the latency τ_n is limited, the spectral efficiency is the concave function with respect to the coding rate r_n and thus the optimal coding rate exists.

Here we note that each NIB in our multi-NIB network shares the bandwidth allocated to the user clusters in the SPC systems which can be expressed as W_n^{iot} for $n = 1,2,\ldots,N$.

4.1.3. Broadband Service

We note that the information for wide broadband service can be achieved by information-theoretic approach under the assumption that the packet length is infinite and the latency is tolerant. The spectral efficiency of mobile broadband data is evaluated by Shannon capacity which is given by

$$\overline{\eta_n}(\boldsymbol{x}) = E[\log_2(1+\Upsilon_n)] \tag{10}$$

where $\Upsilon_n = \frac{|g_n|^2 d_n^{-2}\beta_0}{\sigma_n^2}$ is the received SNR of the $link_n$ with the block fading coefficient g_n in the broadband channel. The spectral efficiency over user distribution in the kth cluster can be computed as

$$\overline{\eta_{n,k}^{\mathrm{bb}}} = \int_{\boldsymbol{x}} \overline{\eta_n}(\boldsymbol{x}) f_k^{\mathrm{bb}}(\boldsymbol{x}) d\boldsymbol{x} \tag{11}$$

Again, the logarithmic function is cumbersome to obtain the closed form results on (10) and (11) and therefore, we consider lower bound of Shannon capacity formula, i.e., $\log(1+x) \geq \log x$, and Jensen inequality to obtain the lower bound of spectral efficiency which is given by

$$\begin{aligned} \overline{\eta_{n,k}^{\mathrm{bb}}} &> \int_{\boldsymbol{x}} E[\log_2(\Upsilon_n)]\, f_k^{\mathrm{bb}}(\boldsymbol{x}) d\boldsymbol{x} \\ &> \mathrm{C_n} - \delta_{\mathrm{k}}(\boldsymbol{q}_{\mathrm{n}}) = \overline{\eta_{\mathrm{n,k}}^{\mathrm{bb,LB}}} \end{aligned} \tag{12}$$

where we define $C_n = \log_2 \overline{\gamma_0} + E[\log_2(|g_n|^2)]$ and

$$\begin{aligned} \delta_k(\boldsymbol{q}_n) &= \log_2\left(\int_{\boldsymbol{x}} \frac{|\boldsymbol{x}-\boldsymbol{q}_n|^2}{2\pi\sigma_{k,\mathrm{bb}}^2} \exp\left(-\frac{|\boldsymbol{x}-\boldsymbol{\mu}_k^{\mathrm{bb}}|^2}{2\sigma_{k,\mathrm{bb}}^2}\right) d\boldsymbol{x}\right) \\ &= \log_2\left(2\sigma_{\mathrm{k,bb}}^2 + |\boldsymbol{q}_n - \boldsymbol{\mu}_k^{\mathrm{bb}}|^2\right). \end{aligned} \tag{13}$$

We note that the lower bound is tightly bounded in the moderate and high SNR regime. Similarly, we assume that the user clusters are allocated to the bandwidth associated with NIB, which is given by W_n^{bb} for $n = 1,2,\ldots,N$.

4.1.4. User Cluster Association

We assume that all the clusters of IoT devices and mobile users are associated with at least one of the NIBs in a network. Defining a binary variable for association between the nth NIB and the kth cluster as $\alpha_{n,k}^{\mathrm{x}}$ for x ∈ {iot,bb}, we formulate the association constraint as

$$0 \leq \alpha_{n,k}^{\mathrm{x}} \leq 1 \tag{14}$$

and each user cluster can be connected to NIBs but his maximum association cannot exceed one for preventing the best user cluster from monopolizing all the NIBs, which is given by

$$\sum_{n=1}^{N} \alpha_{n,k}^{\mathrm{x}} \leq 1, \ \ \forall k, x. \tag{15}$$

4.2. Further Discussion in Network Model

4.2.1. Backhaul

NIB can be connected to a data server wirelessly and the backhaul capacity limits the performance of NIBs. Therefore, total throughput that each NIB communicates with the IoT devices and mobile broadband users is limited by the backhaul capacity. We assume that a local data server connected to a central data server is located at the biggest village with the highest user density. The wireless backhaul capacity can be estimated based on the locations of NIB. Here, we assume that the wireless backhaul capacity of each NIB is much higher than the overall E2E throughput mentioned above.

4.2.2. Mobile Edge Computing

Optionally, in order to enhance the throughput due to the limited backhaul capacity, we introduce the MEC in NIBs to process the amount of data traffic for either health IoT service or broadband services [8]. Now, we assume the ideal backhaul and the latency is controlled by the block length. Therefore, we will take into consideration MEC for future study.

