Integrated Navigation and Frequency-Hopping Communication

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Abstract - This paper presents a novel approach to Integrated Navigation and Communication, where a navigation signal is embedded into a frequency hopping (FH) communication waveform to provide Position, Navigation, and Timing (PNT) information in GPS-denied environments. This method offers an efficient alternative to satellite-based navigation, ensuring continuous operation in contested or obstructed environments, such as urban areas or military operations. We conduct an analysis of the mutual interference between the navigation and FH signals, focusing on decoding error probabilities for both. Our results show that embedding the navigation signal has a negligible effect on the FH communication signal, while the FH signal has a minor impact on the navigation signal. This interference can be mitigated with a slight increase in navigation signal power, not exceeding 0.5 dB. These findings demonstrate the viability of our approach, providing a reliable and secure PNT solution in GPS-denied areas.

I. Introduction

The integration of navigation and communication systems has emerged as a critical area of research and development in recent years, driven by the increasing demand for robust, efficient, and secure positioning and data transmission capabilities across various applications. This convergence of technologies enables devices to perform both tasks simultaneously without requiring additional spectrum, offering significant advantages in terms of spectrum efficiency, system resilience, and overall performance enhancement [1]–[3].

In this approach, the navigation data is sent along with the communication signal (e.g., tactical radio, Wi-Fi, or cellular signals) in such a way that the receiving device can extract both navigation and communication information from the same transmission [4]–[6]. This is particularly useful in GPS-denied environments, such as indoors, urban areas, tunnels, or military operations where GPS signals may be blocked or jammed. Recent advancements in 5G and emerging 6G technologies have opened new avenues for integrated navigation and communication systems. The dense network architecture and high-frequency bands utilized by these technologies enable precise timing and localization capabilities, complementing traditional GPS-based navigation [7].

In this paper, we propose an innovative concept of embedding a navigation signal into a frequency hopping (FH) communication waveform to deliver Position, Navigation, and Timing (PNT) information to FH radio units operating in GPS-denied areas. FH is a spread spectrum technique that rapidly shifts the carrier frequency across a wide bandwidth according to a predefined pattern, providing enhanced security and resistance to interference. This technique, which has evolved significantly since its early applications, is now used in various modern technologies, including satellite communications, Bluetooth, Wi-Fi, public safety networks, emergency services, and cognitive radios.

To evaluate the feasibility of this concept, we perform a detailed analysis of the mutual interference between the navigation signal and the FH signal, assessing the decoding error probability for both. Our results indicate that embedding the navigation signal has a negligible effect on the FH communication signal. However, the FH signal does exert a minor influence on the navigation signal, which can be mitigated by a slight increase in navigation signal power, not exceeding 0.5 dB. This analysis confirms the viability and effectiveness of our integrated approach, demonstrating that it is a robust solution for providing PNT services in GPS-denied environments.

II. System Model

A. Integrated Navigation and Communication Concept

In GPS-denied areas where traditional GPS signals are unavailable or compromised, communication radio units may present a potentially promising solution for navigation. The proposed concept centers on leveraging a number of position-known radio devices (equipped with GPS) or fixed known-position devices to provide essential PNT information in such GPS-denied environments. One of the main driving forces behind this approach stems from the significantly enhanced signal power of communication radio units in contrast to GPS satellites. This capability empowers them to effectively reduce the potential for GPS-denial. Figure 1 offers a visual representation of this concept.

