LEO Satellite Constellations: An Opportunity to Improve Terrestrial Communications in the Canadian Arctic

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Abstract—**This study examines communications options (data, video and voice) for operations in the Canadian Arctic accounting for adverse conditions, such as atmospheric disturbances (both natural and man-made) or adversarial attacks on satellites and terrestrial infrastructure. Potential users include Canadian Armed Forces (CAF), North American Aerospace Defense Command (NORAD), off-grid communities and Public Safety, including their respective systems requiring machine-to-machine low latency data sharing. The technologies considered include satellites, microwave relays, fiber optic links, radios like cellular phones operating in the 700 Mhz band, transceivers in the high frequency bands (20-30 Mhz), and Unmanned Aerial System (UAS) gateways.**

Keywords-communications; satellite; Arctic; latency.

I. Introduction

This Defence Research and Development Canada (DRDC) study was initiated to address Canadian Arctic communication challenges expressed in the new Canada's Defense Policy, *Strong, Secure, Engaged* (SSE) [1], which reaffirmed Canada's commitment to effective operation in the Arctic. SSE defines an extended Canadian Air Defense Identification Zone (CADIZ) that includes the entire Canada's Arctic Archipelago (see Figure 1) as part of the overall North American Aerospace Defense Command (NORAD) modernization with an improved North Warning System (NWS) requiring high-throughput low-latency communications.

In addition this study covers some aspects of current Northern Canada communication systems of the Canadian Armed Forces (CAF), off-grid communities, Search And Rescue (SAR), and Public Safety (PS). Also, the rise in commercial interest, research and tourism in this zone brings increased safety and security demands related to SAR and natural or man-made disasters to which Canada must be ready to respond.

The purpose of this paper is to examine communications options for operations in Northern Canada accounting for adverse conditions such as atmospheric disturbances (both natural and man-made) or adversarial attacks on satellites and terrestrial infrastructures. Users include CAF, NORAD, off-grid communities and PS.

Section II of this paper describes the geographic context, climate, topography and size of the area requiring assured communication in all weather and atmospheric conditions. Section III summarizes some of the communications systems envisaged, deployed and used over the last decades in this area, such as Tropospheric Scatter, Geostationary Earth Orbit (GEO) at approximately 37000 km above the equator and Medium Earth Orbit (MEO) between 2000 to 35786 km altitudes. Section IV brings in perspective of novel options offered by several Low Earth Orbit (LEO) satellite constellations at altitudes below 2000 km. Section V introduces another option using a specific Highly Elliptical Orbit (HEO), the Three APogee (TAP with an apogee around 43000 km) [2]. Section VI proposes a possible terrestrial architecture with the addition of base stations using towers and Unmanned Aerial Systems (UASs) as gateways. Section VII compares latencies among the different satellite orbits and other communication technologies. Section VIII examines the pros and cons of some of these options. Section IX concludes with a short summary of findings and a final recommendation.

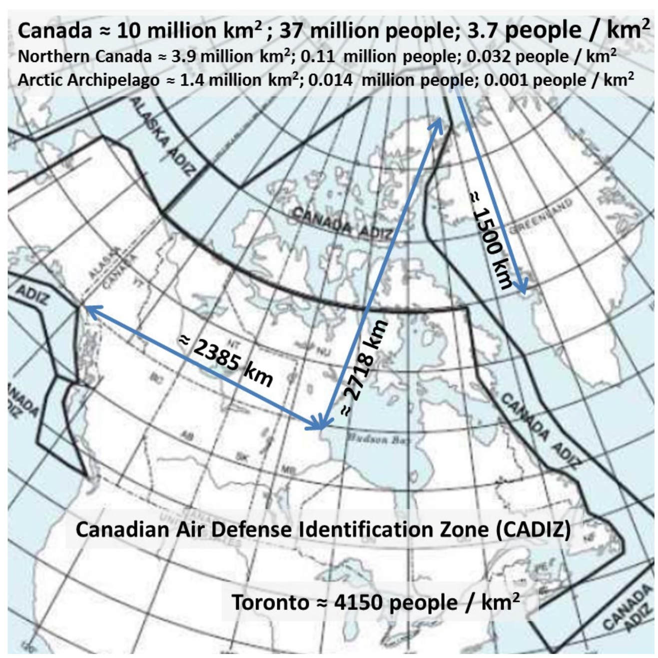

Figure 1. North America Canadian operational areas, new Canadian Air Defense Identification Zone (CADIZ), distance vectors and population densities for Canada, Northern Canada, Canadian Arctic Archipelago and Toronto.

