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PROSPECTS OF TROPOSCATTER SYSTEMS IN MILITARY COMMUNICATION NETWORKS

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Abstract: *In modern military operations, ensuring resilient and secure communications in contested or infrastructure-deficient environments remains a strategic priority. Tropospheric scatter systems (troposcatter) are regaining attention due to their ability to provide beyond-line-of-sight (BLOS) connectivity without relying on satellites or terrestrial infrastructure. This paper explores the role of troposcatter systems in military communication networks, presents the current capabilities of troposcatter systems and provides insights into advancements of this technology such as adaptive beamforming and Multiple Input Multiple Output Orthogonal Frequency Division Multiple Access (MIMO-OFDM) architectures. Building on these insights, the research investigates the use of Orthogonal Time Frequency Space (OTFS) modulation for tropospheric communications. Preliminary simulations conducted under severe multipath conditions demonstrate that OTFS outperforms traditional OFDM, offering improved signal integrity, reduced error vector magnitude, and greater spectral efficiency. These results suggest that OTFS-enabled troposcatter systems could enhance the current performance of military communication networks, particularly in interference-prone environments.*

Keywords: troposcatter, military communications, BLOS, OTFS, multipath fading

1. Introduction

In today's rapidly advancing information and communication technology landscape, ensuring reliable, secure, and efficient communication links has become a strategic priority, particularly in the military sector. Within this framework, tropospheric communications (troposcatter) are distinguished by their ability to realize connections beyond the line of sight (BLOS) without the need for complex ground infrastructures or constant satellite support.

This communications technology, although old, is gaining momentum as advanced countries begin to reintroduce it into their communications systems. Many developed nations are beginning to reap the benefits of this technology and are integrating it into their communications networks to ensure continuity of information exchange in remote areas, rugged terrain or harsh weather conditions [1]. Troposcatter systems are highly directional, employ complex waveforms and exploit scattering phenomenon being difficult to detect and intercept. These characteristics make it particularly well-suited to addressing many of the challenges NATO currently faces.

The major dependence of a communication infrastructure on a single type of communication (eg. satellite communication) presents significant vulnerabilities, tropospheric systems

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offering a robust alternative, less susceptible to external interference or direct attack. This type of communication is proving to be extremely valuable for military applications, where flexibility, speed and resilience are essential.

To this extent, the objective of this paper is to investigate the role of troposcatter systems in military communication networks, with a focus on evaluating the performance and characteristics of current state-of-the-art systems. The research aims to answer the following key questions:

A. How do troposcatter systems contribute to the resilience and efficiency of military communication networks?
B. What are the performance metrics and technological characteristics of the most advanced troposcatter systems currently in use?
C. What potential advancements in troposcatter technology could enhance its applicability and performance in military settings?

To address these questions, a comprehensive methodology will be employed, including a systematic review of recent literature, performance analysis of existing troposcatter systems and emerging technologies in the field. Additionally, the paper will explore the feasibility of integrating one particularly identified technical advancement into tropospheric communication systems by providing preliminary simulation results on the proposed solutions.

2. Troposcatter systems in military communication networks

In the military domain, tropospheric communications systems are essential to provide connectivity between units located at great distances or deployed in difficult terrain, where terrestrial infrastructure is non-existent, destroyed or inadequate, and satellite coverage is unavailable or subject to the risks of jamming and interception. These systems operate effectively in scenarios where direct visibility between stations is impossible (BLOS). Tropospheric communications can overcome geographical obstacles such as mountain ranges, dense forests or urban areas, while maintaining an operational range of more than 200 km.

When designing military communication networks, it is essential to ensure multiple layers of communication redundancy to mitigate disruptions. Figure 1 presents a common point-to-point communications configuration used to interconnect two distant locations using a variety of communication technologies including fiber optics, line-of-sight (LOS) radio relays, satellite communications (SATCOM) and troposcatter systems.

