Wireless Connectivity for Remote and Arctic Areas – Food for Thought

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***Abstract*—This paper addresses various aspects that should be considered to improve the digital inclusion of remote, and specifically arctic areas, so that the geographical location would play a lesser role in equality among the people. To this end, technological challenges and potential solutions are discussed. They are further elaborated by three examples that have different architectural use case specific challenges for remote area wireless connectivity. The active role of society is seen pivotal alongside with the technological solutions to make this happen.**

Keywords—equality, broadband, backhaul, satellite, incentive

I. Introduction

Broadband Internet access and wireless mobile technologies have evolved at a tremendous pace as well as the coverage of these technologies among their potential users. However, the newest technological advances, such as 5G, are to a high degree predominantly enjoyed by the people living in the densely populated urban areas of the developed societies. Vast rural, remote, arctic, isolated, and oceanic territories are still largely uncovered. These regions have significantly lower user density but yet as urgent need to be within the reach of modern digital services. When all these remote areas with limited broadband connectivity are summed up we end up with millions of citizens that are minimally connected (if at all) to Internet and/or wireless mobile networks [1]. Even the seemingly highly advanced western countries have coverage gaps and intermittent connections in the rural broadband service as [2] demonstrates. Therefore, practical cost-efficient alternatives for connecting these severely overlooked areas are highly regarded.

The challenges of creating remote areas digital connectivity are multidimensional. The technological side might eventually be one of the easier challenges to be resolved, since the existing networking and wireless mobile technologies are capable enough to provide feasible solutions to remote areas. However, the main obstacle slowing down the progress seems to be the poor payoff from the commercial business perspective. Therefore, conventional mobile operators with their current business models do not see much incentive to invest on these last percentile regions. Thus, it is important that politicians, local governments and municipalities, take action to promote connectivity in remote areas and prevent the digital divide to expand any further.

This paper overviews the connectivity challenges in different kinds of remote districts from several angles as follows. Section II discusses common and specific challenges faced in various remote areas. Then, Section III points out that remote areas also have unique opportunities to offer. Section IV elaborates some key elements for establishing network connectivity. Exemplary network architecture and usage scenarios are investigated in Section V, and finally the concluding remarks are drawn in Section VI.

II. Challenges for Remote Areas Connectivity

A. Common Challenges for Remote Areas

Although it is easy to divide remote areas to several subcategories, it is equally easy to find a lot of commonalities in the majority of them. The most obvious similar feature is the sparse supporting infrastructure. The distance to the closest core network connection point can be very long. Typically, the capacity of the remote area network is far beyond its urban counterparts. Due to the sparsity of the backbone the vulnerability to outages is high.

Low-income is also a common denominator to many rural and remote areas. This means that the cost of the connection for the end user cannot be too high to be viable. It also means that most business-driven options are not directly applicable, and thus require subvention from the public domain.

Sporadic access to energy grid is also a common fact in many places. It is then natural to favor devices that are self-sufficient in power creation. Large areas relatively near the equator are generally in favorable positions to utilize solar power. Another already widely applied technology is wind energy. Batteries should be applied as a backup and short-term storage devices to smoothen temporary outages and variations in energy production of network nodes relying on solar or wind power. Water power could also be an option, but its availability is restricted to geographical locations near rivers and seas.

B. Extra Challenges for Arctic Areas

Arctic areas form the kind of worst-case scenario for remote connectivity. In addition to the common challenges listed above, there are some specific location and weather induced obstacles to overcome. The further you go from the equator the more extreme are the seasons from each other and thereby, e.g., temperature and sunlight have huge variations depending on the time of the year. Even worse is the joint impact of these harsh conditions and dark periods. Cold temperatures, snow and ice together make running and maintaining the equipment harder and more expensive. Battery-driven appliances have dramatically shortened on-durations between charging times in the cold weather. Snow and ice are harmful to antennas and all other outdoors mechanical structures, causing additional signal attenuation and strain. Energy consumption tends to be at the peak in the cold months, e.g., due to heating, which is yet another complication and cost issue.