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II. CONTEXT

Northern Canada, aka the North, is the vast northernmost region of Canada variously defined by geography and politics. Politically, the term refers to three territories of Canada: Yukon, Northwest Territories, and Nunavut. This area includes the Arctic Archipelago and covers about 39% of Canada's total land area, but has less than 1% of Canada's population.

More specifically, the Arctic Archipelago, aka the Canadian Arctic Archipelago, groups together all islands lying to the north of the Canadian continental mainland excluding Greenland (an autonomous territory of Denmark). Situated in the northern extremity of North America and covering about 1424500 km^2 (550000 sq mi), this group of 36563 islands in the Arctic Sea comprises much of the territory of Northern Canada—most of Nunavut and part of the Northwest Territories. This is about 15% of Canada’s geography that homes only about 0.04% of Canada's population. The Canadian Arctic Archipelago is experiencing some effects of global warming, with some computer models estimating that ice melting will contribute 3.5 cm to the rise in sea levels by 2100.

CAF’s preparedness training and exercises involve several thousand participants and some observers, which temporally substantially increase the population density in Northern Canada. For example, Operation Nanook series is an annual military CAF exercise in the Arctic. It is intended to train different CAF elements (Canadian Army, Royal Canadian Air Force and the Royal Canadian Navy) along with other government organizations, such as the Canadian Coast Guard and Royal Canadian Mounted Police in disaster training and sovereignty patrols in Northern Canada. Another series conducted south of Northern Canada near CAF Base Cold Lake is MAPLE FLAG, which brings about 5000 participants. In both cases, these exercises represent significant demand of information interoperability exchange, including voice, data and video, with some requiring low latency in order to fulfill machine-to-machine requirements.

A poignant factor in deploying communication systems in Northern Canada is the low population density. With reference to Figure 1, population densities of Europe and India are respectively about 2.3 and 11.6 thousand times that of Northern Canada. It is worth noting that some aspects of evolving 5G technologies are tuned to improve network capacity in high-user density areas like cities.

A. *Environmental and Logistical Considerations [3]*

The North has extreme weather conditions, with temperatures ranging from -50 to +20 degrees Celsius and wind gusts of up to 150 km/h. There is very little precipitation in the Arctic, with an average total of 100 to 200 mm of rain and snow per year. The amount of daylight varies with time of year and with latitude. In Resolute Bay, for example, the sun does not rise above the horizon from early November to early February and does not set from early May to late July.

Permafrost (perpetually frozen ground) is present in most of the Arctic and although typically roughly 10 m thick, it can extend down 1 km below the surface. Construction of stable platforms required for large satellite ground stations or microwave towers is costly because support pillars must be driven below the permafrost; otherwise the platform will shift as the permafrost partially melts during the short Arctic’s summers. This requires careful site selection to ensure placement where the permafrost is thin enough to enable installation. Furthermore, this type of environment is challenging for underground fibre installation.

Year-round access to all communities in the high Arctic is by plane only, increasing the overall cost of travel and accommodation when planning and installing communications equipment. Communities also have seasonal sealifts, which transport non-perishable dry cargo (e.g., construction material, household goods, vehicles, etc.) and bulk fuel to them once or twice per year. Items that are too large or costly to transport via air cargo, for example, large aperture satellite dishes or microwave towers and associated construction materials must be shipped by sea. This increases the logistic phase of any communication equipment deployment.

III. PRACTICAL ARCTIC COMMUNICATIONS SYSTEMS

This section includes the following communications systems: Tropospheric Scatter, High Frequency Ground Wave (HFGW), Point-to-Point (P2P) backhaul radio links, Fiber Optic Cable (FOC) and GEO systems. Skywave propagation modes are excluded due to their susceptibilities to radiation and atmospheric changes.

