

A comparison between LoRa-inspired Chirp Spread Spectrum and Frequency Shift Keying modulations for underwater acoustic communications in snapping shrimp noise like environments

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Abstract—This paper provides a simulation-based comparison between LoRa-inspired Chirp Spread Spectrum (CSS) and Frequency Shift Keying (FSK) modulations. It considers CSS modulation with different Spreading Factors (SF) and FSK modulation including frequency diversity. As for the channel, additive white gaussian noise, shallow water and snapping shrimp like noise (UWAN) environments are considered. Results show that LoRa SF 7 exhibits superior robustness and achieves the lowest BER across all scenarios, outperforming both 16-FSK and 8-FSK including frequency diversity under AWGN and UWAN conditions. In frequency-selective channels for 200 m range, LoRa SF 7 provides the best performance across most of the SNR range, while at 500 m range it becomes more robust when a guard-time is introduced. The results highlight a fundamental trade-off between data rate and BER, confirming that LoRa-CSS is a suitable modulation scheme for underwater acoustic communications.

Keywords—Underwater Acoustic Communications, LoRa, Snapping Shrimp Noise.

I. INTRODUCTION

Underwater acoustic communications constitute the foundational enabling technology for wireless connectivity in shallow and deep-water environments. They support a wide range of applications, including oceanographic data collection, environmental and pollution monitoring, offshore exploration, infrastructure inspection, unmanned underwater vehicle coordination, and maritime surveillance [1], [2].

The underwater acoustic channel is, however, one of the most challenging communication media in engineering practice. Its behavior is shaped by severe bandwidth limitations, frequency-dependent attenuation, long and variable propagation delays caused by the low speed of sound in water, time-varying multipath propagation, doppler spreading, and ambient noise from natural and man-made sources. These impairments produce strong intersymbol interference (ISI), carrier and timing distortions, and large performance fluctuations across distance, depth, and sea-state conditions [3]. As a result, modulation and detection techniques that work efficiently in terrestrial radio channels often require adaptation before they can operate reliably underwater [4], [5].

These physical constraints directly influence the design objectives of underwater acoustic systems. Instead of maximizing raw throughput alone, practical systems must balance reliability, spectral efficiency, power consumption, implementation complexity, and robustness to nonstationary channel conditions. This is particularly important in realistic operational environments such as harbors, coastal waters, and shallow-water regions, where shipping activity, machinery, reverberation, and dense multipath can significantly degrade link quality [6]. Accordingly, the selection of an appropriate modulation scheme becomes a central design problem in underwater acoustic communications.

Within this context, the comparison of modulation techniques such as Frequency Shift Keying (FSK) and LoRa-inspired Chirp Spread Spectrum (CSS) is especially relevant. FSK has long been regarded as an attractive option for underwater links because of its relative simplicity and resilience in low-data-rate operation [7]. Noncoherent FSK detection avoids strict carrier phase tracking. For additional robustness, FSK can be also combined with frequency diversity, in which the same information is transmitted across multiple tones or frequency-separated channels so that deep fading or frequency-selective attenuation affecting one band does not necessarily destroy the symbol decision.

However, the limitations of FSK have motivated the investigation of LoRa-CSS as an alternative modulation strategy for underwater acoustic communications [8], [9], [10], [11]. Although FSK remains attractive because of its robustness and straightforward implementation at low bit rates, its performance can be significantly affected by limited spectral efficiency, sensitivity to severe frequency-selective fading, and the increasing receiver burden associated with higher-order M-FSK detection. These constraints become more pronounced in shallow-water and harbor-like environments, where strong multipath propagation, doppler spread, and intense anthropogenic noise may compromise the reliable detection of discrete tonal components.

In contrast, LoRa-CSS employs chirp-based signaling, in which information is distributed over a broader time–frequency structure rather than being confined to isolated tones. This characteristic provides inherent processing gain and improves robustness against synchronization errors, narrowband interference, and channel distortions commonly observed in realistic underwater scenarios.

Moreover, from an implementation perspective, LoRa-CSS detection can be efficiently realized through dechirping followed by a single FFT-based peak search, whereas orthogonal M-FSK reception generally requires the evaluation of multiple frequency hypotheses through a bank of correlators or matched filters. Consequently, the investigation of LoRa-CSS is of particular interest not only because of its potential for improved communication reliability, but also because it may offer a more scalable and energy-efficient receiver structure for embedded underwater platforms and UUV applications with strict energy-efficiency requirements. Despite recent advances, the performance of LoRa-inspired CSS under impulsive biological noise remains comparatively less explored, particularly in shallow-water environments affected by snapping-shrimp-like noise. This motivates an evaluation that goes beyond conventional AWGN assumptions and considers noise records representative of this type of environment.