4.3. Problem Formulation

The objective is to find the optimal deployment of NIBs maximizing the total network throughput that multiple NIBs are receiving from multiple medical IoT devices in SPC systems and from mobile broadband users in cellular systems. In order to guarantee the mandated amount of health information, we calculate the average amount of information from health IoT devices in a network that is always above the certain threshold. The optimal deployment locations of NIBs are varying over the ratio of spectrum utilization between massive health IoT communications and broadband services, upper limit of end-to-end delay and packet size in a SPC system for massive health IoT communication. Moreover, network association among villages and NIBs will be jointly optimized. Then, we can formulate the problem to maximize the weighted sum of throughput in our proposed system model with respect to the NIB locations, $Q = \{q_n, \forall n\}$, user association, $\alpha = \{\alpha^{\mathrm{x}}_{k,n}, \forall k, n, \mathrm{x}\}$, and coding rate, $r = \{r_n, \forall n\}$ as follows.

$$(\mathcal{P}_{\mathrm{o}}) \quad \max_{\boldsymbol{Q},\boldsymbol{\alpha},\boldsymbol{r}} \quad \sum_{n=1}^{N}\sum_{k=1}^{K} \alpha^{\mathrm{iot}}_{n,k}\omega^{\mathrm{iot}}_{k}W^{\mathrm{iot}}_{n}\overline{\eta^{\mathrm{iot}}_{n,k}} + \alpha^{\mathrm{bb}}_{n,k}\omega^{\mathrm{bb}}_{k}W^{\mathrm{bb}}_{n}\overline{\eta^{\mathrm{bb}}_{n,k}} \tag{16.1}$$

$$\mathrm{s.t.} \quad (14), (15) \tag{16.2}$$

$$\sum_{n=1}^{N} \alpha^{\mathrm{iot}}_{n,k} W^{\mathrm{iot}}_{n}\overline{\eta^{\mathrm{iot}}_{n,k}} \geq \omega^{\mathrm{iot}}_{k}R_{\mathrm{th}}, \quad \forall k \tag{16.3}$$

$$\frac{(1+c_d)l_n}{W^{\mathrm{iot}}_{n}} \leq \tau_{\mathrm{th}}, \quad \forall n \tag{16.4}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{N} \alpha^{\mathrm{iot}}_{n,k} W^{\mathrm{iot}}_{n} + \alpha^{\mathrm{bb}}_{n,k}W^{\mathrm{bb}}_{n} = W_{\mathrm{tot}}. \tag{16.5}$$

where $\omega^{\mathrm{x}}_{k} = \frac{\rho^{\mathrm{x}}_{k}}{\sum_{k'=1}^{K}\rho^{\mathrm{x}}_{k'}}$ is the weight indicating the ratio of users among clusters supported by NIBs and R_{th} and τ_{th} is the threshold of threshold and latency. Eq. (16.3) is the per-cluster minimum rate constraint, Eq. (16.4) is per-NIB maximum latency constraint of IoT information, and Eq. (16.5) is the total bandwidth constraints in the multi-NIB network.

Due to the difficulty of original problem in Eq. (16), we maximize the lower bound of throughput using Eq. (9) and Eq. (12), which is formulated as

$$(\mathcal{P}_{1}) \quad \max_{\boldsymbol{Q},\boldsymbol{\alpha},\boldsymbol{r}} \quad \sum_{n=1}^{N}\sum_{k=1}^{K} \alpha^{\mathrm{iot}}_{n,k}\omega^{\mathrm{iot}}_{k}W^{\mathrm{iot}}_{n}\left(\frac{r_n\left(1-\frac{2^{r_n}-1}{\bar{\gamma}_0}\left(2\sigma^2_{k,\mathrm{iot}}+|\boldsymbol{q}_n-\boldsymbol{\mu}^{\mathrm{iot}}_{k}|^2\right)\right)}{1+c_d}\right)$$

$$+\alpha^{\mathrm{bb}}_{n,k}\omega^{\mathrm{bb}}_{k}W^{\mathrm{bb}}_{n}\left(C_n - \log_2\left(2\sigma^2_{k,\mathrm{bb}}+|\boldsymbol{q}_n-\boldsymbol{\mu}^{\mathrm{bb}}_{k}|^2\right)\right) \tag{17.1}$$

$$\mathrm{s.t.} \quad (14), (15) \tag{17.2}$$

$$\sum_{n=1}^{N} \alpha_{n,k}^{\text{iot}} W_n^{\text{iot}} \left(\frac{r_n \left(1 - \frac{2^{r_n} - 1}{\bar{\gamma}_0} \left(2\sigma_{k,\text{iot}}^2 + |\boldsymbol{q}_n - \boldsymbol{\mu}_k^{\text{iot}}|^2 \right) \right)}{1 + c_d} \right) \geq \omega_k^{\text{iot}} R_{\text{th}}, \ \ \forall k \qquad (17.3)$$

$$\frac{(1 + c_d) l_n}{W_n^{\text{iot}}} \leq \tau_{\text{th}}, \ \ \forall n \qquad (17.4)$$

$$\sum_{n=1}^{N} \sum_{k=1}^{N} \alpha_{n,k}^{\text{iot}} W_n^{\text{iot}} + \alpha_{n,k}^{\text{bb}} W_n^{\text{bb}} = W_{\text{tot}}. \qquad (17.5)$$

Here, we note that the considered optimization problem mentioned above is still difficult to obtain the optimal value due to the non-convexity of objective function in Eq. (17.1) and the minimum rate constraint in Eq. (17.3).