Tropospheric scatter, or Troposcatter, is a beyond-the-horizon communications solution in which microwave signals are scattered as they propagate through the troposphere. This phenomenon allows signals to be successfully received without line-of-sight between the transmitter and receiver at vast distances, even up to 500 km. Troposcatter systems have been in use for several decades and the technology has seen many advances in recent years, including improvements in throughput to 20 Mbps. However, for applications in the North it was found to be too expensive due to its power demand and infrastructure.

HFGW was documented for an alternate communications network for “nuclear-survivable means of communication for land-mobile missile systems in Europe” [4]. So, HFGW appears to be a potential communication means in case of satellite communications disruption due to solar activities or other manmade disturbances. According to International Telecommunication Union (ITU) [5] there are different uses of the terminology and the surface wave is often called the ground wave, or sometimes the Norton ground wave or Norton surface wave, after Norton who developed tractable methods for its calculation. The ground wave is the sum of direct wave, reflected wave, and surface wave. When the transmitting and receiving antennas are close to the ground, the ground reflection coefficient is -1, so the direct and ground-reflected waves act to cancel each other out, leaving the surface wave as the only important component. In such conditions, the ground wave is essentially equal to the surface wave. Empirical results [4] using broadband discone antennas with a cut-off frequency of 19 MHz operating over 20 to 30 MHz near Norway Arctic Circle and Germany

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showed good link connectivity for voice and data using narrowband channels for paths over irregular terrain over distances ranging between 19 and 115 km. Based on the empirical results reported, a communication system with its signal spread over 10 MHz with code division multiplexing and sufficient coding gain would offer throughput and fading resilience for a high-reliability medium-data-rate channel.

Microwave links have been extensively used in the North providing reliable connectivity to smaller communities in the Yukon and Northwest Territories that do not have direct access to FOC backhaul. Microwave links provide high throughput with low latency, a significant advantage over GEO systems. Since microwave frequencies require line-of-sight propagation, towers and topographic features are exploited to extend the range of links beyond the limitations imposed by the curvature of Earth and terrain features.

An example of microwave technologies used in remote Arctic locations is the High Arctic Data Communication System (HADCS) of Ellesmere Island, which links Canadian Forces Station Alert (CFS Alert) to Eureka over a distance of roughly 500 km. Then the data are sent via GEO satellite from Eureka to Ottawa (4147 km). HADCS was retrofitted in 2003 to run entirely using solar power, despite prolonged darkness during winter months. Each HADCS station is powered by eight 120 W photo-voltaic (solar) panels arranged in an octagon (eight vertical panels distributed at 45° angular intervals to cover all azimuths). During the summer, with 24 hours of day light, the sun does not dip below the horizon, and all of the solar panels contribute to charging the battery banks [3]. This network comprises seven individual links ranging from 18 to 121 km in length each. The current system operates in bands near 1800 and 2100 MHz, and provides 6.3 Mbps of throughput. Helicopter is the only means of access to these repeater sites [3].

The main challenges in providing microwave backhaul throughout in the North using towers are the overall lack of infrastructure, the inaccessibility of the locations where towers would be built and powering these sites. In the North, costs of construction per kilometre for FOC and microwave links are about equal (approximately $65K/km), when serving a population of roughly 300 people. Above this number of users, fibre is less expensive [3]. These networks have at least one point of service via a satellite terrestrial terminal; the trend is two or more to increase dependability.

UAS gateways (either aerostats and high-altitude high-endurance autonomous drones) [3] provide possible communication solutions that merit some discussion. The Internet.org consortium has conducted some research into the feasibility of using UAS as communications platforms for remote and underserved locations [15]. These UAS would be deployed at an altitude of approximately 20 km. By using solar power, UAS systems would be capable of remaining above one geographic location on earth, thereby reducing complexity and cost of the ground infrastructure when compared to microwave links, or will not require tracking as for MEO and LEO satellites. As the UAS would be relatively close to Earth, cheaper low-power transmitters could be used, while still enabling high-throughput communications with low latency. A previous study [3] assessed that this type of range extenders might have an availability no greater than 80%, but with technology advances this is different today, such UAS might be sufficiently reliable for commercial broadband.