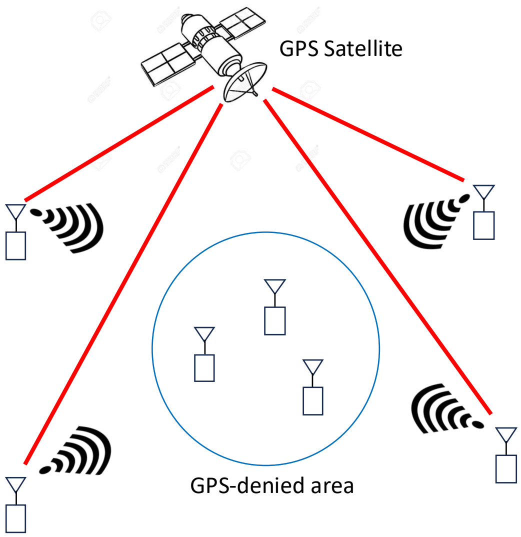

Fig. 1. Use case scenario. Radio units with GPS-based location awareness transmit integrated navigation and communication signals to deliver PNT information to radio units in GPS-denied areas.

To ensure seamless integration, both the navigation signal and the communication signal are simultaneously transmitted, with their spectra overlapping. This clever approach eliminates the need for an additional band to transmit the navigation signal by the communicatio radio units, thereby enhancing operational efficiency and effectiveness. The proposed concept takes advantage of the wideband nature of both the FH communication signal and the navigation signal, allowing their mutual interference to be suppressed effectively through processing gain.

B. Communication Signal

The communication signal, $x_f(t)$, utilizes an orthogonal frequency-hopping (FH) waveform. It serves as the carrier for information exchange among radio units. The signal operates with a bandwidth of B_f Hz, with its location periodically changing due to the FH waveform. The frequency hopping pattern is visualized in blue color in Figure 2.

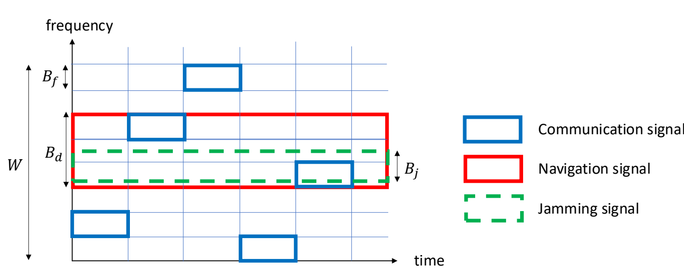

Fig. 2. Frequency and time of the communication signal (blue), navigation signal (red), and jamming signal (green).

In communication system, we allocate W Hz of spreading bandwidth, resulting in W/B_f frequency bins for hopping by each radio unit. We assume a uniform distribution of frequency hopping across the entire W Hz bandwidth. The received power of the communication signal is denoted by P_f.

C. Navigation Signal

The navigation signal, $x_d(t)$, comprises crucial components, including a pseudo-noise (PN) sequence essential for Time of Arrival (ToA) calculations by the receiving units, information about the time of transmission of the TOA message, and the precise location of the communication radio units.

This navigation signal operates as a direct-sequence spread-spectrum signal with a bandwidth of B_d Hz in the passband. If the chip duration is T_c, $B_d = 2/T_c$. Before transmission, the navigation signal is superimposed onto the communication signal, resulting in an overlap of their spectra as illustrated in Figure 2. Consequently, the navigation signal acts as a form of partial band jamming to the communication signal. The received power of the navigation signal is denoted by P_d.

D. Jamming Signal

The jamming signal, characterized by a bandwidth of B_j Hz, partially overlaps with the navigation signal band, as illustrated in Figure 2. The received power of the jamming signal is denoted by P_j.

III. Interference Analysis

When a FH communication signal falls within the navigation signal band, it gives rise to mutual interference between the communication signal and the navigation signal. In this section, we conduct an analysis to assess the magnitude of this mutual interference power, assuming that the system has established a perfect synchronization. Considering uniform frequency hopping, the probability of a communication signal falling into the navigation signal band can be expressed as:

$$q = \frac{B_d}{W}. \tag{1}$$

A. Interference to Navigation Signal

Figure 3 depicts the two-sided power spectral density (PSD) of the communication signal at carrier frequency f_c' and the navigation signal at carrier frequency f_c when they are collided. Upon down-converting the RF signal to the baseband and performing de-spreading (top of Figure 4), the PSD of both the communication signal and navigation signal undergo changes, as illustrated in Figures 4(A) and 4(B).