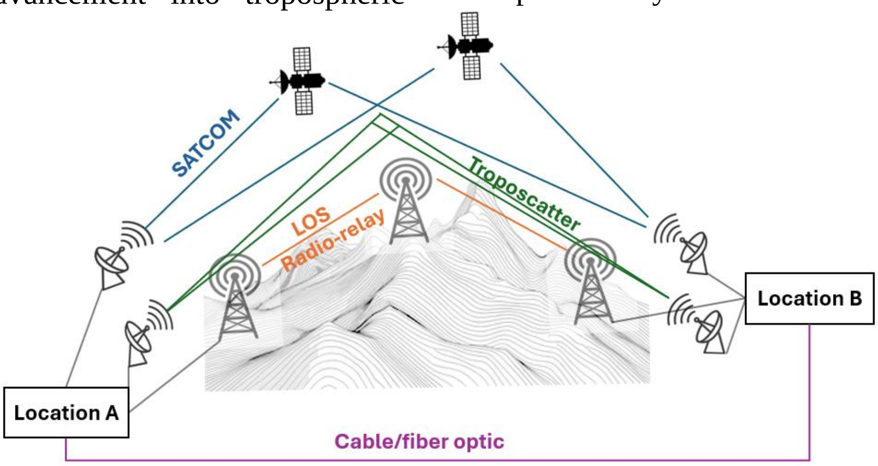

Figure 1: Point-to-point communication configuration

The achievable channel capacity and data transfer rates for troposcatter systems are quite low compared to LOS microwave systems operating in the same bands or satellite systems. However, there are situations where they have advantages over other radio transmission methods. Troposcatter systems are characterized by low initial costs, low latency (7-20 ms) [2], and greater flexibility in deployment compared to satellite systems, which require expensive infrastructure and have higher latency, especially in the case of Geostationary Orbit (GEO) satellites. Additionally, unlike LOS microwave systems, which are limited by terrain and require a dense network of repeater stations, troposcatter systems can cover longer distances over varied terrain with fewer installations. These attributes make troposcatter particularly useful for applications where rapid deployment, cost efficiency, and operational independence from satellite networks are critical—especially in emergency and crisis response environments.

The PACE (Primary, Alternate, Contingency, Emergency) plan provides a structured approach to communication fallback options, where each tier offers an alternative should the primary system fail [3]. Given their aforementioned characteristics, when integrated within the PACE plan, tropospheric communications are usually used as contingency and emergency options, especially in scenarios where satellite or terrestrial line-of-sight systems are unavailable or impractical. Figure 2 illustrates the appointment of troposcater systems in the PACE plan.

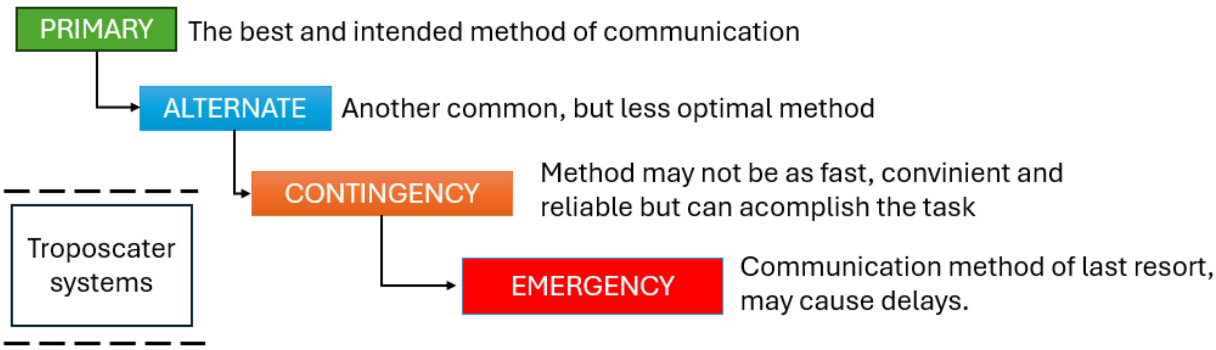

Figure 2: Troposcatter systems appointment in PACE plan

3. Troposcatter systems characteristics

Tropospheric communication systems intentionally exploit the natural inhomogeneities of the troposphere - specifically, local fluctuations in the index of refraction - to achieve long-range, BLOS communications. To this end, the systems use directional antennas that emit the signal at an angle to the horizon between 0.5° and 5°, focusing the energy into a narrow beam that intersects the receiver beam at an altitude of the order of kilometres. The region where the two beams overlap is called the common volume and is the area where the RF signal interacts with the tropospheric medium. Within the common volume, the existence of air cells with a refractive index higher than that of the surrounding air causes the signal to be scattered in several directions. A significant part of this scattered energy is redirected to the receiving antenna, allowing a radio link to be established. The efficiency of this transmission depends on several factors: transmitted power, bandwidth, operating frequency, atmospheric conditions and the geometry of the common volume. Due to the multiple propagation paths, the received signal is composed of several time-delayed waves (multipath), which can lead to interference and fading, but can be compensated for by modern diversity, adaptive modulation and error correction techniques [2,4,5].