Since the lacking infrastructure in the Arctic is not restricted to communications, things get even more complicated. The lack of power grid is a reality in vast geographical areas. This means that sustainable autonomous power sources are needed. Already mentioned solar and wind power are the most obvious energy sources to be harnessed in these circumstances. Unfortunately, both of them have severe limitations in the Arctic. The first is because of the dark winter time when the sun is not visible at all near the ground level above the Arctic Circle. The latter does not have such a strong systematic seasonal variation, but suffers from the coldness, ice and snow. Therefore, if the energy needs to be available without outages throughout the year, multiple sources need to be combined or backed-up as a hybrid energy source. Practically, this means the usage of batteries and, e.g., diesel fuel generators, whose CO_2 footprint is not desirable in the pursuit of green energy.

Regarding satellite communications the arctic coverage is weak since, e.g., geostationary satellites do not reach polar regions. Lower orbit satellites also tend to have their coverage and active operation optimized to areas with the largest customer-base. Hence, customized orbits and/or satellite systems would be needed to serve the Arctic reasonably well.

III. Opportunities for Remote Areas Connectivity

The previous section painted a grim and almost desperate picture of the demanding circumstances in extreme remote areas. Luckily, there are also positive motives to go ahead. One of them is the abundance of (unused) spectrum in these areas. This is the turnside of the coin for the ultra-dense networks. In the densely urbanized cities, the need for more radio capacity pushes the development towards higher center frequencies where it is easier to find wide junks of spectrum. This is not the case in sparsely populated areas where the access and availability are much larger problems than capacity in the lower legacy bands. It is well-known that the coverage scales negatively down when increasing the carrier frequency. To maximize the coverage in remote regions it is useful to utilize as low center frequencies as possible. Flexible spectrum management and sharing concepts may easily be taken into use in remote areas where they are much simpler to handle than in urbanized areas. For example, TV broadcast frequencies offer one tangible option to be tackled (TV white spaces).

The climate change gradually reforms logistic route options in arctic waters. It can be foreseen that the opening of the Northeast Passage grants huge prospects for maritime cargo transport and access to natural resources, e.g., oil, in new areas. Especially, the interactions between China, Russia, and Europe could be boosted quite dramatically by this shortcut.

Since the traditional mobile network operators (MNOs) do not have a real incentive to invest on the sparsely populated areas, it opens room for new operator models. The local actors could run their own networks under a so-called micro operator model [3]. For example, remote villages, factories or farms may be highly motivated to build wireless connectivity if it is rewarding for their operation. This kind of new local operation models benefit from the liberal spectrum regulation. It should be easier to realize flexible spectrum policies in remote regions where the competition and spectrum occupancy is low.

IV. Technology Elements for Remote Areas Connectivity

Here we look at some key building blocks and technologies to be considered in the design of communication networks for remote regions.

A. Short-Range Local Access

For the clusters of population concentrated to a relatively small geographical area, e.g., in the small rural towns and villages (so-called hot spots), it is straightforward to utilize existing wireless technologies. So, in this regard there is not much difference whether the technology is applied in an urban or in a rural environment. For example, 3G, 4G and WiFi are currently widely available for wireless connectivity and 5G is about to follow shortly. The main difference between the cellular 3GPP standard and the IEEE standard radio technologies is that the former has generally better support to ubiquitous outdoors coverage and mobility while the latter suits better to more static indoor environments, e.g., homes. Frequency regulation is also different in the sense that mobile operators typically utilize dedicated and exclusively licensed bands and WiFi can be operated freely in unlicensed frequency bands. Indoor wireless broadband can also be implemented by the means of visible light communications (VLC) technology (Li-Fi). One of its main benefits is that is does not interfere with radio systems. These aforementioned state-of-the-art technologies are viable for places where the infrastructure is rich enough to allow their usage. They are then capable of providing high data rate and low latency wireless access connection locally.

B. Long-Range Backhauling

Since the distance is an issue with remote connectivity, the backhauling is one of the fundamental questions to be answered while designing the network architecture. Several terrestrial and satellite-based alternatives are available, all with their specific pros and cons. Land and sea cables form the backbone for long-range backhauling, but their presence in remote regions is very sporadic. Even if the sea cable would be nearby the connection may not. Terrestrial fiber/copper cable grids concentrate to a large extent to densely populated areas and villages around them. Very isolated spaces seldom have cable connectivity for backhauling and it may not be economically feasible to build such. Then, long-range microwave links may offer a solution for the backhaul. Their reach can be extended by chaining multiple relay links. This is illustrated in Fig. 1 where the access point AP uses the carrier frequency f_0 to serve nearby users, and four wireless relays R1-R4 are used for the backhaul and range extension at frequencies $f_1 - f_4$ in a half-duplex mode. Although relaying consumes radio and infrastructure resources and causes delay, the good point in sparsely populated areas is that there is plenty of bandwidth per user available, thus compensating for many negative effects. This allows also a flexible frequency reuse as illustrated in Fig. 1.