1) Communication Signal: The communication signal exhibits a two-sided PSD of S_f over the bandwidth B_f, centered at its carrier frequency f_c'. After down-conversion and de-spreading, the spectral height of the communication signal is reduced to:

$$S_f' = \frac{S_f B_f}{B_d + B_f}. \tag{2}$$

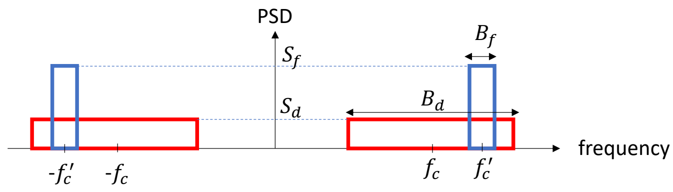

Fig. 3. Power spectral density of communicatio signal (blue) and navigation signal (red) when they are collided.

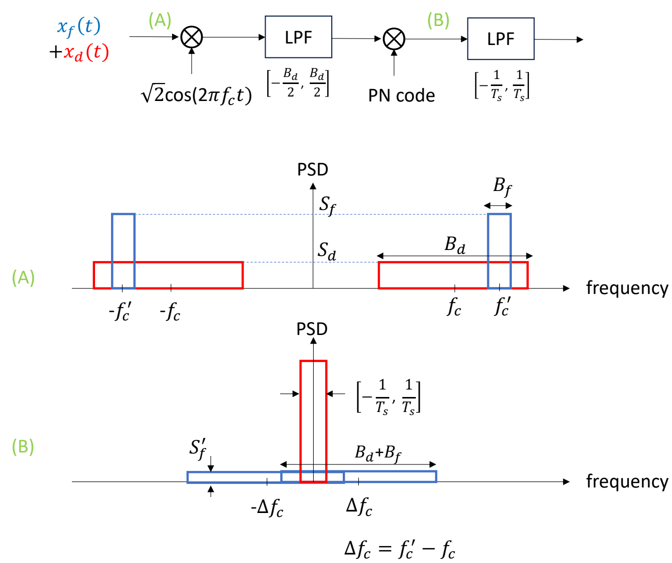

Fig. 4. Downconversion and despreading. Power spectral density of communication signal (blue) and navigation signal (red) before (A) and after (B) down-conversion and de-spreading.

Following low-pass filtering with a cutoff frequency of $1/T_s$, where T_s represents the code symbol duration of the navigation signal, the communication signal's power decreases to[1]:

$$P_f' = \frac{2S_f B_f}{B_d + B_f} \cdot \frac{2}{T_s} \quad (3)$$
$$= \frac{P_f}{B_d + B_f} \cdot \frac{2}{T_s} \quad (4)$$

where $P_f = 2S_f B_f$ denotes the received power of the communication signal. In general, when k communication signals fall into the navigation band, their total power decreases to:

$$P_f' = \frac{\sum_{i=1}^{k} P_{f,i}}{B_d + B_f} \cdot \frac{2}{T_s} \quad (5)$$

after de-spreading, where $P_{f,i}$ denotes the received RF power from the ith communication radio unit.

2) Jamming Signal: The jamming signal exhibits a two-sided PSD of S_j over the bandwidth B_j, centered at its carrier frequency f_c''. After down-conversion and de-spreading, the spectral height of the jamming signal is reduced to:

$$S_j' = \frac{S_j B_j}{B_d + B_j}. \quad (6)$$

Following low-pass filtering with a cutoff frequency of $1/T_s$, the jamming signal's power decreases to:

$$P_j' = \frac{2S_j B_j}{B_d + B_j} \cdot \frac{2}{T_s} \quad (7)$$
$$= \frac{P_j}{B_d + B_j} \cdot \frac{2}{T_s} \quad (8)$$

where $P_j = 2S_j B_j$ denotes the received power of the jamming signal.