This work evaluates the performance of LoRa-CSS for SF 6 and 7 in comparison with 16-FSK and 8-FSK including frequency diversity, on the 5-10 kHz bandwidth. As for the channel, additive white gaussian noise, shallow water, and snapping shrimp noise like environments are considered, utilizing data collected in Arraial do Cabo, RJ, Brazil. The underwater propagation model Kraken [12] is used for channel impulse response purposes. By incorporating nonwhite gaussian noise into the analysis, the study provides a more realistic assessment of communication performance in real world situations. The remainder of the paper is organized as follows: Section II presents LoRa-CSS modulation scheme; Section III the underwater acoustic channel modeling; Section IV results and discussion, and Section V the conclusion.

II. LORA MODULATION

LoRa modulation is based on Chirp Spread Spectrum (CSS), where the symbols alphabet is composed of chirp signals, all of them spreading across the entire bandwidth (BW), with start and stop frequencies that depend on the symbol order. The spreading factor (SF) defines the number of bits per symbol, which also determines the symbol duration (T_{sym}) for a fixed bandwidth, as shown in Eq. 1.

$$T_{sym} = \frac{2^{SF}}{BW}. \quad (1)$$

The higher the SF, the longer T_{sym} , and the lower the bit rate (R_b), which is given by Eq. 2.

$$R_b = \frac{SF}{T_{sym}} = \frac{SF \cdot BW}{2^{SF}}. \quad (2)$$

The LoRa-CSS symbol is created in a two-step process. It is first defined in baseband, spanning from $-\frac{BW}{2}$ to $\frac{BW}{2}$ Hz, as shown in Figure 1a. The upchirp is defined by Eq. 3,

$$x_S(t) = \begin{cases} e^{j2\pi\left(\frac{BW}{2T_{sym}}t^2 + \left(f(S) - \frac{BW}{2}\right)t\right)}, & 0 \leq t < t_{fold}, \\ e^{j2\pi\left(\frac{BW}{2T_{sym}}t^2 + \left(f(S) - \frac{3BW}{2}\right)t\right)}, & t_{fold} \leq t < T_{sym}, \end{cases} \quad (3)$$

where $x_S(t)$ represents the baseband chirp signal associated with symbol S , $f(S)$ is the chirp start frequency, and t_{fold} denotes the time instant at which the upchirp reaches the BW maximum frequency and wraps around towards the initial frequency again. Next, the symbol is upconverted to bandpass for transmission.

For symbol detection, 2^{SF} matched filters are used at the receiver utilizing a more efficient process, which takes advantage of the way the LoRa-CSS symbol is constructed. Instead of doing correlation calculations for each symbol, which is computationally expensive, a lower complexity approach known as dechirping is applied. The received signal is down converted to baseband and a Hadamard product calculated with a downchirp. The output for all matched filters are then obtained through signal resampling at a rate equal to BW, and a discrete Fourier Transform (DFT) is applied, which results in exactly 2^{SF} frequency bins. The bin with the highest amplitude represents the estimated transmitted symbol as shown in Figure 1b. More details on the LoRa-CSS modulation can be obtained in [13].

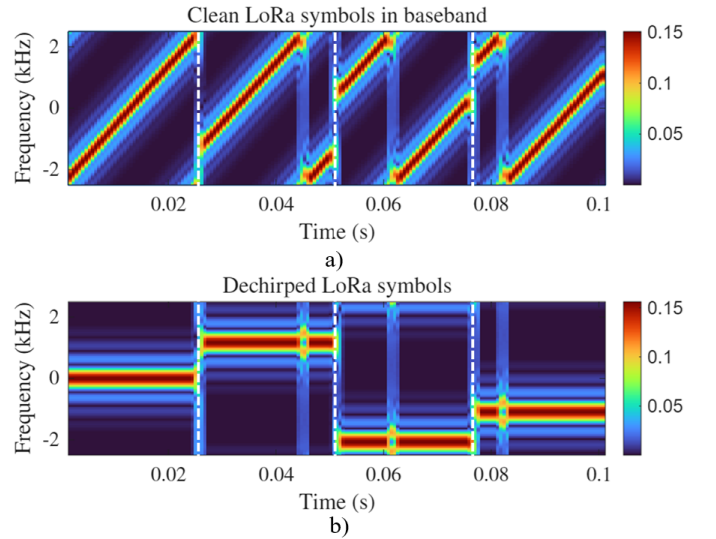


Fig. 1: Spectrograms of four LoRa symbols for $SF = 7$, with $S = \{0, 30, 75, 100\}$: (a) baseband modulated symbols; (b) dechirped symbols, in which each symbol is mapped into a single-tone at a discrete baseband frequency.