4.4. Solutions

Then, the overall optimization problem formulated will not be typical in a conventional optimization framework due to joint association, deployment position, and coding rate allocation which yield non-convexity. The optimal solution is hard to achieve and decomposing the original problem into sub-problem is a promising choice to obtain sub-optimal solution close to the optimal one [44]. Then, we can utilize the block coordinate descent (BCD) method by alternately optimizing the variables for another fixed variables at the local points in each iteration. Even though we use BDC method to decompose the original problem into sub-problems, some of sub-problems with respect to the position of NIBs $\boldsymbol{Q} = \{\boldsymbol{q_n}, \forall n\}$ and coding rate $\boldsymbol{\alpha} = \{\alpha_{k,n}^{\text{x}}, \forall k, n, \text{x}\}$ are still non-convex optimization problems. In order to overcome non-convexity of sub-problems, we utilize successive convex approximation (SCA) method by using the first-order and exponential lower bounds of non-convex functions. Conventional linear programming will be solved for optimizing $\boldsymbol{\alpha} = \{\alpha_{k,n}^{\text{x}}, \forall k, n, \text{x}\}$ for user cluster association problem. Each sub-problem in a convex optimization form can be solved by the convex optimization solver in a computer software such as CVX in Matlab. We now describe the optimization techniques used in our optimization problem and provide the overall proposed algorithm.

4.4.1. Block Coordinate Descent Method

BCD algorithm is an iterative optimization technique which successively minimizes the objective functions along one coordinate while fixing the local values at the other coordinates. It guarantees to converge to the local stationary point by iteratively solving the optimization regarding one coordinate for other coordinates being held fixed since the objective function is monotonically increasing after each iteration, i.e., $f(x_1, x_2, \ldots, x_k) \leq \max_{x_1} f\,(x_1; x_2, \ldots, x_k) \leq f(x_1^*, x_2, \ldots, x_k) \leq \max_{x_2} f\,(x_2; x_1^*, x_3, \ldots, x_k) \leq f(x_1^*, x_2^*, \ldots, x_k) \leq \cdots \leq f(x_1^*, x_2^*, \ldots, x_k^*)$ when $f(x_1, x_2, \ldots, x_k)$ is the concave function and x_j^* is the optimal value of single coordinate optimization with respect to the jth variable. Figure 8 shows the example of graphical representation of BCD procedure in 2-D coordinate to minimize the convex objective function $f(x, y)$.

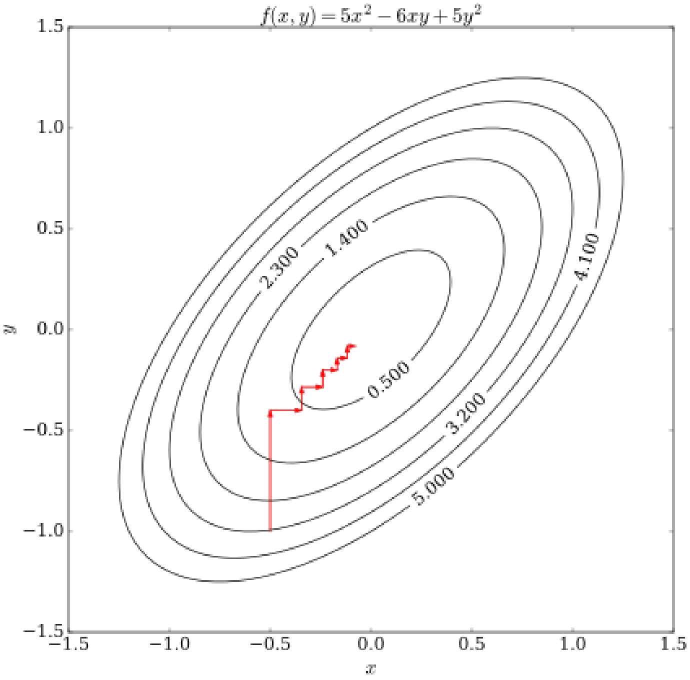


Figure 8. Example of 2-D block coordinate descent algorithm. Source: Wikipedia

4.4.2. Successive Convex Approximation

Here, we are facing non-convexity in the problem and a powerful but simple technique to replace the original nonconvex functions with appropriate surrogate functions, which is called successive convex approximation (SCA). At local point of original nonconvex function, the proxy of the nonconvex function can upper or lower-bound the original function. The optimization problem is successively optimized with surrogate functions at local values and converged to local stationary points. We show in Figure 9 the example of SCA techniques applied to our optimization problem with respect to coding rate. The original function $f(x)$ is the non-convex function and $f(x|x_k)$ is the concave surrogate function at local value x_k. We easily observe that $f(x)$ is lower-bounded by $f(x|x_k)$ at any given value x_k. Moreover, the objective value to maximize $f(x)$ is reaching the optimal value by successively optimizing the surrogate functions which satisfy $f(x|x_k) \leq \max_x f(x|x_k) \leq f(x_{k+1}) \leq \max_x f(x|x_{k+1}) \leq f(x_{k+2})$, where $x_{k+1} = arg \max_x f(x|x_k)$ and $x_{k+2} = arg \max_x f(x|x_{k+1})$. The convergence of SCA algorithm to local stationary point is guaranteed. Even though we apply SCA technique into BCD algorithm, the convergence of local stationary point is satisfied, i.e., $f(x_1, x_2, \dots, x_k) \leq \max_{x_1} f\,(x_1; x_2, \dots, x_k | x_{1*}) \leq f(x_1^*, x_2, \dots, x_k) \leq \max_{x_2} f\,(x_2; x_1^*, x_3, \dots, x_k | x_{2*}) \leq f(x_1^*, x_2^*, \dots, x_k) \leq \cdots \leq f(x_1^*, x_2^*, \dots, x_k^*)$.