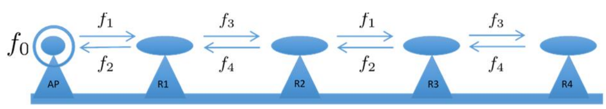

Fig. 1. Relay chain for backhauling.

For truly inaccessible locations, e.g., polar areas, satellite or high-altitude platforms are viable alternatives as they can cover huge areas at one shot in non-pervasive manner. Satellite systems are commonly classified based on the orbits and trajectories their individual satellites move around the earth. Geostationary (GEO) satellites reside above the equator at the distance of 35 786 km from the Earth surface. They have a wide coverage footprint but above 72 degrees north the service quality starts to decay fast and eventually leaves big parts of the Arctic without GEO satellite coverage. Low Earth orbit (LEO) satellites travel at 600 – 1500 km altitudes and medium orbit (MEO) satellites above that. Both LEO and MEO systems can have either global or partial coverage depending on the number of satellites and their orbit design. In addition, there are high elliptic orbit (HEO) satellites that are specifically targeted for the Arctic coverage. These have an elliptic orbit and they are close to the Earth just a part of time. Several plans aim at operational high throughput LEO satellite networks in near future. OneWeb [4] and Starlink [5] are concrete examples that include up to thousands of satellites in the orbit when ready. It remains to be seen if they will become serious alternatives for the remote area long-range backhaul.

Very long-range radio links are easiest to achieve at the lower end of frequencies, i.e., at high frequency (HF), very high frequency (VHF) and ultra high frequency (UHF) bands that respectively correspond to 3-30 MHz, 30-300 MHz, and 300-3000 MHz. HF radios operate in dual fashion, either over ground propagation near the surface of the Earth or beyond radio horizon propagation via skywave refractions from the ionosphere. The latter type allows for truly long-range connections but is unfortunately susceptible to many abrupt spatiotemporal phenomena. However, by utilizing cognitive radio and networking techniques, it is possible to mitigate highly variable channel conditions and improve the reliability of HF communications. As an example, KNL Networks [6] works in this area and provides cognitive HF radio -based solutions for maritime, public safety, and security & defense applications. In any case, HF solutions have such bandwidth and intermittency restrictions that they are more like a last resort connectivity option for large unpopulated areas rather than a serious broadband service alternative.

Regarding the coverage extension in the areas having connectivity problems there are commercial solutions readily available on the market. For example, Finnish KUHA Mobile Network [7] promises to offer a simple and affordable LTE/4G mobile internet to local communities and companies suffering from a poor coverage. HajaKaista [8] is another example of the network service providers for challenged connection areas. Their network utilizes 3G/4G mobile and WiFi technologies and high-gain steerable antennas to enhance mobile broadband connection distance and data throughput.

C. *Network Slicing and Caching*

Emerging 5G networks introduce new ways to customize the network structure and data storage. This way it is easier to adjust and tailor the data pipeline according to the need of each application to optimize its key performance indicators. This makes sense as the range of applications is wide, as well as are the radio interface demands, e.g., in the form of data rate, latency and mobility. In 5G, we can therefore differentiate network slices for enhanced mobile broadband (eMBB), massive internet of things (MIoT), and ultra-reliable and low latency communications (uRLLC) services. The performance targets of these are so diverse that a single solution would be highly suboptimal. Thus, network slicing allows the network an easier and more precise adaptation to each particular need without compromising the performance. Caching, on the other hand, reduces unnecessary data transfer and delay by bringing the frequently requested popular content close to the network/cell edge, i.e., close to the users.

These new networking technologies provide an opportunity to be utilized in the remote area connectivity. Network virtualization allows for thinking about a specific network slice taking the remote area access constraints into account, mainly the limitations in backhaul capacity, latency, and reliability. Due to limited infrastructure induced constraints the prioritization of services in the remote slice may become necessary, giving more weight to public safety, authority, health, and education type of societal services over the entertainment purposes. Delay tolerant networking technologies can be combined to caching. For example, during the night time when the network utilization otherwise is low, even the modest backhaul capacity is adequate for caching a sizable amount of new data.