III. ENVIRONMENT MODEL

As for the channel impulse response, the environment is modeled as a two-layer Pekeris isospeed waveguide, as depicted in Figure 2. The water column is 20 m deep with 1500 m/s sound speed. The bottom is treated as a fluid with sound speed 1700 m/s, density of 1.9 g/cm³ and attenuation coefficient of 0.5 dB/m/kHz. A sound source ranging from 5 to 10 kHz is placed at 2 m depth and a pressure sensor is placed at 18 m depth at ranges of 200 and 500 m. The impulse responses $h(t)$ were obtained from Kraken normal mode propagation model, in the frequency range of 4 to 11 kHz, as shown in Figures 3a and b. The amplitude spectrums $|H(f)|$ for both impulse responses are shown in Figure 3c.

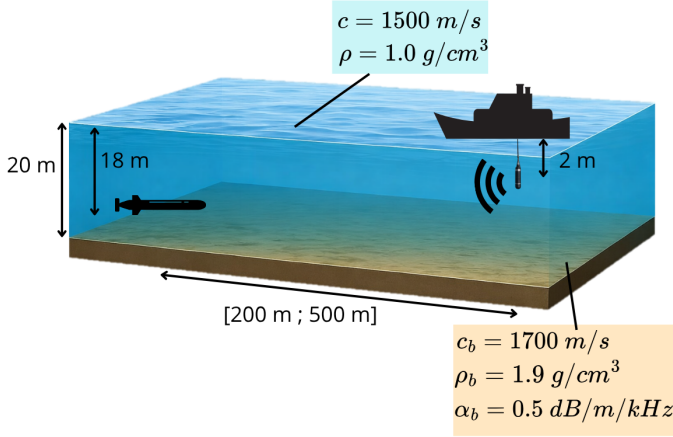


Fig. 2: Schematic representation of the waveguide properties used in calculations.

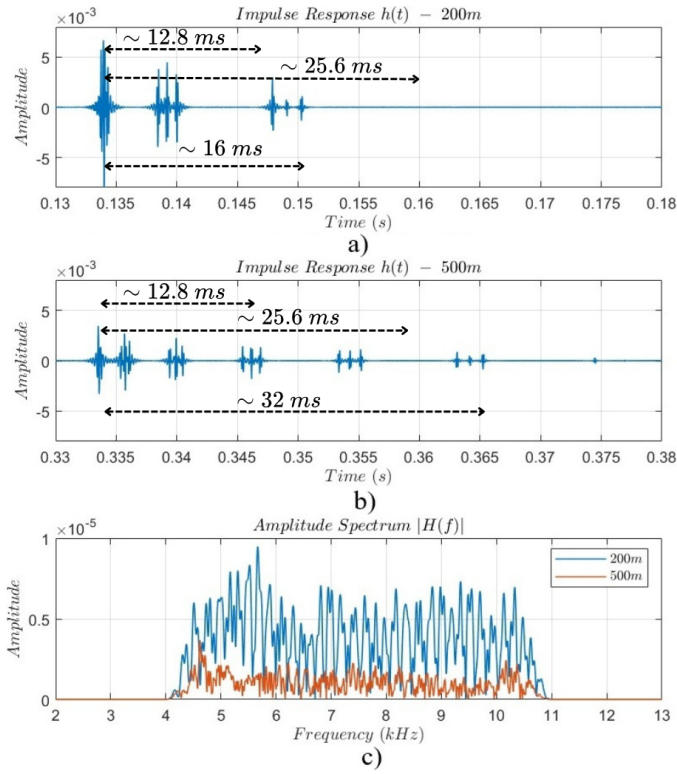


Fig. 3: Impulse responses for horizontal propagation (a) 200 m, (b) 500 m and (c) amplitude spectrums.

