Narrowband Satellite Communications: Challenges and Emerging Solutions

Emre Gündüzhan and K. Dewayne Brown

ABSTRACT

Narrowband satellite communications (NB-SATCOM) technology is used by the DoD primarily for communications among dismounted soldiers, as well as among ground vehicles, ships, and aircraft. It is attractive because of the favorable propagation properties of the frequencies in the ultra-high-frequency, L-, and S-bands. NB-SATCOM has continuously been evolving in both military and commercial domains. This evolution is necessary to keep up with the technological advances and to meet increasing user requirements; however, the high cost of terminal replacement demands continued support for the existing terminal base. This article focuses on the challenges faced by DoD for future NB-SATCOM services, along with potential options for next-generation systems. Emerging technology enablers and recent advances in SATCOM services are also discussed.

INTRODUCTION

In the context of satellite communications (SATCOM), the term *narrowband* (NB) generally refers to the ultra-high-frequency (UHF)-, L-, and S-bands, where available bandwidth is limited compared to the higher-frequency bands. These lower-frequency bands in the 300-MHz to 4-GHz range are attractive to the DoD because of their better penetration into buildings and through foliage and their reduced signal attenuation in adverse weather conditions. Because of limited available bandwidth, primary applications of NB-SATCOM are voice and low-rate (e.g., 64 kb/s) data transfer.

The existing legacy DoD NB-SATCOM constellation consists of the UHF Follow-On (UFO) and Fleet Satellite systems operating in the 240- to 320-MHz range. Each UFO satellite supports seventeen 25-kHz channels and twenty-one 5-kHz channels.[1] This legacy constellation is currently approaching the end of its life; hence, it is being replaced by the Mobile User Objective System (MUOS), which is the DoD's next-generation NB-SATCOM system.[2] MUOS operates at 300–320 MHz for the uplink and 360–380 MHz for the downlink. It consists of four operational satellites in geosynchronous Earth orbit (GEO) plus one in-orbit spare. When fully operational, MUOS is expected to provide 39.2 Mb/s of global capacity to terminals compatible with the new Wideband Code Division Multiple Access (WCDMA) waveform.[3] Each MUOS satellite also includes a legacy payload to support the legacy UHF terminals. The DoD also uses leased services from commercial SATCOM providers such as Iridium and Inmarsat.

Although MUOS and leased commercial SATCOM services are expected to provide orders of magnitude more capacity compared to the legacy UHF system, emerging requirements still present significant challenges. These challenges include developing low-cost, low-power, small-footprint terminals; continuing support for legacy SATCOM terminals; achieving resilience against kinetic and electronic attacks; and increasing the efficiency of spectrum usage. This article discusses these challenges and some emerging potential solutions, such as advances in cognitive devices, lower-orbit and nanosatellite systems, and terminals for specialized applications.

In the next section of this article, we present some of the main NB-SATCOM challenges. This is followed by a discussion of several technological enablers as potential solutions in future systems. We conclude the article with a summary.

NB-SATCOM CHALLENGES

Small Terminal Footprint

The primary NB-SATCOM users include dismounted soldiers, special operations forces, and small unmanned vehicles. Their missions require terminals with low size, weight, and power (SWaP) operating in remote locations, areas with unsecure infrastructure, or areas with denied access.

MUOS is the next-generation military NB-SATCOM system, but current MUOS form factors are impractical for such missions. Although some commercial NB-SATCOM systems (e.g., Iridium) support handheld radios, the only program-of-record handheld, manpack, and small-form-fit radio for MUOS is the General Dynamics PRC-155, which is a manpack. One of the main reasons for the lack of handheld MUOS terminals is the large link margin that was used in link budget calculations.[4] The link margin that was used satisfied >97% link availability and resulted in a maximum transmit power specification of 8.5 dBW. This power level would be impractical to implement in handheld terminals because of heat-dissipation issues. However, recent analyses showed that much lower power levels (e.g., 6 dBW) can achieve acceptable performance. These results seem to eliminate one of the key barriers to developing a low-SWaP terminal.

Another challenge for a small-form-factor MUOS terminal is the requirement for full-duplex operation. MUOS is based on the 3rd Generation Partnership Project (3GPP) WCDMA standards and does not support a half-duplex mode. Because that mode is not supported, the terminal must have separate transmit and receive chains, which increases its SWaP.

Legacy Terminal Support

A key characteristic of NB-SATCOM is its relatively large number of users. This large user base drives the need for a large number of terminals in the field. The replacement cost for such a large number of terminals puts significant constraints on new NB-SATCOM systems. New satellite systems should continue to support the legacy terminals until they are replaced by newer terminals, and currently it is not known when support of legacy terminals will end. For this reason, each MUOS satellite carries a legacy UHF payload for existing terminals in addition to the payload for the new WCDMA waveform.