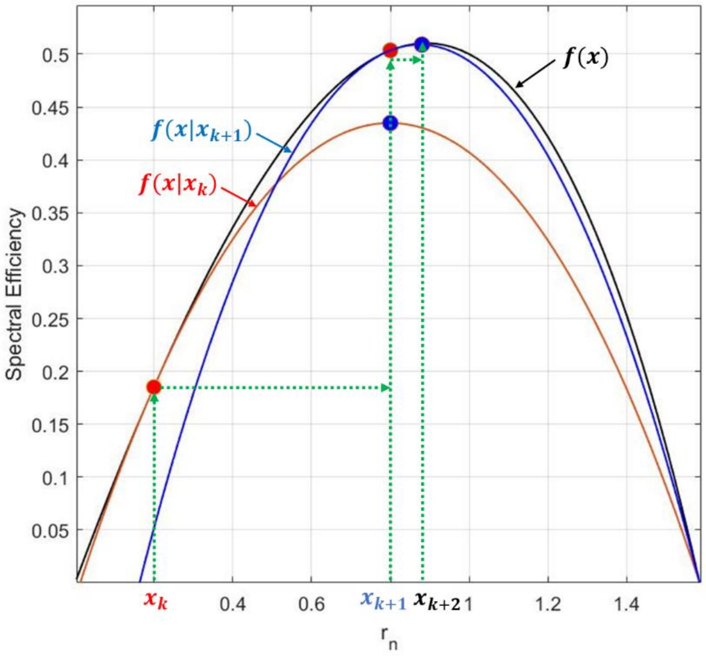


Figure 9. Example of successive convex approximation in coding rate optimization Source: K. Park

4.4.3. Proposed SCA-Based BCD Algorithm

```
Algorithm 1: Proposed Iterative Algorithm
Set $j := 0$;
Initialization: feasible starting points of $\boldsymbol{Q}_j$, $\boldsymbol{\alpha}_j$, and $\boldsymbol{r}_j$;
Repeat
    Solve SCA-based convex optimization to obtain optimal solution $\boldsymbol{r}^*$ for given $\boldsymbol{Q} \rightarrow \boldsymbol{Q}_j$, and $\boldsymbol{\alpha} \rightarrow \boldsymbol{\alpha}_j$;
    Solve SCA-based quadrature-constrained quadratic programming to obtain optimal solution $\boldsymbol{Q}^*$ for given $\boldsymbol{r} \rightarrow \boldsymbol{r}^*$ and $\boldsymbol{\alpha} \rightarrow \boldsymbol{\alpha}_j$;
    Solve linear programming to obtain optimal solution $\boldsymbol{\alpha}^*$ for given $\boldsymbol{r} \rightarrow \boldsymbol{r}^*$ and $\boldsymbol{Q} \rightarrow \boldsymbol{Q}^*$;
    Set $j := j + 1$;
    Update $\boldsymbol{Q_j} = \boldsymbol{Q}^*$, $\boldsymbol{r_j} = \boldsymbol{r}^*$ and $\boldsymbol{\alpha_j} = \boldsymbol{\alpha}^*$;
Until Convergence;
Output $\boldsymbol{Q_j}$, $\boldsymbol{r_j}$ and $\boldsymbol{\alpha_j}$.
```

The previous three sub-problems regarding the NIB locations, $\boldsymbol{Q} = \{\boldsymbol{q_n}, \forall n\}$, user association, $\boldsymbol{\alpha} = \{\alpha_{k,n}^{\mathrm{x}}, \forall k, n, \mathrm{x}\}$, and coding rate, $\boldsymbol{r} = \{r_n, \forall n\}$ will be iteratively and successively optimized to maximize the lower bound of system throughput. The pseudo code of the proposed algorithm is described at following.

5. Results

In this section, we present the examples of simulation results to verify the proposed algorithm and to interpret the feature of NIB deployments with health IoT devices and broadband services. For simulation set-up regarding system and channel parameters, we listed the parameter values in Table 2. We will present the simulation results under these values, unless stated otherwise. For setting the location of user clusters, we mimic a rural scenario where one town center with higher user density and high variance of user distribution in a cluster is located at the origin and four low density user clusters are located around town center. Reference minimum data rate threshold is set to 5 [Mbps], while each cluster should satisfy individual minimum data rate threshold $\omega_k^{\text{iot}} R_{\text{th}}$ ($\approx 0.714 \text{ and } 2.14$) [Mbps] at low density user clusters and a town center cluster. The latency of health IoT information is limited to 10 [ms].

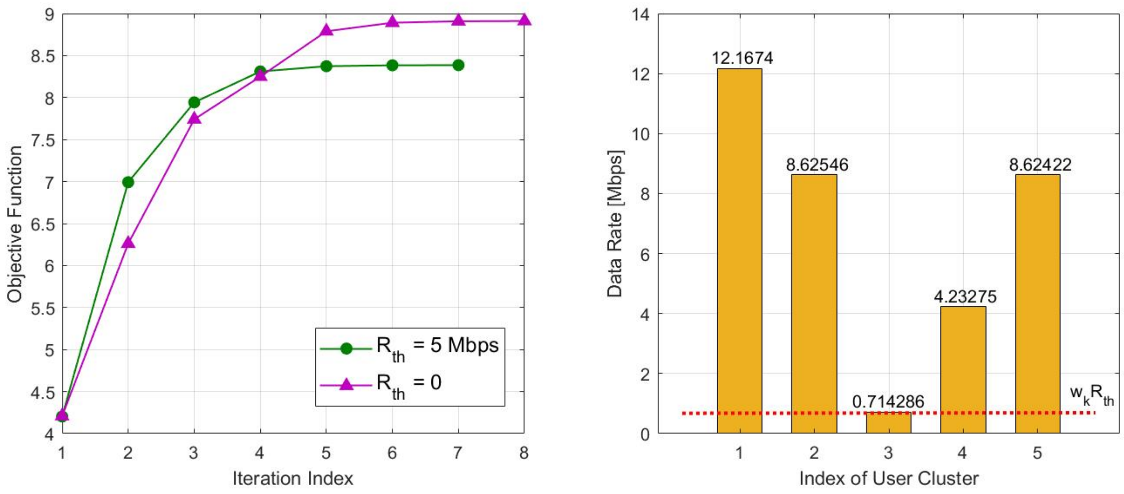
Table 2. Simulation Parameters.