GEO satellites are well suited to some applications in the North, given that they remain at the same point in the sky when viewed from a particular location on Earth, and therefore, do not require tracking antennas on the ground as for MEO and LEO systems. This enables the use of lower-cost stationary antennas at ground stations, which is particularly advantageous in harsh environments where moving parts are undesirable. GEO satellites provide much of the broadband Internet coverage for communities in the North; the coverage in Nunavut is currently provided by two GEO satellites, Anik F2 and Anik F3, both using C-band [3].

However, the use of GEO satellites in the North has some drawbacks. Due to geometry and the curvature of Earth, there is no line-of-sight between equatorial GEO satellites and North locations above roughly 80 degrees latitude. Furthermore, communities at latitudes higher than about 70 degrees have elevation-look angles below ten degrees to the satellite. This leads to increased absorption and scattering of radio frequency signals by the atmosphere (known as absorption) and at higher frequencies from precipitation (rain, snow and ice, known as rain fade). The five northernmost communities in Nunavut are above 70 degrees latitude. Another disadvantage of GEO satellite use for broadband applications is signal latency; due to the distance to and from the satellite, the minimum delay for a round trip is 480 ms with a median latency of 600 ms. This is an order of magnitude higher than for fibre and microwave links [3].

Tests of Mobile Satellite (MSAT) and Iridium capabilities for emergency communications in Northern Quebec showed their insufficiencies. The Canadian MSAT system uses GEO satellites, which requires, at such latitude, a high-gain antenna and higher antenna siting (implying larger installations, location constraints and thus greater costs). These conditions make emergency operations difficult and cost-ineffective. The US commercial Iridium system with its current handheld, vehicle-mounted and fixed-remote equipment demonstrated different logistic problems, such as the high cost and poor performance of the handheld telephone, which usually cannot be used inside buildings [6]. For a Canadian Arctic Underwater Sentinel Experimentation (CAUSE) project, transmission of data over a period of 7 months showed that the Iridium Pilot system (antenna about six meter above ground) did not fulfill the requirement [7]. "The Pilot data transfer rate for polar transceivers is far less than the advertised rate" [7].

The Iridium system was designed to be accessed by small handheld phones, the size of a cell phone. The omnidirectional antennas, which are small enough to be mounted on such a phone, and the low battery power, are insufficient to allow the set's radio waves to reach a GEO satellite. In order for a handheld phone to communicate with them, the Iridium satellites are at LEOs closer to Earth, at about 780 km above the surface. With an orbital period of about 100 minutes a satellite can only be in view of a handset for about 7 minutes, while the call being automatically

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"handed off" to another satellite when the previous one passes beyond the local horizon. This requires a large number of satellites, carefully spaced out in polar orbits, to ensure that at least one satellite is continually in view from every point on Earth's surface. For seamless coverage at least 66 satellites are required, in 6 polar orbits containing 11 satellites each.

IV. Perspective of New LEO Constellations

Out of the 11 LEO satellite communications service proposals registered within the US Federal Communications Commission (FCC), the following three will be considered based on their maturity [8]: OneWeb, SpaceX and Telesat on Ku (12-18 GHz) and Ka (27-40 GHz) bands.

To ensure access to affordable high-speed Internet connectivity across rural and Northern Canada, the Government of Canada has invested $85 million and is committed to buy up to $600 million in some services over 10 years following launch in 2022 of Telesat’s LEO Satellite Constellation, which is leveraging Telesat’s worldwide rights to ≈4 GHz of Ka-band spectrum.