Resilience

NB-SATCOM systems must be resilient against a number of threats, including kinetic attacks, jamming, and cyberattacks.[5] In general, resilience can be achieved by preventing an attack, withstanding an attack, or by rapid restoration of services after an attack. In this article, we talk about some potential approaches for robustness against kinetic attacks and jamming and for rapid restoration of services in the event of an attack. Preventing kinetic attacks and jamming requires eliminating the attacker and is outside the scope of this article. Resilience techniques against cyberattacks on NB-SATCOM are similar to techniques used for other cyber systems, and they are also not discussed in this article.

Increased Spectral Efficiency

Another challenge for NB-SATCOM is efficient use of the relatively narrow spectrum. Although new technologies can help, the significant time required to design and deploy a new satellite system will prevent their rapid introduction. As technological advances continue at a rapid pace, the technology used in a satellite system can be obsolete by the time it is launched. For instance, an analysis-of-alternatives study for MUOS was concluded in 2001, but the first MUOS satellite was launched in 2012. The challenge, therefore, is to reduce the design phase for a new system and keep up with the newest technologies.

POTENTIAL SOLUTIONS

Miniature Terminals for Specialized Applications

One approach for developing low-cost, small-form-factor NB-SATCOM terminals is customizing terminal functionality for the intended uses and applications. It is critical to minimize the functional scope to include only those functions that are necessary. The Johns Hopkins University Applied Physics Laboratory (APL) has begun to explore this approach, developing a Miniature MUOS Terminal (MMT) proof of concept as an independent research and development project. The end goal of this project is a potential MUOS terminal to support specialized operational applications such as data infiltration/exfiltration in denied, remote, or unsupported areas.

The MMT is realized in two risk-reduction form factors: MUOS on a printed circuit board and MUOS in a multichip package. These small form factors will enable low-profile handheld capability, use on unmanned vehicles, and unattended sensor bidirectional interfaces to an operations center across the MUOS satellite system. The independent research and development project evaluated feasible small-form-factor RF power profiles for compatibility with MUOS and determined that useful data rates and link availabilities can be achieved.

The critical enabler to achieve the small form factor in the MMT is waveform scope tailoring. There is a direct correlation between the amount of processing and the SWaP of the terminal. Effective trades between operational requirements and terminal SWaP can be achieved by developing terminals that provide only a sponsor-defined subset of the full functionality.

Cognitive Systems

Cognitive communications capabilities are likely to be supported in future SATCOM systems. Wireless communication resources, including SATCOM resources, are scarce and expensive; therefore, communication channels are designed as a trade-off between performance and cost. Furthermore, both the channel characteristics and the link requirements in terms of geometry, environments, and resources are time-varying processes in general. Communication equipment configurations need to be adaptive in order to maintain optimum performance and efficient use of resources in this highly dynamic environment. As shown in Fig. 1, a cognitive architecture enables adaptive configurations by using environmental sensing and cognitive processing.

Environmental sensing is used to estimate a number of critical communication parameters, including frequency, power, bandwidth, waveform, multiple access, location, and angle of arrival. It provides input to cognitive processing engines to implement real-time communication policy. Cognitive processing generally includes a cognitive memory, a learning process for self- and environmental awareness, and a decision-making process for adaptive configuration and dynamic resource allocation. For example, adaptive network, digital, RF, and antenna processing functions can be used to enable flexible maneuvers in the communication and networking services, and dynamic resource allocation can control resources such as frequency, power, multiple access, and beam direction according to environmental conditions. Cognitive communication algorithms will increase robustness against interference and jamming by seamlessly switching to an optimal operational configuration in highly dynamic environments.

Advances in 3GPP

3GPP is the standards forum supporting the development of many commercial mobile network standards. Advances in 3GPP standards can be adopted by satellite systems as well. For instance, the new MUOS waveform is based on the 3GPP WCDMA standards.

Because the electromagnetic spectrum is a valuable resource, 3GPP and other wireless standards organizations have performed extensive work to improve the spectral efficiency of modulation schemes. Orthogonal frequency-division multiplexing (OFDM) emerged as a main trend and has become the modulation of choice in Wi-Fi, WiMAX (Worldwide Interoperability for Microwave Access), and LTE (Long-Term Evolution) systems.[6] This embrace of OFDM suggests that it is worth considering OFDM-based waveforms for future NB-SATCOM systems as well, given that satellite spectrum is also a valuable resource. Applying OFDM to NB-SATCOM is a promising solution to increase user throughput and overall system capacity.