The multipath propagation is evident with multiple delayed components in the impulse responses. The delay spread is more pronounced at 500 m range. It is also observed lower amplitude in the impulse response for longer range due to geometric spreading and attenuation effects. Stronger fluctuations in the amplitude spectrum are also observed for 500 m range. In discrete time, the received signal $y[n]$ was obtained by convolving the transmitted signal $x[n]$ with the channel impulse response $h[n]$ of length L , and noise $r[n]$ added, as shown in Eq. 4,

$$y[n] = \sum_{l=0}^{L-1} h[l] x[n-l] + r[n] \quad (4)$$

where $x[n]$ is the transmitted signal, $h[l]$ is the sampled channel impulse response of length L , and $r[n]$ represents additive noise.

Synthetic white gaussian noise and data were utilized for performance analysis. The data was collected using a hydrophone installed in a cage close to the seafloor at ≈ 10 m depth. The hydrophone was deployed at the Praia dos Anjos, Arraial do Cabo, RJ, Brazil. The local underwater soundscape is heavily influenced by boats traffic, strong northeast winds and marine species living in the rocky shore, like barnacles, snapping shrimps, sea urchins, different types of fish and so on. Even though noise produced by boats is little compared to other sources of noise in the frequency range from 5 to 10 kHz, a time series restricted to the period from 8 pm to 8 am next day was picked to focus on noise produced mainly by natural and biological sources.

Figure 4 shows a chunk of underwater noise collected data. As can be observed, the underwater ambient noise exhibits non-stationary and impulsive snapping shrimp like characteristics.

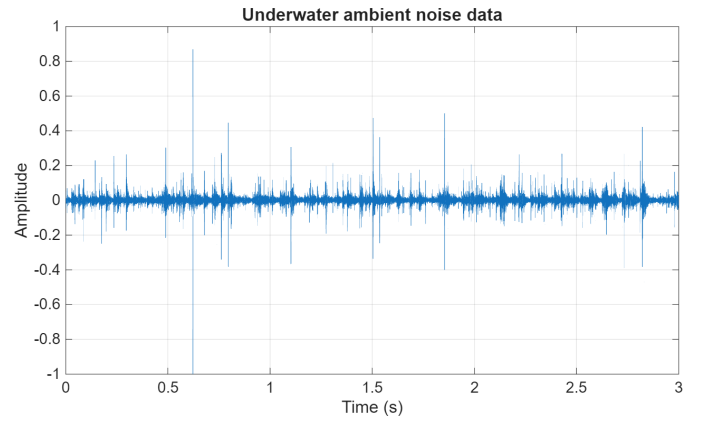


Fig. 4: Underwater ambient noise data collected in Arraial do Cabo, RJ, Brazil.

IV. EXPERIMENTS: RESULTS AND DISCUSSION

This section compares the performance for LoRa and FSK modulations. All simulations were carried out in the 5 to 10 kHz frequency range. For the 16-FSK scheme, the symbols are represented by Hanning-weighted pulses with a fixed duration of 12.8 ms, and carrier frequencies equally spaced within the bandwidth. As for the 8-FSK including frequency diversity, the 5 to 10 kHz frequency range is broken into two sub-bands, the lower band from 5 to 7.5 kHz and the upper band from 7.5 to 10 kHz. The redundancy includes the transmission of two symbols simultaneously from both sub-bands. Regarding LoRa, $SF = 6$ and $SF = 7$ were considered in the simulations. Table I summarizes the transmission rate and symbol duration for the modulation schemes. Figure 3 compares the spread of impulse responses in time to the symbol duration. The performance is evaluated by bit error rate (BER) versus Signal-to-Noise Ratio (SNR).

TABLE I: Symbol duration and bit rate for the modulations considered in the simulations (BW = 5 kHz)

Modulation	Symbol duration (ms)	Bit rate (bps)
LoRa (SF = 6)	12.8	468.75
16-FSK	12.8	312.50
LoRa (SF = 7)	25.6	273.44
8-FSK	12.8	234.38

A. Experiment 1: Flat channel

Figure 5 shows results for flat channel, i.e., all frequency components of the transmitted signal are equally affected by the channel response. Two types of noise are included: additive white Gaussian noise (AWGN) and snapping shrimp noise like data, from this point referred to as Underwater Ambient Noise (UWAN). The results for AWGN and UWAN are represented by dashed and continuous lines respectively. The 8-FSK scheme including frequency diversity is not presented in the flat-channel plot because frequency diversity is mainly beneficial for frequency-selective channels; under flat-channel conditions, its performance remains similar to that observed for conventional 16-FSK.