If $B_d \gg B_f$ and $B_d \gg B_j$, we can approximate (3) and (8) as:

$$P_f' \simeq P_f T_c / T_s \quad (9)$$
$$P_j' \simeq P_j T_c / T_s. \quad (10)$$

From (9) and (10), it is evident that the interference introduced by the communication signal and jamming signal onto the navigation signal is suppressed by a factor of T_c/T_s. For the L1C navigation signal, where $T_c = 10^{-7}$ and $T_s = 10^{-2}$, the interference caused by the communication signal onto the navigation signal is suppressed by a factor of 10^{-5}.

3) SINR: The Signal-to-Interference-Noise Power Ratio (SINR) of the navigation signal is given by:

$$\gamma_d = \frac{P_d}{P_f' + P_j' + N_0/T_s} \quad (11)$$
$$= \frac{P_d}{\frac{\sum_{i=1}^{k} P_{f,i}}{B_d+B_f}\frac{2}{T_s} + \frac{P_j}{B_d+B_j}\frac{2}{T_s} + \frac{N_o}{T_s}}. \quad (12)$$

B. Interference to Communication Signal

1) Navigation Signal: The interference power that the navigation signal imposes onto the communication signal is $2S_d B_f$ (refer to Fig. 4(A)). Since the received navigation signal power is $P_d = 2S_d B_d$, the interference power affecting the communication signal is:

$$P_d' = P_d B_f / B_d. \quad (13)$$

From (13), we observe that the interference introduced by the navigation signal onto the communication signal is suppressed by a factor of B_f/B_d. For the L1C navigation signal, where $B_d = 20$ MHz, and for Protected Tactical Waveform (PTW) [8], where $B_f = 1$ MHz, the suppression factor is 0.05. This value is much less significant than the suppression factor from the communication signal onto the navigation signal.

2) Jamming Signal: The SINR of the communication signal in the presence of jamming can be calculated based on the interference power imposed by the jamming signal, denoted as P_j, which represents the received jamming signal power. In a scenario where partial band jamming occurs, with a fraction of the navigation signal band jammed, i.e., $B_j < B_d$, the

[1]This assumes $\Delta f_c - (B_d + B_f)/2 < -1/T_s$, which holds true because $\Delta f_c < B_d/2$ and $B_f/2 > 1/T_s$ (communication data rate is higher than navigation data rate) in practice.

probabilities for a tactical radio signal falling into different bands are as follows:

- Probability of communication signal falling into the jamming band and the navigation band: $P_{\text{jam and nav}} = B_j/W$
- Probability of communication signal falling into the non-jamming band but within the navigation band: $P_{\text{no jam but nav}} = (B_d - B_j)/W$
- Probability of communication signal falling into neither jamming nor navigation band: $P_{\text{no jam no nav}} = (W - B_d)/W$.

The SINR of the communication signal can then be expressed as:

$$\gamma_f = \begin{cases} \frac{P_f}{P_d B_f/B_d + P_j + N_0 B_f}, & \text{w/ prob } B_j/W \\ \frac{P_f}{P_d B_f/B_d + N_0 B_f}, & \text{w/ prob } (B_d - B_j)/W \\ \frac{P_f}{N_0 B_f}, & \text{w/ prob } (W - B_d)/W. \end{cases} \tag{14}$$

IV. Decoding Error Probability

In this section, we conduct an analysis of the decoding error probability for both the communication signal and the navigation signal, considering the mutual interference between them. We assume that there are K communication radio units and that their received powers are identical. Furthermore, we assume that the navigation signal utilizes Binary Phase Shift Keying (BPSK), while the communication signal employs Quadrature Phase Shift Keying (QPSK).