The conclusion of the main analysis of [8] was summarized as follows:

- The maximum total system throughput (sellable capacity) for OneWeb's, Telesat's and SpaceX's constellations are 1.56 Tbps, 2.66 Tbps and 23.7 Tbps respectively.
- A ground segment comprising of 42 ground stations will suffice to handle all of Telesat's capacity, whereas OneWeb will need at least 71 ground stations, and SpaceX more than 123.
- In terms of satellite efficiency (ratio between the achieved average data-rate per satellite and its maximum data-rate), Telesat's system performs significantly better (~59% vs. SpaceX's 25% and OneWeb's 22%). This is due to the use of dual active antennas on each satellite, and the lower minimum elevation angle required in their user links.
- OneWeb's system has a lower throughput than Telesat's, even though the number of satellites in the former is significantly larger. The main reasons for this are the lower data-rate per satellite that results from OneWeb's low-complexity satellite design, spectrum utilization strategy, orbital configuration, and payload design, as well as the lack of use of Inter Satellite Links (ISLs).
- If ISLs were to be used in OneWeb's constellation, (even with modest data-rates of 5 Gbps), the number of ground stations required could be reduced by more than half to 27 ground stations.

“To conclude, our analysis revealed different technical strategies among the three proposals. OneWeb's strategy focuses on being first-to-market, minimizing risk and employing a low-complexity space segment, thus delivering lower throughputs. In contrast, Telesat's strategy revolves around high-capable satellites and system flexibility (in diverse areas, such as deployment, targeted capacity allocation, data routing, etc.), which results in increased design complexity. Finally, SpaceX's system is distinctive in its size; although individually each satellite is not significantly more complex than Telesat's, the massive number of satellites and ground stations increases the risks and complexities of the overall system considerably” [8]. However, this offers a high level of redundancy.

V. Envisaged HEO/TAP Constellations

HEO/TAP [2], which could be considered under the Enhanced Satellite Communications Project – Polar (ESCP-P) program to provide dedicated, secure and reliable Beyond Line-Of-Sight (BLOS) communications for domestic and continental CAF operations in the Arctic. Current GEO communication satellites leave the poles uncovered; consequently, Department of National Defence (DND) is exploring options of building the capability or acquiring services from commercial providers who have future plans to cover this area. The initial operational capability is tentatively scheduled for 2029.

Quasi-geostationary coverage of Polar Regions can be achieved from HEO satellites. In accordance with Kepler’s second law HEO spends most of the time in the vicinity of apogee (i.e., the farthest point from the Earth’s surface). The orbit could be oriented in such a way that the apogee is over one of the two Polar Regions, so that only two HEO satellites can maintain a continuous view of an entire polar zone [9]. When satellite A leaves the optimal viewing zone and heads toward the perigee (i.e., the closest point to the Earth’s surface), satellite B rises over the region to maintain the complete circumpolar region in sight. Interestingly, there are periods of several hours per day of coincident (i.e., stereo-like) imaging from the two satellites over most of a circumpolar area. Such a system could provide meteorological imaging and communication capacity, similar to GEO, focused on the polar region. The first HEO satellite system with a period of rotation equal to 12 h was called Molniya was implemented for communication purposes in 1965. It is established that a two-satellite Molniya HEO constellation can achieve continuous coverage of the polar region 58°–90°N with a Viewing Zenith Angle (VZA) less than 70°. Another HEO system—with a 24-h period—called Tundra is currently used by the satellite Sirius XM Radio service operating in North America. Both orbits, 12-h Molniya and 24-h Tundra, are launched with an orbit inclination equal to 63.4°. This value called the critical inclination, corresponds to a zero rate of apogee drift due to the second zonal harmonic of the Earth gravitational field, and insures a stable position of apogee over the polar zone. If the HEO orbit inclination differs from the critical value, then the apogee gradually drifts toward the equator. Orbital maneuvers are then required to maintain the intended orbit position. The farther the orbit inclination is from the critical value, the more resources are required to maintain the orbit. A drawback associated with the 12-h Molniya orbit is the risk linked to hazardous levels of ionizing radiation due to passing through the Van Allen belts. The highest danger originates from high-energy protons. The Molniya orbit crosses the proton radiation belts at the region of maximum concentration of energetic protons with energies up to several hundred MeV. As an alternative, the 16-h TAP HEO orbit was proposed, providing similar polar coverage as the Molniya HEO system while minimizing the proton ionizing

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hazards by extending the apogee to 43000 km [2]. The TAP orbit has a ground track with three apogee points repeatable over two days. Such a constellation of two satellites in TAP orbit still revisits ground tracks every 24 h.