V. Remote Network Architecture Examples

As selected examples of various network architectures we categorize them to these three: 1) *extremely remote areas without existing infrastructure*, 2) *outdoor areas with limited infrastructure*, and 3) *backhaul connectivity solutions to areas with basic infrastructure*. More thoughts on these are given below with research topic suggestions to be investigated in each scenario.

A. *Extremely Remote Areas without Existing Infrastructure*

This is the most demanding research item as there is no existing infrastructure to build upon to. At the same time it leaves all options open to seek for best-suiting feasible architectures and technologies. Large geographical areas should be covered with economically as low cost as possible. Fig. 2 illustrates some of the candidate technologies/network elements that seem promising. In addition to terrestrial solutions, satellites, balloons [9], and other airborne solutions are viable alternatives to be carefully scrutinized as they are able to serve large coverage areas with light ground installations or purely remotely. Regarding satellite networks it is noteworthy that most of the existing satellite systems have such orbits that do not provide coverage to polar areas [10]. Terrestrial options should also have long range, low installation cost and long maintenance cycles. As already discussed in Section II, sustainable self-sufficient power sources for network nodes are essential for this use case. Solar and wind power are natural candidates but they have their limitations especially in harsh arctic conditions [11], [12], [13]. Therefore, some form of short-term energy storage is essential to minimize operational outages. In the arctic areas snow, ice, permafrost, etc. make the infrastructure building and maintenance difficult. Due to long distances, both inside the remote areas and to/from the core network via the backhaul, it is not realistic to keep all the technical requirements as strict as in the urban environment. For example, a more substantial end-to-end latency is inevitable and a lower peak data rate is likely. A reliable connection as such is in many cases more important than the data rate. It is important to realize these fundamental constraints due to the use case and find the best ways to adapt to them in a meaningful way.

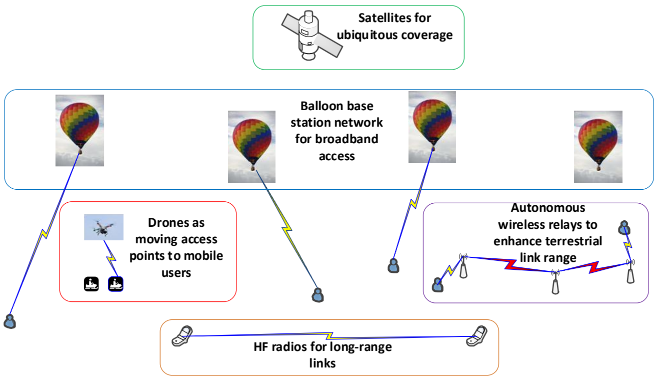

Fig. 2. Airborne and terrestrial elements for the arctic wireless connectivity.

Research problems worth investigating in this kind of framework are at least:

- Study of data network architecture possibilities including terrestrial and airborne solutions,
- Investigation of autonomous network device power source alternatives,
- Coverage vs. cost vs. reliability evaluations between candidate architectures,
- Elaboration of various radio technologies from robustness and coverage point of view,
- Study of feasible relaying and HF radio architectures for coverage extension.

B. *Outdoor Areas with Limited Infrastructure*

This scenario assumes that some radio communications and/or power grid infrastructure is available in the near vicinity of the usage scenario. However, the infrastructure is sporadic and has coverage holes that should be filled with novel solutions. Typical examples of this scenario are many sparsely populated terrains between rural villages that neither have permanent residences nor big roads nearby. On the other hand, they may be important recreational surroundings for weekend journeys, hunting, hiking, berry picking and so on. Furthermore, it would be important to stay connected in these environments, e.g., for emergency reasons. Fig. 3 depicts a possibility to cover very large areas with a small amount of base stations by harnessing the television broadcast infrastructure (where available) for the broadband wireless connectivity. TV antenna masts are typically much taller than mobile radio network masts and thus enable a long range. Massive MIMO technology could be coupled to the same concept to further help in the link range and data rate balancing. In the absence of these umbrella cells the coverage could be enhanced by small cells utilizing the latest 4G or 5G technology. Also, extra capacity within umbrella cells can be established by deploying small cells, e.g., to improve the cell-edge data rate at the hot spots where the additional data rate is most desperately needed.