A. Bit Error Probability

1) Navigation Signal: The average bit error probability of the navigation sginal (before channel decoding) is given by

$$\epsilon_d = \sum_{k=0}^{K} Q\left(\sqrt{\frac{2P_d}{\frac{kP_f}{B_d+B_f}\frac{2}{T_s} + \frac{P_j}{B_d+B_j}\frac{2}{T_s} + \frac{N_0}{T_s}}}\right) \cdot \binom{K}{k} q^k (1-q)^{K-k}, \tag{15}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-u^2/2}du$ is the tail probability of normal distribution, and $\binom{K}{k}q^k(1-q)^{K-k}$ is the probability that k FH communication signals fall into the navigation signal band.

2) Communication Signal: The average bit error probability of the communication signal is given by

$$\epsilon_f = \frac{B_j}{W} \cdot Q\left(\sqrt{\frac{P_f}{P_d B_f/B_d + P_j + N_0 B_f}}\right) \tag{16}$$

$$+\frac{B_d - B_j}{W} \cdot Q\left(\sqrt{\frac{P_f}{P_d B_f/B_d + N_0 B_f}}\right) \tag{17}$$

$$+\frac{W - B_d}{W} \cdot Q\left(\sqrt{\frac{P_f}{N_0 B_f}}\right). \tag{18}$$

B. Decoding Error Probability

For a given transmission rate R (bits per channel use) and block length N, the decoding error probability is approximated by [9]

$$P_e \simeq Q\left(\sqrt{\frac{N}{p(1-p)}}\frac{\mathcal{C} - R}{\log_2((1-p)/p)}\right), \tag{19}$$

where p is the bit error rate (BER) before channel decoding and

$$\mathcal{C} = 1 + p\log_2(p) + (1-p)\log_2(1-p) \tag{20}$$

is the capacity (bits per channel use) of the binary symmetric channel with crossover probability p. The decoding error probability in (19) is tight even for relatively small N, e.g., $N = 200$ [9]. Hence, the decoding error probability for the navigation signal and the communication signal can be computed by replacing p in (19) with ϵ_d and ϵ_f, respectively.

V. Numerical Results

Figure 5 illustrates the decoding error probability of the communication signal with respect to P_f/N_0 (dB-Hz) for different values of P_d/N_0 (the carrier power to noise density ratio of the navigation signal). Notably, the decoding error probability of the communication signal remains virtually unaffected by the presence of the navigation signal, provided that P_d/N_0 is smaller than 55 dB-Hz. In this range, the interference from the navigation signal on the communication signal is significantly smaller than the background noise. It will be seen in Figure 6 that the operational range of P_d/N_0 for the navigation signal is well below 55 dB-Hz. Hence, the navigation signal has virtually no impact on the communication signal.

Figure 6 illustrates the decoding error probability of the navigation signal with respect to P_d/N_0 (dB-Hz) for different values of P_f/N_0 (the carrier power to noise density ratio of the communication signal). It can be seen from Figure 5 that P_f/N_0 needs to be in the range of $62 \sim 64$ dB-Hz where the desired decoding error probability can be achieved for the communication signal. In this range of P_f/N_0, the navigation signal power needs to be increased by at most 0.5 dB to achieve the same decoding error probability as in the case of no communicatio signal is transmitted. Hence, unlike the communication signal, the decoding error probability of the navigation signal is affected by the interference from the communication signal. However, the required power increase for the navigation signal to mitigate the communication interference is not significant (less than 0.5 dB).

VI. Conclusion and Furture Works

We investigated embedding a navigation signal into a FH communication signal to provide PNT information to the communication radio units in GPS-denied area. We found that the navigation signal has virtually no impact onto the