Modern troposcatter systems can provide reliable communications over distances of

up to 400 km [6] without the need for intermediate relay stations. Depending on the type of modulation used and the separation distance, troposcatter systems can support data rates between 2 and 100 Mbps, with some configurations reportedly achieving rates as high as 210 Mbps [4,5].
The public literature reports several technological advancements related to tropospheric communication systems. One of these advancemets refers to the use of phased arrays and beamforming enabling dynamic adjustment of beam shapes to match the non-homogeneous scattering medium, improving signal-to-noise ratio (SNR) and data rates compared to traditional dish antennas [7,8].
Other findings suggest the use of cognitive and adaptive systems to enhance signal quality and capacity. These systems adapt to link geometry, meteorological conditions, and channel non-homogeneities, optimizing frequency and reception strategies [9,10]. Techniques like maximal ratio combining improve detection performance, especially under challenging conditions such as rain, low SNR, and high antenna elevation [9].
State-of-the art tropospheric communications systems are based on Orthogonal Frequency Division Multiplexing (OFDM). OFDM has been known to effectively combat multipath fading and inter-symbol interference, which are significant issues in troposcatter channels, enabling higher transmission rates and improved communication quality [11-13].
By dividing the available bandwidth into multiple orthogonal subcarriers, OFDM allows more efficient use of limited frequency resources, supporting higher data rates and larger capacity [11]. Combining OFDM with Multiple Input Multiple Output (MIMO) technology has been shown to further increase system capacity and reliability by exploiting spatial diversity [14-15]. MIMO-OFDM systems are generally robust to Doppler shifts, but performance can degrade with significant channel estimation errors [16].
Orthogonal Time Frequency Space (OTFS) is a novel type of modulation used in next-generation wireless communication systems to provide robust performance in high-mobility environments and time-varying channels. OTFS can be a promising technology for tropospheric communications due to the unique way it handles channel dispersion, making it much more robust than classical schemes such as OFDM, especially in multipath or high mobility environments [17-19].

4. OTFS modulation for tropospheric communication advancements

The tropospheric channel is often affected by multipath, frequency-selective fading and rapid time variations caused by moving air, clouds or moving objects (including atmospheric reflections or ducting) which can be a prerequisite for the effective use of OTFS modulation. To this extent the tropospheric channel can be modelled like a severe multipath channel, as suggested in figure 3.

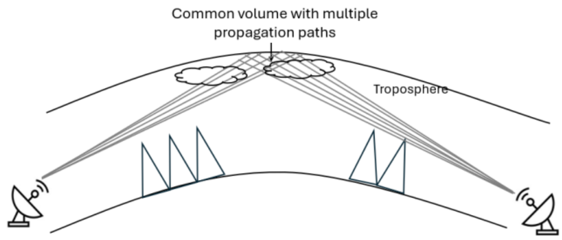

Figure 3: Multiple propagation paths for tropospheric channel modelling

In order to preliminarily test the hypothesis of using OTFS modulation in tropospheric communications, we performed a simulation in Matlab under the conditions of a severe multipath propagation channel (50 propagation paths) using 16 QAM modulation. We compared the performance of OFDM modulation with that of OTFS modulation in terms of signal constellation and implicit value of error vector magnitude (EVM).
As can be seen in figure 4 the signal sparsity for 16 QAM modulation under severe multipath propagation channel

conditions is much higher when using OFDM, having many scattered points in the constellation, leading to a higher EVM value. In contrast, OTFS manages to keep a more concentrated and compact constellation with fewer scattered points. This behavior is a direct result of the OTFS modulation, which optimizes the use of time and frequency spaces, managing to mitigate interference and distortion caused by multiple reflections and signal delays.