Heterogeneous network deployment is another trend in cellular wireless communications.[7] The basic concept is building a layered organization of cell towers. Low-power towers are used to form "pico" cells that provide coverage to hard-to-reach locations, while regular towers provide service to larger "macro" cells. A related concept is the relaying functionality, where mobile phones communicate with a base station via a relay node. Relaying extends the coverage area of a base station.

These concepts can be adopted by NB-SATCOM to provide service to small disadvantaged terminals, as illustrated in Fig. 2. Portable ground stations or an aerial layer can be positioned to serve disadvantaged terminals that cannot communicate with the satellite directly. In a heterogeneous configuration, the portable ground stations or an aerial layer would handle local communications, while the satellite would provide reachback to the global network. In a relay mode, portable ground stations or an aerial layer would strengthen the signals to and from the satellite, extending service to disadvantaged terminals.

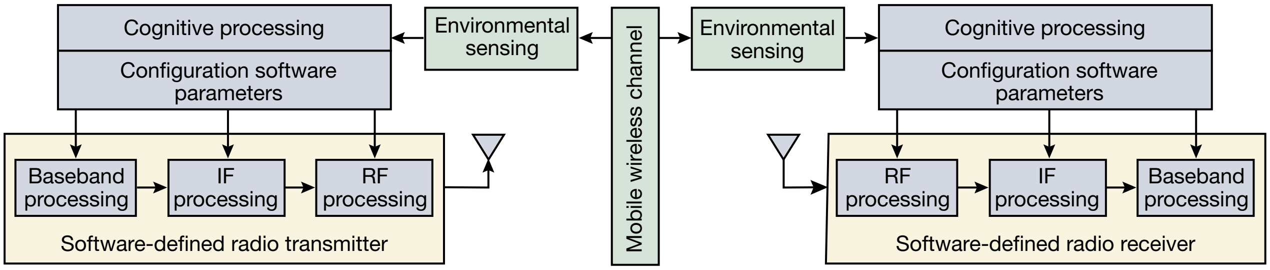

Figure 1. Cognitive communication architecture. IF, intermediate frequency.

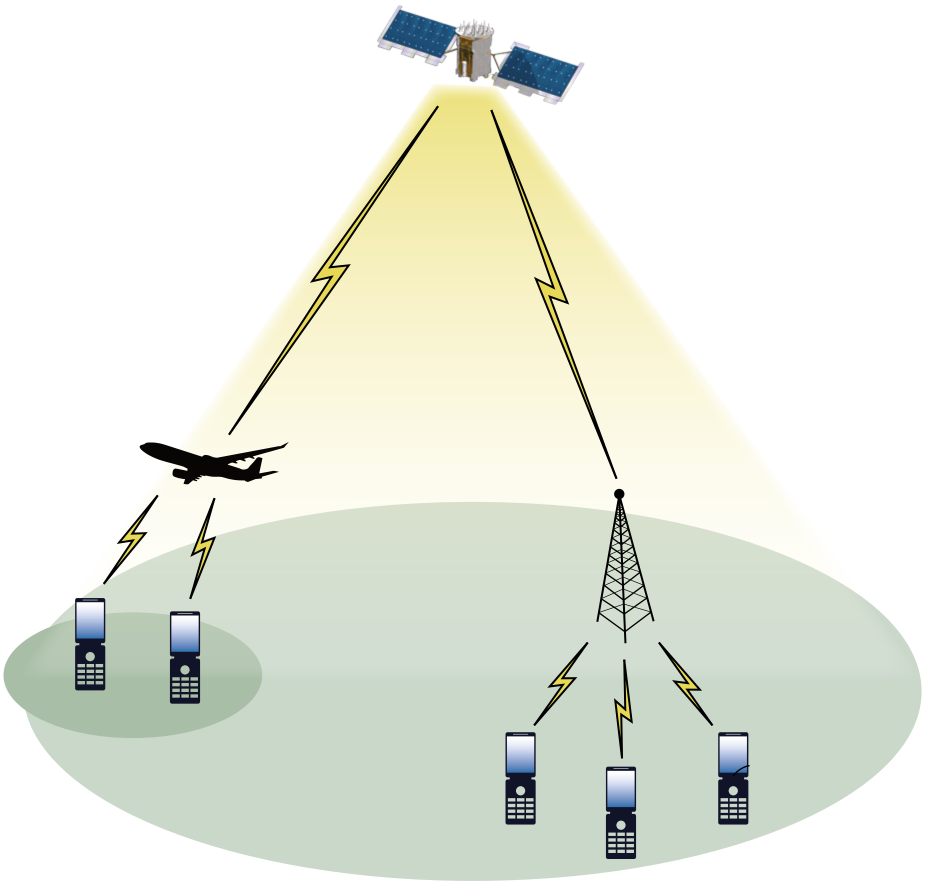

Figure 2. A conceptual heterogeneous network for SATCOM.