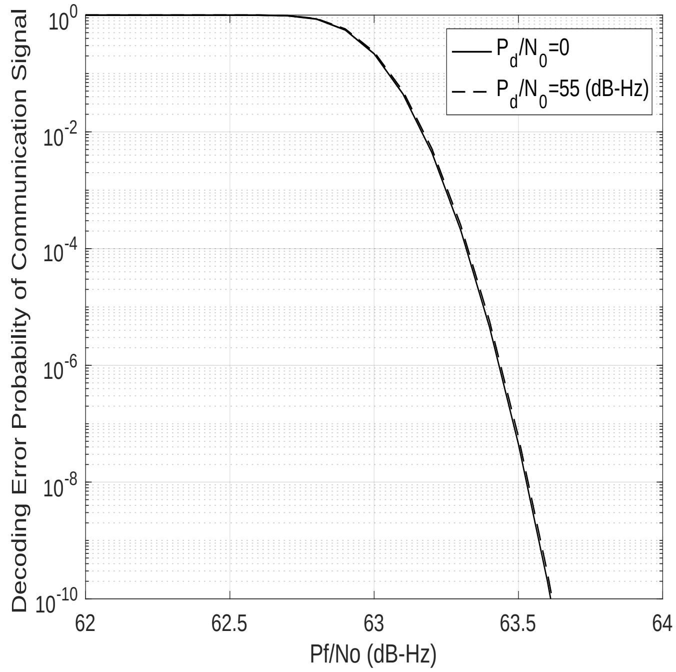

Fig. 5. Decoding error probability of the communication signal versus P_f/N_0 (dB-Hz) for different values of P_d/N_0; $K = 20$, $P_j/N_0 = 80$ dB-Hz, $B_f = 1$ MHz, $B_j = 10$ MHz, $B_d = 20$ MHz, $W = 125$ MHz, $N = 16200$, $R = 1/2$, $T_s = 0.01$.

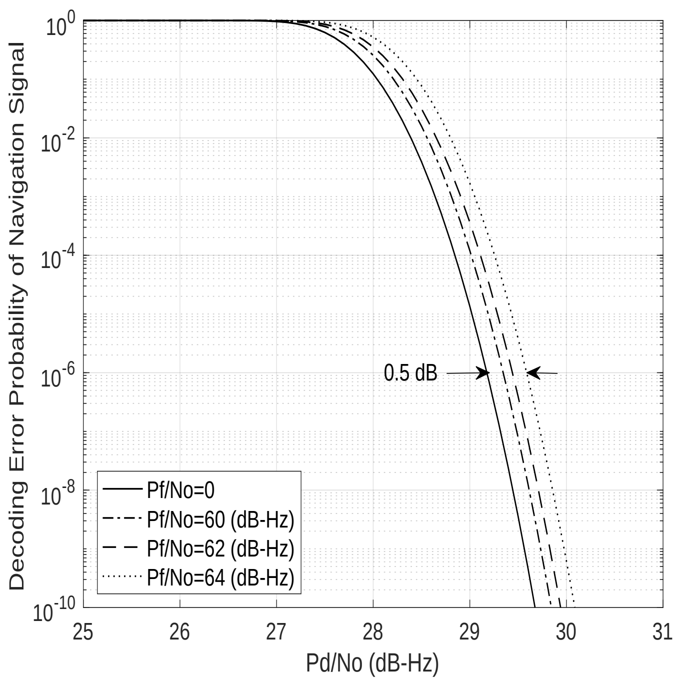

Fig. 6. Decoding error probability of the navigation signal versus P_d/N_0 (dB-Hz) for different values of P_f/N_0; $K = 20$, $P_j/N_0 = 80$ dB-Hz, $B_f = 1$ MHz, $B_j = 10$ MHz, $B_d = 20$ MHz, $W = 125$ MHz, $N = 1200$, $R = 1/2$, $T_s = 0.01$.

communication signal, but the communication signal has a minor impact on the navigation signal. It is found that the latter can be mitigated by increasing the navigation signal power by not more than 0.5 dB.

As a potential area for future investigation, it holds promise to explore the application of successive interference cancellation. This technique involves decoding the strong communication signal first, and then canceling it from the received signal. Subsequently, the navigation signal can be decoded without any interference from the communicatio signal. This approach has the potential to eliminate the need for a 0.5 dB increase in transmission power to compensate for the interference caused by the communication signal.

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