For the modulation schemes and parameters considered, the results suggest a trade-off between data and bit error rate: the lower the bit rate, such as for LoRa SF 7, the fewer the errors (lower BER), whereas the higher the bit rate the greater the errors (higher BER). Figure 5 shows that independent of the modulation scheme, BER is increased when non-stationary UWAN noise is utilized. The worsened performance is expected due to the impulsive and bursty nature of this type of noise, which exhibits heavy-tailed amplitude statistics and temporal memory [14]. These properties can produce localized high-amplitude events that disturb symbol decision even at the same SNR.

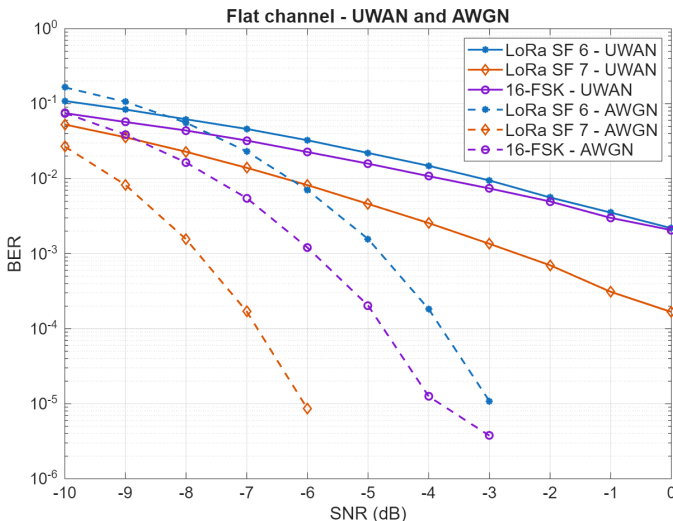


Fig. 5: Performance of LoRa and FSK for flat channel.

Furthermore, considering only the AWGN scenario, the best performance is achieved by LoRa with SF 7, reaching BER of 10^{-5} at -6 dB SNR. For the same SNR, LoRa SF 6 and 16-FSK have worse BER around 10^{-2} and 10^{-3} , respectively.

LoRa SF 6 and 16-FSK including UWAN tend to have similar performance at higher SNR, particularly for values greater than 0 dB. LoRa SF 7 has BER approximately one order of magnitude better than SF 6 for the same SNR. The results show that for UWAN situation, higher SF still provides better performance.

B. Experiment 2: Frequency-selective channel for 200 m

Figure 6 shows results for frequency-selective 200 m range channel including UWAN noise. LoRa SF 7 achieves the best BER compared to the other schemes. The first reason has to do with the symbol duration (25.6 ms) greater than the impulse response spread in time (16 ms). The ISI in this case is less pronounced, compared to the symbol duration of 12.8 ms for the other modulation schemes. 16-FSK had the worst performance. LoRa SF 6 and 8-FSK had similar performance at reasonable BER (10^{-3}), although LoRa SF 6 provides twice the bit rate. These results also show the trade-off between bit rate and BER, where LoRa SF 7 achieves the lowest BER at the cost of reduced bit rate, whereas LoRa SF 6 offers higher bit rate with increased errors.

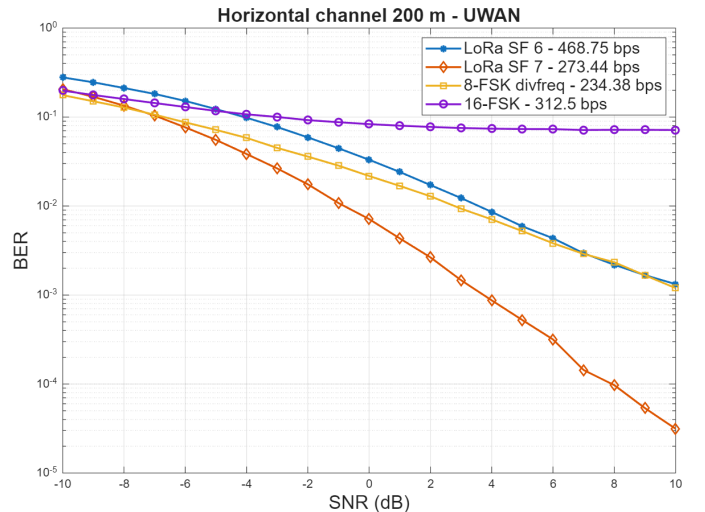


Fig. 6: Performance of LoRa and FSK for 200 m range.