VI. TERRESTRIAL ARCHITECTURES

Architecture options offered by new LEO satellite constellations and terrestrial communications, such as UAS, FOC and HFGW given advances in signal processing, multi-beam antennas, spatial diversity and low cost software-defined radios could substantially improve communications availability and reliability in the North. Figure 2 illustrates such a multi-technology architecture where ISLs and Inter UAS Links (IUASLs) play important roles. Potential services provided with appropriate parameters and technologies should allow anticipating improvement in coverage, resilience, redundancy, dependability, data rate and low latency for services, such as:

- fixed installations like CFS Alert, NWS radar networks, and Forward Operating Bases (FOBs);
- mobiles near fix installations, air or tower gateways or their communication relays; and
- deployed personnel and platforms for military exercises and operations, emergency operations or off-grid communities of Northern Canada.

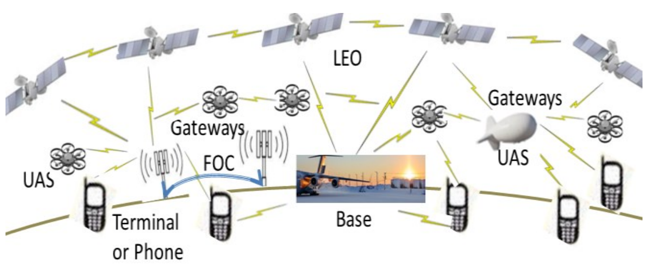

Figure 2. Simplified Northern Communications Architecture.

VII. LATENCY

Latency is the delay, usually measured in milliseconds (ms), that occurs in a round-trip data transmission. The latency of a message is the amount of time it takes to reach its destination from its source. Results for FOC in large networks based on Round-Trip Times (RTTs) [10] using Content Delivery Network (CDN) show useful latency information, such as 18 ms for a distance of 1418 km. HADCS and HFGW offer low latency in this order of magnitude but with lower data rates. High latency typical of GEO satellite links can be very disruptive for some applications, such as video conferencing, and could increase risk in remote health applications including remote surgery. Satellite link latencies can also cause low data throughput, caused by the default behaviour of communication protocols, which are optimized for shorter distances. A GEO satellite one-way propagation delay is approximately 240 ms due to the distance between Earth and satellite. Therefore, round-trip delivery of a data packet with acknowledgement is approximately 480 ms. This does not include the network delay, which can generally add 50 to 200 ms, depending on where the server is located. GEO satellite systems have a median latency of nearly 600 ms, which includes a median delay of 120 ms due to processing speed and networks in both directions. This makes GEO systems an unsuitable replacement for cable or fiber systems for applications requiring low latency, such as machine-to-machine interoperation. The lower orbits of LEO satellites, however, should result in latencies that are much closer to landline quality. The average orbit of the proposed constellations is around 1200 km, that is a round trip of 2400 km or delay of 31 ms. This is 93.5% improvement over a GEO round trip of 480 ms. If the processing speed of LEOs equaled that of GEOs then their total median latency time would be 151 ms. However, OneWeb tune-up, recorded an average latency of 32 ms in July 2019. As new LEO satellites are designed for high throughput, their overall processing time and network delay must be lower than those used in legacy GEO systems in order to obtain such small latency score.

For LEO latency, in this article, since no large sets of empirical results are available, a conservative approach is to use some of the simulation results from [11] for optimal Expected Latency Minimization (ELM) algorithm using Software-Defined Networking (SDN) context, which addresses more completely the entire network aspect including fading dependence on atmospherics. An interpretation of [11] for its ELM-SND hypotheses is that LEO's average latency be around 40 ms while the maximum average latency be around 90 ms.

For HEO TAP with an apogee of 43000 km this means that the round-trip time is increased by16% from GEO, i.e., 558 ms or a median latency of 778 ms. Assuming a MEO median orbit of 18893 km, that is 51% of GEO, then MEO median latency could be in the order of 306 ms.