Definition	Parameter value
Number of NIBs (N)	4
Number of IoT user clusters (K)	5
Number of BB user clusters (K)	5
Center location of IoT user cluster ($\boldsymbol{\mu}_k^{\text{iot}}$)	(0,0), (1.4,1.5), (1.5,-1.6), (-1.6,-1.4), (-1.5, 1.5) [km]
Center location of BB user cluster ($\boldsymbol{\mu}_k^{\text{bb}}$)	(0,0), (1.1,1.2), (1.3,-1.3), (-1.3,-1.1), (-1.2, 1.2) [km]
Radius of IoT user clusters ($R_{k,\text{iot}}$)	0.7, 1.5, 1.5, 1.5, 1.5 [km]
Radius of BB user clusters ($R_{k,\text{bb}}$)	0.63, 1.35, 1.35, 1.35, 1.35 [km]
Weight of IoT user density (ω_k^{iot})	3/7, 1/7, 1/7, 1/7, 1/7
Weight of BB user density (ω_k^{bb})	1/3, 1/6, 1/6, 1/6, 1/6
Variance of IoT user distribution ($\sigma_{k,\text{iot}}^2$)	0.0532, 0.244, 0.244, 0.244, 0.244 [km^2]
Variance of BB user distribution ($\sigma_{k,\text{bb}}^2$)	0.0431, 0.198, 0.198, 0.198, 0.198 [km^2]
Processing delay (c_d)	1.5
Latency limit (τ_{th})	10 [ms]
Number of bits in a block (B_n)	256 [bits]
Minimum rate threshold for IoT (R_{th})	5 [Mbps]
Total bandwidth (W_{tot})	40 [MHz]
Individual bandwidth for IoT and BB links	5 [MHz]
Path loss exponent (α)	2
Reference SNR (β_0)	80 [dB]

Source: K. Park

5.1. NIB-Based Network with Health IoT Service Only

We first present in Figures 10 and 11 the simulation results on NIB deployment when NIBs only serve the health IoT service. In the left of Figure 10, we show the convergence behavior of the proposed algorithm for two cases, e.g., with/without minimum data rate threshold. Here, we note that the algorithm is terminated under 0.1% increase of objective function. In both cases, the outer loop of the proposed algorithm ends after 7 or 8 iterations which are relatively reasonable numbers. In the right of Figure 10, the data rate achieved by each IoT cluster is presented. All the user clusters meet their minimum data rate threshold, while one of them is tightly satisfied with the requirement. This is because one of five NIBs serves two clusters at the same time but is placed closest to one of two clusters to the best of data rate maximization. The SPC throughput is convex with respect to the distance between NIB and cluster and it is the best to deploy the NIB as close as possible to the NIB. In order to get more fairness among clusters, we should carefully determine the minimum data rate threshold.

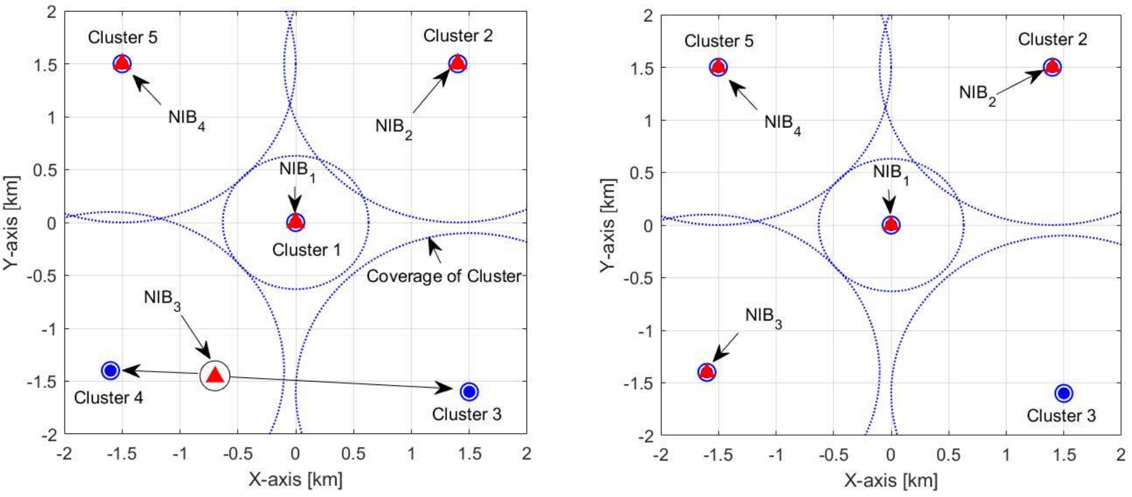


(a)