Non-GEO Constellations

MEO and LEO Constellations

Military satellites, including NB systems, traditionally operate in GEO. GEO satellites cover larger areas of Earth compared to satellites in lower orbits. This allows coverage of all of Earth between 65S and 65N latitude with as few as three satellites. Also, GEO satellite position is stable relative to the ground, which simplifies use of directional antennas and reduces required Doppler compensation.

The major disadvantage of a GEO satellite compared to those in lower orbits is the substantially greater distance that signals have to travel. Transmitted signals experience a high level of attenuation and a large propagation delay because of this distance. The free-space propagation loss and propagation delay of GEO are compared with medium Earth orbit (MEO) and low Earth orbit (LEO) in Table 1, which shows that GEO has 11 dB and 37 dB more attenuation compared to MEO and LEO, respectively. The table also shows that the propagation delay for a satellite in GEO is 172 ms and 236 ms larger than for one in MEO and LEO, respectively.

Reduced attenuation and propagation delay make MEO and LEO attractive options for future NB-SATCOM systems. Use of these orbits would reduce the transmission power requirements of terminals, allowing terminal designs with lower SWaP, and would also substantially improve the quality of voice conversations by reducing the end-to-end delay.

Unlike GEO satellites, LEO and MEO satellites are not stationary as viewed from Earth. But, NB-SATCOM terminals typically use omnidirectional antennas; hence, tracking satellites in non-GEOs would not be an issue. However, MEO and LEO satellites would be traveling at very high speeds relative to Earth, which means a larger range of Doppler effects would have to be compensated. Although this would add to terminal and satellite payload complexity, it is not expected to be a significant issue. Doppler compensation methods are well known, relatively inexpensive, and currently deployed for some commercial LEO systems (e.g., Iridium).

Another benefit of using MEO and LEO satellites would be the increased number of satellites in orbit compared to those in GEO. This can enhance the resilience of the system against kinetic attacks to the space segment. If a satellite is disabled because of an attack resulting in a lack of satellite coverage and thus a gap in communications in a particular area, that gap would be filled when other satellites move into that area. Therefore, a given point would experience only periodic service disruptions several times per day. This is a significantly more graceful degradation of service compared to the loss of a GEO satellite, which would result in a large area completely without satellite coverage until a spare satellite replaced the lost one.

Table 1. Propagation delay and path loss at different orbits

	GEO	MEO	LEO
Altitude (km)	35,768	10,000	500
Ground-to-ground propagation delay (ms)	239	67	3
Free-space path loss (dB)	173	162	136

The resilience and propagation benefits of LEO and MEO constellations must be weighed against the total cost of the entire deployed system. On one hand, these lower orbits use smaller satellites compared to GEO, but more satellites are required for global coverage. On the other hand, the launch cost per satellite is reduced because of smaller size and weight.

Nanosatellites

An emerging technology that can potentially be utilized for SATCOM resilience is nanosatellites.[8] These small, low-cost satellites can be deployed in significant quantities with a single launch. Although nanosatellite capabilities and limitations are still being researched, deploying a mesh network of such spacecraft could potentially provide substantial resilience against kinetic attacks. Nanosatellites can also be deployed as relays to reach disadvantaged terminals or to expand SATCOM coverage areas.

CONCLUSION

Several difficult challenges must be addressed to meet the emerging requirements for NB-SATCOM. Small and low-cost terminals are required for dismounted soldiers. These could speed replacement of legacy terminals with newer terminals, alleviating the need to support legacy systems. Achieving resilience against kinetic, electronic, and cyberattacks is also a difficult challenge. Finally, keeping up with technological advances is required for improved spectral efficiency and SATCOM traffic capacity.

Promising solutions to these challenges include developing terminals for specific applications to drive down terminal SWaP and cost; using lower orbits and nanosatellites to improve resilience and shorten propagation distances; and utilizing new technologies such as cognitive systems, OFDM-based waveforms, and heterogeneous network architectures.

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THE AUTHORS

Emre Gündüzhan was the APL Technical Lead for the Future Narrowband SATCOM study. He is the Supervisor of the Next-Generation Network Systems Section in the Communication and Networking Systems Group and is also the APL MUOS Project Manager. **K. Dewayne Brown** was the Technical Lead for the Miniature MUOS Terminal independent research and development project. He is the Supervisor of the Resilient Tactical Communications Section in the Communication and Networking Systems Group and is also a technical leader for several current DoD communication development projects. For further information on the work reported here, contact Emre Gündüzhan. His e-mail address is emre.gunduzhan@jhuapl.edu.