VIII. ANALYSIS

Considering the advantages of LEOs in extending communications coverage and throughput in the North in conjunction with terrestrial network communications with appropriate gateways, this study must be extended to include experimentation. Also, there is a need to investigate how Canada could protect space and terrestrial network installation assets.

Satellites are more susceptible to radiation, jamming and atmospheric disturbances than FOC and over-the-horizon HFGW propagation. HFGW at 20 to 30 MHz is expected to provide reliable medium throughput terrestrial communications [4]. FOC offers high throughput and low latency, commonly deployed around the world and expanding in Northern Canada [12][13]. FOC and HFGW do not offer the area coverage of LEO satellites.

Two challenges of LEO constellations are the frequent handover and terrestrial base station antenna tracking. These seem achievable under low energy and cost regimes by the availability of lower-cost components, such as high-speed low-power chip sets and Active Electronically Scanned Array (AESA) integrated boards for microwave systems in Ka and Ku bands. However, Figure 3 shows the disadvantage of transmitting at higher frequencies, but such higher frequencies offer higher throughput.

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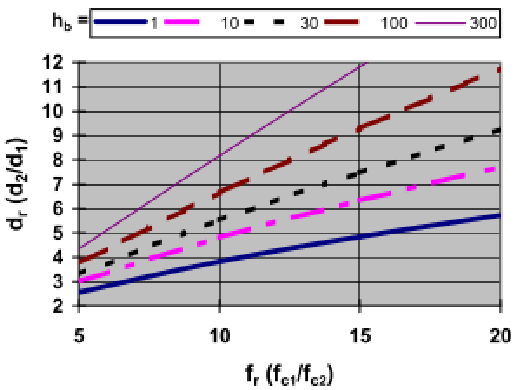

Figure 3. Path loss distance ratio d_2/d_1 as a function of the carrier frequency ratio f_{c1}/f_{c2} for five base heights and mobile at one meter [6].

Figure 3 allows estimating the increase in radio coverage when stepping down from 1500 MHz to 150 MHz. Reducing the mobile operating frequency by a factor of 10 extends the communication range by a factor of about 5 for a base station whose effective antenna height is 30 m. If the cell size were 5 km for normal service, it might extend to 25 km for the emergency temporary service, reducing the logistic burden of covering an area affected by a disaster. Currently, the frequency of 700 MHz is allocated for emergency in Canada.

Colman *et al.* [3], present an example with microwave link systems. One is operating at 1.8 GHz and the other at 11 GHz, both with similar radiating power. The system at lower frequency offers a free space maximum range of 333 km while the other, at six times the frequency, qualifies for a free space maximum range of 30 km. That is 11 times shorter. However, the maximum effective throughput rises from 65.4 Mbps to 232 Mbps, which is 3.5 times faster.

Other considerations include the challenge of powering terrestrial systems in the North. Sources like solar and wind mill could be combined with sodium-ion batteries, which could operate at low temperature. Long endurance UAS could be using solar with hydrogen fuel-cells. However, sources requiring refueling every six months would be ideal.

IX. Conclusion

This article addressed some of difficult challenges that remain after many years of research and development for communications systems in the North. Findings address DND/CAF challenges to improving capabilities required by future demands from expected developments in the Arctic and for NORAD operations.

Selected options to improve communications in off-grid areas, more specifically in the North, are expected to provide timely improved shared situational awareness in support of operations where it is currently not well provided, or not available. Such solutions would be revolutionary for our Defense and Security (D&S) capabilities and would progressively provide significant advantages to coalition forces and when CAF operates in collaboration with other Canadian departments including PS and local police in the most demanding emergency and disaster situations.

In the North, if low latency communications are critical for applications or operation objectives, GEO, MEO and HEO satellite systems are not recommended. The least expensive communications systems with low latency in the North should include UAS and LEO systems to ensure fast deployment and access to all participants. UAS offers rapid deployment capability on demand in response to PS and CAF situations. LEO/UAS hybrid systems could definitely extend capabilities of available legacy infrastructures.

The most significant finding is that the advent of low-cost high-performance LEO satellite systems will definitely improve communications in the North.

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