(b)

Figure 10. (a) Convergence behavior of proposed algorithm (on the left side) and (b) data rate comparison among user clusters (on the right side). Source: K. Park

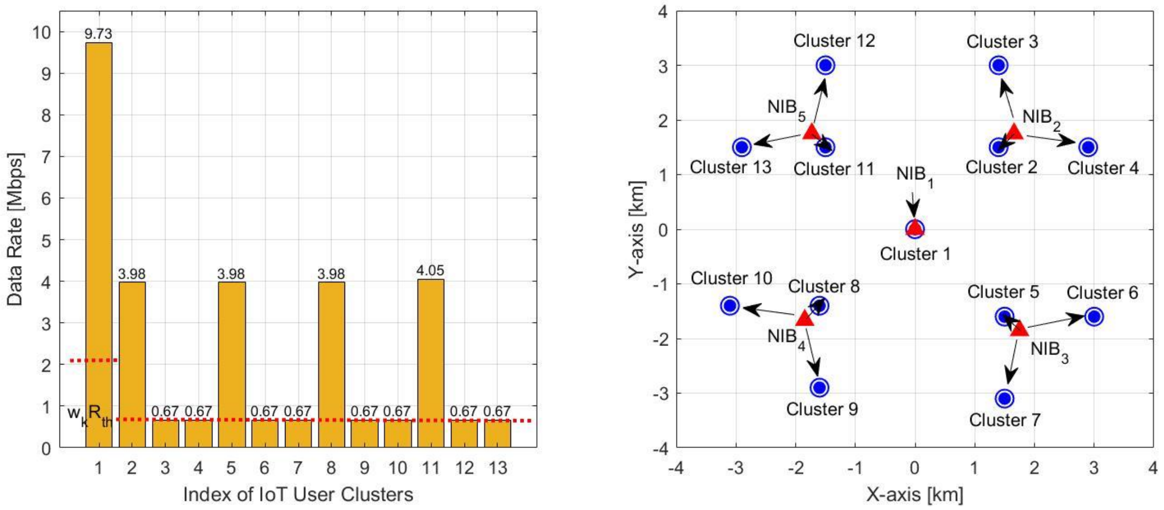
Figure 11 shows a comparison of network deployment map with/without minimum data rate threshold. We first see that the NIB deployment is highly dependent on minimum data rate threshold. As we mentioned above, the NIB tends to be placed on the location of cluster centers. The right diagram of Figure 11 shows that if there is no minimum rate threshold, all NIBs are located at the center of clusters in order to maximize the throughput. In this case, cluster 3 cannot be associated with any of the NIBs in a network because this cluster center is farthest away from other clusters. In comparison, one of the NIBs serves two clusters at the same time under minimum data rate threshold as shown in the left diagram of Figure 11. This NIB is located between two clusters (Cluster 3 and Cluster 4).



(a) (b)

Figure 11. (a) NIB deployment map over health IoT user clusters with minimum data rate constraints (on the left side) and (b) without constraint (on the right side). Source: K. Park

Figure 12 shows the simulation results in the scenario where more IoT user clusters are located outside of five clusters simulated in Figure 11. We set the number of NIBs to $N = 5$. We clearly see that all the clusters experience their data rate above the threshold. One NIB serves the town center cluster with maximized data throughput, while other NIBs serve three surrounding IoT user clusters. Again, due to the convexity of throughput with respect to the distance, each NIB endeavors to approach one of the IoT clusters as close as possible. For instance, NIBs are placed near the cluster close to the centroid of three clusters (e.g., Cluster 2, 5, 8, and 11).



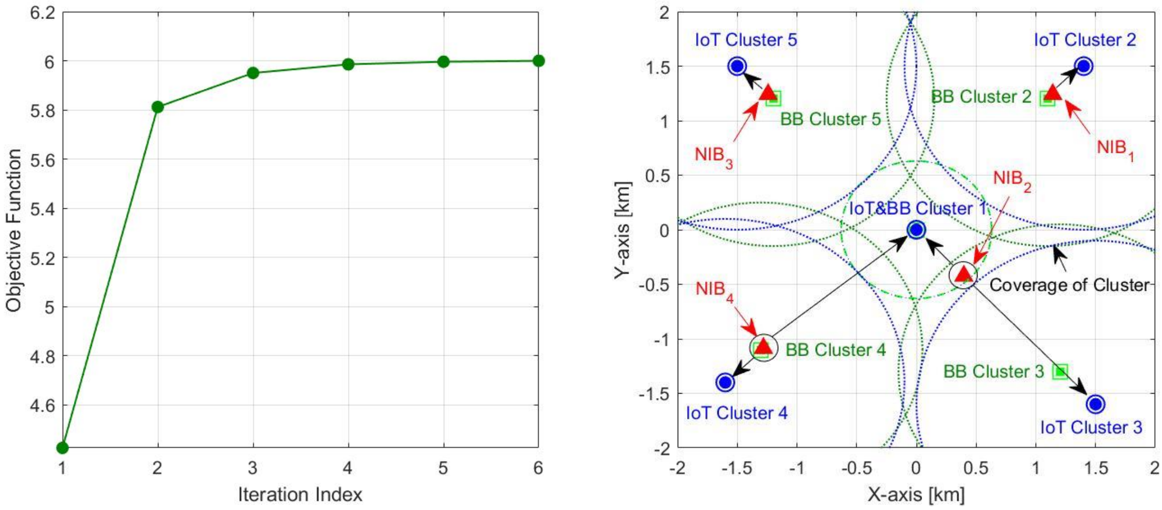
(a)