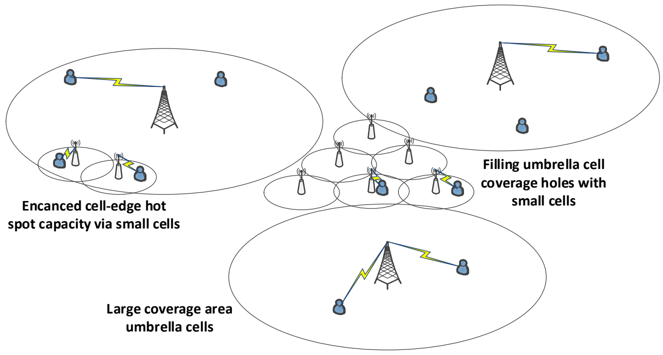

Fig. 3. A mix of large and small cells to optimize coverage, reliability and capacity.

Potential research problems in this scenario are at least:

- Provision of large umbrella cells that extend coverage, e.g., via high TV masts,
- Utilization of massive MIMO technology in the beam management,
- Enhancement of umbrella cell-edge capacity through the hot spot small cell deployment,
- CAPEX/OPEX calculations to optimize the mix of large and small cells,
- Derivation of novel performance metrics to capture area coverage, energy efficiency, throughput and reliability.

C. *Backhaul Connectivity Solutions to Areas with Basic Infrastructure*

This case assumes that the supporting infrastructure is available and modern. A typical use case would be a rural village or small town with a locally higher concentration of people in a small area. Small cell wireless technologies (4G, 5G) could be straightforwardly applied to provide very high data rate and low latency inside the cluster. The bottleneck then becomes from the connectivity to the rest of the network as the backhaul may be much more limited in capacity than in the urban environment. Thus, it is very difficult to achieve a low end-to-end latency in these circumstances. The TV infrastructure could again be repurposed for the backhaul use. Assisted by massive MIMO, directive beams could be pointed toward surrounding villages in the coverage area of the large umbrella cell (see Fig. 4). Due to a long physical distance to the core network the available backhaul has to be deployed at its maximum capability. For example, night time could be used to upload fresh content to local servers and then during the daytime, e.g., e-education and e-health applications would be able to make good use of the data at high rate and low latency locally inside the village.

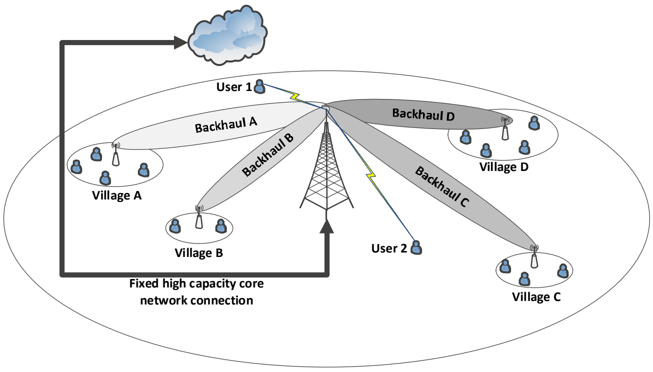

Fig. 4. Usage of TV towers for the backhaul of the remote villages and the umbrella cell coverage.

Among others the issues of interest to be considered are:

- Utilization of TV infrastructure for the backhaul connections of remote small cells,
- Deployment of massive MIMO technology in the beam steering,
- Usage of edge computing, caching and delay-tolerant networking techniques for the data content management and an enabler to localized 5G experience,
- Research of up- and downlink access possibilities in the large coverage area umbrella cell (see User 1 and User 2 in Fig. 4).

VI. Conclusions

We have elaborated the challenges of getting the weakly or completely non-connected regions to be provided with the digital services. We have learnt that the technology itself is not the main hindrance for that goal. Many of the existing and emerging wireless communications and networking technologies are directly applicable or adjustable to remote areas almost the same way as for the more urban environments. The larger bottleneck seems to be the difficulty to find enough economical incentive and societal responsibility to make things happen in remote, arctic, and otherwise challenged geographical locations around the globe.

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