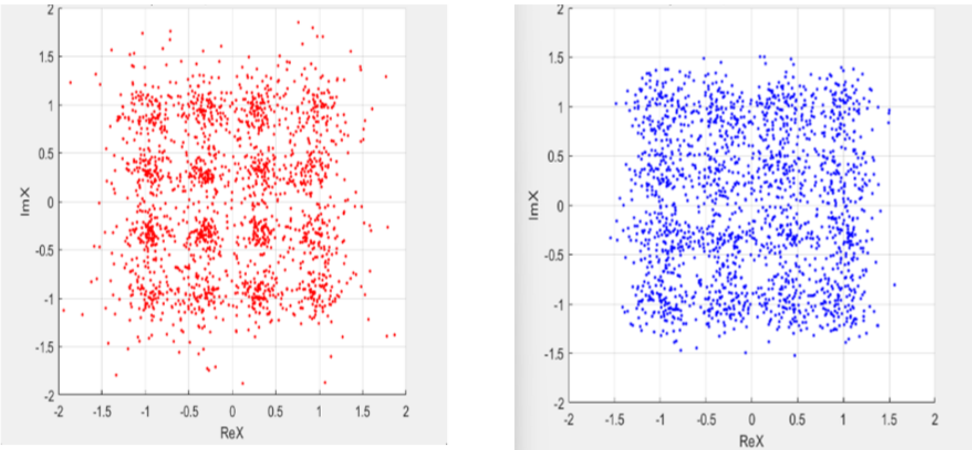

Figure 4: The constellation of a 16 QAM signal transmitted in a multipath channel using OFDM (a) and OTFS (b) at an SNR of 17 dB

As for the EVM value, Figure 5 compares the simulation result for the calculated EVM values for OFDM and OTFS modulation as a function of SNR value. The 13% threshold which is considered the limit for the correct operation of 16 QAM modulation is marked on the graph. The improvement of the minimum detection threshold when using OTFS is almost 4 dB, which confirms the superiority of OTFS modulations for channels affected by severe multipath propagation, like the tropospheric channel. The theoretical spectral efficiency improvement obtained in this case is presented in Figure 5(b).

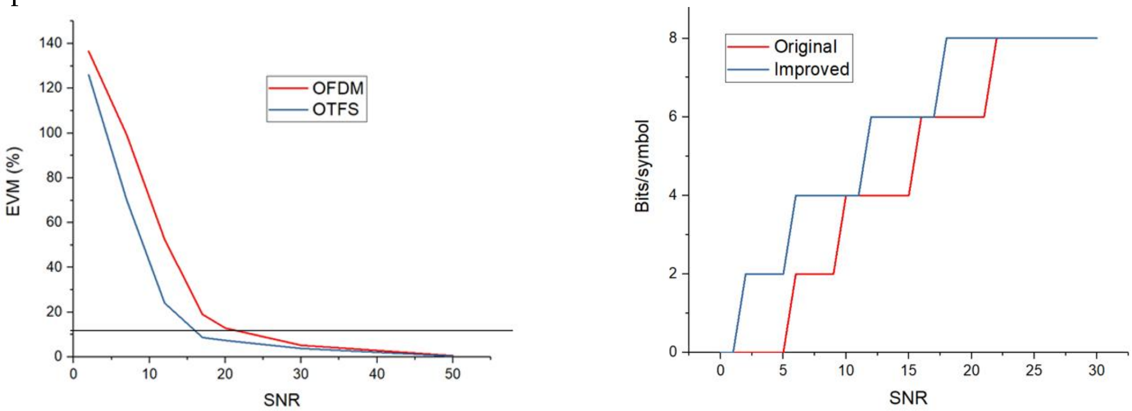

Figure 5: Simulated EVM versus SNR for OFDM/OTFS (a) and corresponding spectral efficiency improvement (b)

6. Conclusions

The research conducted in this paper highlights the relevance and growing potential of troposcatter systems in modern military communication networks, particularly in contested, remote, or infrastructure-deficient environments. Modern enhancements like adaptive beamforming, MIMO-OFDM, and cognitive adaptation have improved performance, overcoming legacy limitations. The research also identifies

OTFS modulation as a promising technology that troposcater systems could benefit from, with simulations showing improved signal integrity, EVM, and spectral efficiency under severe multipath conditions. Continued research and field testing, particularly of OTFS and other emerging waveform strategies, will be essential to fully realize the potential of troposcatter in future military communications architectures.

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