(b)

Figure 12. NIB deployment (on the left side) and (b) data rate comparison among clusters when K=13 (on the right side). Source: K. Park

5.2. NIB-Based Network with Health IoT and Broadband Services

Here, we present the simulation results on a NIB-based network where health IoT clusters and broadband service clusters exist in a network. First of all, we guarantee the convergence of the algorithm after 6 iterations as shown in the left diagram of Figure 13. We can see that the location and association of NIB are significantly affected by introducing broadband service. For a fixed location, the capacity of broadband service is always higher than the throughput of SPC systems under limited block-length for IoT information and NIBs tend to approach broadband user cluster as close as possible as shown in the right diagram of Figure 13. One NIB is no longer supporting the town center cluster right at the origin, this is unlike the situation in Figure 11. Now, the association mapping becomes more complicated through the relation of two NIBs and two clusters.

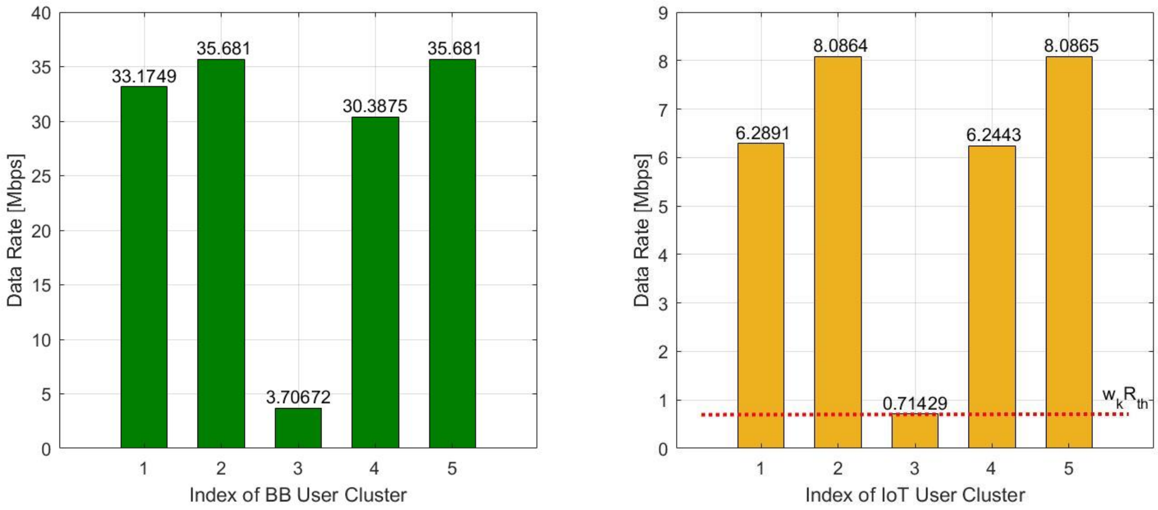


(a)

(b)

Figure 13. (a) Convergence behavior of proposed algorithm (on the left side) and (b) NIB deployment (on the right side). Source: K. Park

In Figure 14, we present the comparison among clusters in health IoT and broadband services. Again, the minimum data rate constraint for each IoT cluster is well satisfied. The throughput of IoT service is overall reduced compared with Figure 10 due to the increased distance between NIB and IoT user cluster. The data rate of Cluster 3 is much lower than other NIBs due to the farthest distance to the NIBs, while we can balance the throughput among clusters by carefully determining the minimum threshold or maximizing the minimum data rate among user clusters.



(a)

(b)

Figure 14. (a) Data rate comparison among health IoT clusters (on the left side) and (b) among broadband users (on the right side). Source: K. Park

6. Further Discussion

6.1. Backhaul

Backhaul is the connection from access points/base stations to the core network or to the Internet (or vice versa). Typically, a NIB would require backhaul in order to integrate to the network core, and we should take into consideration how to connect NIBs to the Internet or to an external data center. In rural areas or for mobile situations where NIBs are moving, wired connection through fiber optics may not be considered, but other alternative options such as satellite, wireless backhaul using microwave or FSO, and aerial relaying platforms can be considered [45]. As opposed to the fiber optic option which enables enough backhaul capacity in rural areas, the alternative options are highly restricted in their backhaul capacity depending on the operating conditions. Therefore, backhaul links with finite capacity can be applied to optimize the end-to-end network model entirely consisting of backhaul, fronthaul, and end-user provisioning links.

6.2. Age of Information

The information in low latency network including health IoT information in this research report is required to meet their link delays within a few milliseconds. However, packet congestion and backlogged jobs in MEC disturb the delay-constrained transmission of IoT information. Such sensing information includes the time status and the system needs to be aware of the state of this sensing data as timely as possible. Too many periodic update delivery of information might cause delayed updates that were congested and backlogged in the system. Instead, reducing the update rate can improve the timeliness of updates, while leading to monitoring too outdated information.

So, in order to evaluate the timeliness of data, the “age of information” (AoI) performance metric has been introduced [46]. The age of information at the current time is said to be zero, while increasing as time goes by. Minimizing AoI in wireless systems at the physical layer has been studied previously. The impact of physical interference, random access techniques, and scheduling has been considered. We can consider the problem of optimizing AoI in a NIB-based network in a decentralized way covering multi-NIB scenarios.