C. Experiment 3: Frequency-selective channel for 500 m

Figure 7 shows results for frequency-selective 500 m range channel including UWAN noise. LoRa SF 7 with 4.26 ms guard-time is considered for the sake of comparison with 8-FSK including frequency-diversity, since both schemes occupy the same bandwidth and have approximately the same bit rate. The 500 m range has a spread of the impulse response in time ≈ 32 ms, which is greater than the symbol duration for all modulation schemes, including SF 7 with guard-time, from this point referred to as SF 7 GT.

LoRa SF 7 GT achieves the best BER (10^{-2}) compared to the other schemes. LoRa SF 7 comes in second place, which makes sense, since SF 7 GT suffers less from ISI. However, it can be noted that ISI worsened the results for all modulation schemes. That indicates the need for equalization

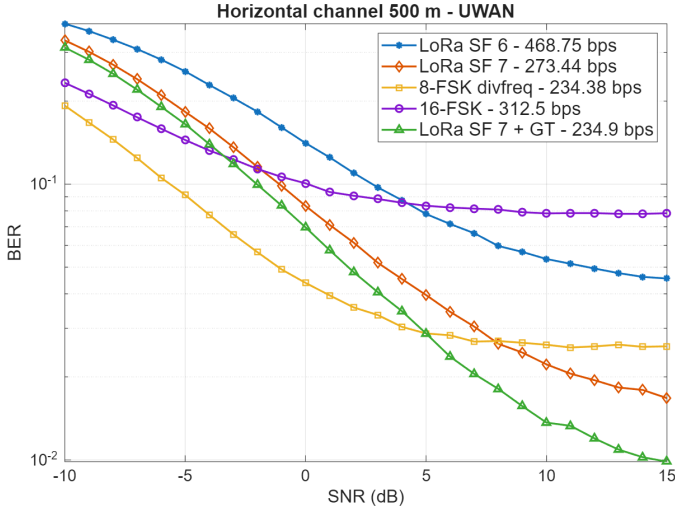


Fig. 7: Performance of LoRa and FSK for 500 m range.

for results compared to 200 m, otherwise the increase in SNR seems to be the way to go, which can be a problem for systems with restrictions on power consumption. LoRa SF 7 GT and LoRa SF 7 seem to work with much lower SNR than 8-FSK including frequency-diversity, for approximately the same BER and bit rate, which is especially interesting for many underwater applications. Finally, for the range of SNR considered in the simulations, 16-FSK had the worst results. It is also worth noting the impact of introducing a guard interval in the LoRa SF 7 configuration. With this adjustment, LoRa not only maintains a comparable data rate to 8-FSK with frequency diversity, but also achieves superior BER performance. At $\text{SNR} \approx 15$ dB, the BER is reduced to around 10^{-2} with the guard interval. This result highlights the effectiveness of combining higher spreading factors with guard intervals to improve robustness in longer links.

V. CONCLUSION

This paper evaluates the performance of LoRa-CSS modulation for SF 6 and 7 in comparison with 16-FSK and 8-FSK including frequency diversity under realistic underwater acoustic conditions. Simulation results incorporate snapping shrimp noise like data, thereby advancing the realism and practical applicability of the study. By utilizing actual underwater ambient noise characteristics, rather than relying solely on idealized AWGN assumptions, the evaluation provides insights that more accurately reflect real-world deployment scenarios. The results demonstrate that LoRa SF 7 exhibits superior robustness and achieves the lowest BER across the different scenarios analyzed. Under AWGN conditions, LoRa SF 7 outperforms both LoRa SF 6 and 16-FSK. Under UWAN conditions, the same tendency is observed, with LoRa SF 7 maintaining the best performance despite the higher BER caused by the impulsive and nonstationary characteristics of the real ambient underwater noise. For the 200 m scenario, LoRa SF 7 achieves the best performance over most of the SNR range. For the 500 m scenario, LoRa SF 7 becomes more robust as the SNR increases, especially when a guard-time is introduced.

The results highlight the fundamental trade-off between data rate and BER, since higher-rate configurations tend to suffer from increased error levels, particularly in more severe channel conditions. Although lower spreading factors (e.g., SF 6) can be an option when there is no limitation on power for increased SNR, the choice of spreading factor is critical for achieving reliable communication. The incorporation of snapping shrimp noise like data validates that LoRa's superior performance is not merely an artifact of simplified simulation assumptions but rather a genuine advantage in realistic underwater acoustic environments.

Overall, LoRa-CSS demonstrates reliable performance with competitive data rates, confirming its potential for underwater acoustic communications in shallow-water and harbor-like environments. Future work may explore the inclusion of equalization techniques and at-sea tests to further validate the findings and assess performance under dynamic real-world conditions.

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