6.3. Mobile Edge Computing and Caching

NIBs can be suitable for providing mobile edge computing (MEC) supporting third-party services at the edge of mobile networks in order to reduce the traffic from the central cloud of mobile network and meet the requirements of delay-sensitive traffic [13]. Since NIBs are directly linked to the end users and allow MEC, they can be leveraged as edge cloud for offloading the traffic and provisioning real-time data services. MEC-enabled NIB network will face open challenges to resolve the network design allowing different use cases under the same NIBs such as re-factoring network functions [47] and re-designing software defined networking (SDN) and network function virtualization (NFV) based NIBs [48].

Traditionally, caching has been used and studied for several decades in computer systems and recently content caching has gained more attention in wireless networks to benefit from reduced networking cost and improved quality of end user service [49]. Caching management has become more and more complicated as the network size of Internet grows and data traffic increases significantly. Content delivery through caching in wireless network can help by reducing latency, alleviating network traffic congestion in bottleneck links (especially, massive MTC and IoT), and enhancing transmission efficiency over broadcast channels. The wireless transmission and scheduling schemes should be revisited at the existence of cache-enabled network. The energy-efficient NIB-based network can exploit caching techniques to alleviate the traffic congestion due to the finite backhaul capacity in rural regions but it will significantly change the design of transmission techniques.

6.4. Coverage Mapping

In our considered network model, we directly model the user distribution and density by extracting real statistical information regarding the geographical representation of user population in the designated area. This modeling approach is quite suitable when network condition is static. In some cases, a user cluster with a very large coverage area cannot be optimized well in the current form of optimization due to high packet error probability within this large space of coverage. Another suitable method is deterministic planning [50], which plans coverage for fixed areas such as circular packing algorithm through graph theory to cover a big circular area which is full of non-overlapping (or overlapping), small, and circled coverage by small base stations. The coverage mapping can be highly influenced by the shape of the coverage area [51]. In the future, we can combine the current coverage modeling with packing algorithm.

6.5. Transport Means

Once the number and positions of NIBs are determined, the next problem is how to transport these NIBs to the determined locations [8]. The NIB could be carried by a person in a backpack, a ground/aerial vehicle, or even aerial platforms. The mode of transport chosen will affect the deployment time based on their dynamics of mobility and environmental conditions. The best means of transport will be determined by comparing different means of transport using the multi-objective optimization to trade-off deployment time and cost. Combining the above two tasks, we will be able to optimally deploy the NIBs to provide on-demand and ubiquitous coverage in rural area.

7. Conclusions

In this research report, we investigated the feasibility of NIB-based network optimization to support smart health IoT services in rural areas. NIB is a powerful tool to build a pop-up network including service provisioning and network core in a box with efficient SWaP characteristics. If NIBs are operated under appropriate network and environmental conditions, they can be deployed for on-demand service, massive IoT service for health, and broadband service for education and economic development. The proposed mathematical modeling of two different communication systems for combining broadband service and IoT service enables readers to further extend to analyze and optimize the mobile and heterogeneous networks with latency constraint. The proposed algorithm for NIB deployment is a locally optimal solution to find the positions of NIB to be deployed in the specific network model under user distribution and clustering in sparsely populated areas. If the user distribution and clustering for the target remote areas are modelled precisely, the network operator can deploy and operate cost-effective NIB-based network rather than conventional optic fiber-based network.

The mathematical modeling of NIB-based network can guide the extension to the related works described further in the discussion to enhance the network efficiency for different purposes and use cases. In near future, we investigate the interoperability and coexistence of NIB-based network along with conventional cellular networks. In the current research, we assume a stand-alone NIB-based network to support mobile broadband service and IoT service. There is high probability that the mobile broadband users in the town center and nearby in the rural areas are supported by traditional cellular networks. We first considered the coexistence of two or more networks in the same spectrum bands which requires us to take into consideration spectrum sharing, spectrum allocation, or cognitive radio to efficiently utilize the frequency spectrum. The coexistence of two networks will make us re-define the NIB deployment problem since it will change the spectrum usage and SINR.

The NIB-based network is flexible and can be combined with different communication systems in the remote areas in order to reduce the deployment, operation, and maintenance cost. In the current research, we considered mobile broadband service and IoT service. Future areas of research can consider the situation where the NIB embeds the network functions for sensing, localization, and radar communications. In addition, researchers can also consider the NIB deployment that is more complex with multi-objective optimization which needs to balance different performance indicators such as throughput, delay, and localization accuracy. We plan to unify heterogeneous performance indicators by satisfaction indicator which quantifies the amount of performance indicators to the percentage of satisfaction within a finite range. The NIB deployment is optimized with respect to unified satisfaction indicator.

Finally, the user's distribution and clustering in sparsely populated areas can be varying over time. For example, the user distribution is more concentrated in the town center at daytime when the economic, social, and educational activities are performed during working hours. At nighttime, the density of user population in town center becomes lower and the users are distributed to other areas, which means that the user distribution and clustering models at night might not be the same as that at daytime. The NIB is a mobile solution to easily transport and change the positions. We plan to design the deployment scheduling scheme which changes the NIB deployment over time under different network user distribution and modeling. Based on the mean of transportation and re-configuration constraint, we optimize the deployment scheduling scheme which defines deployment positions of NIBs in multiple network models, re-deployment timing, and the path planning of transportation.

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