Enhancing Resilience of Space Communications to Pulsed Jamming through Spatially Coupled Low-Density Parity-Check Codes

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***Abstract*—It is well known that one of the most dangerous attacks against space transmissions is jamming. In particular, space telemetry downlinks are subject to extremely tight power and bandwidth limitations and are hence vulnerable to intentional and accidental interference. While the Consultative Committee for Space Data Systems (CCSDS) has already standardized Low-Density Parity-Check (LDPC) codes for the use in space telemetry communications, we show that their performance is significantly deteriorated by the impact of pulsed jamming. We investigate the use of spatially coupled LDPC (SC-LDPC) codes as a promising alternative for improving reliability of telemetry channels in interference-heavy environments. We perform Monte Carlo simulations to assess the sensitivity of SC-LDPC-coded deep space communications to pulsed jamming, comparing attainable error rate performance with an LDPC code recommended in the CCSDS standard for telemetry synchronization and channel coding issues. Our results show that SC-LDPC codes can achieve improved error performance under different pulsed jamming conditions.**

***Index Terms*—Jamming, LDPC codes, Space communications, Spatially Coupled LDPC codes.**

I. Introduction

Jamming poses a serious threat to the reliability of downlink space communications, particularly in deep-space missions, where signals transmitted from spacecraft to ground stations undergo extreme attenuation, are subject to stringent power constraints, and remain highly exposed to intentional interference. Intentional jamming by adversarial entities, as well as unintentional interference, can severely compromise the integrity of communication links and lead to the loss of critical telemetry signals and scientific measurements. In such conditions, robust error correction becomes essential. Coding-based countermeasures proposed in the literature include code concatenation [1], [2] and bit-interleaved coded modulation with iterative decoding (bit-interleaved coded modulation with iterative decoding (BICM-ID)) [3].

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The Consultative Committee for Space Data Systems (CCSDS) 131.0-B-5 recommendation [4] for telemetry synchronization and channel coding issues includes several error correcting code families, i.e., convolutional, Reed-Solomon, and turbo codes, with Low-Density Parity-Check (LDPC) codes being the most recent addition and the primary focus of our study. The Accumulate, Repeat-by-4, and Jagged Accumulate (AR4JA) code family [5], standardized in [4], is a family of protograph-based LDPC codes. It exhibits an excellent trade-off between power efficiency and spectral efficiency, which makes these codes well suited for bandwidth-constrained space channels [6]. While the performance of AR4JA LDPC codes over Additive White Gaussian Noise (AWGN) channels is well studied [6], their behavior under jamming is less explored. Previous studies addressing LDPC-coded and Bose-Chaudhuri-Hocquenghem (BCH)-coded links under jamming focus on telecommand applications [7]–[10], which require short block-length codes. Preliminary evaluations of the error rate performance of an AR4JA LDPC codes under solar scintillation are reported in [11]–[13]. Other coding schemes have been evaluated in the presence of jamming in the downlink scenario, such as turbo codes [14].

In this work, we consider the scenario of LDPC-coded telemetry communications affected by jamming, and show that they suffer from significant performance degradation under jamming when standard CCSDS codes are used. Motivated by this observation, we investigate the use of Spatially Coupled Low-Density Parity-Check (SC-LDPC) codes (first introduced in [15] as LDPC convolutional codes) for space telemetry communications. The idea of considering these codes, which to our knowledge have never been tested in communication scenarios affected by jamming, is motivated by the fact that they have capacity-approaching properties under iterative decoding [16]. Through numerical simulations we show that using protograph-based SC-LDPC codes results in enhanced resilience to jamming with respect to standard LDPC block codes.

The paper is organized as follows. The necessary pre-

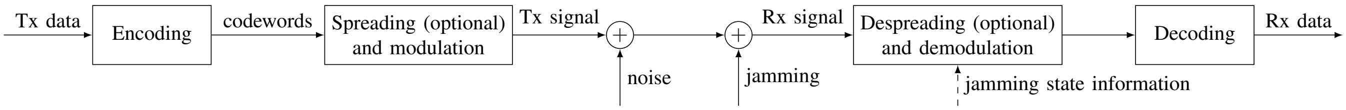

Fig. 1. Communication with jamming system model

liminaries on SC-LDPC codes and jamming are given in Section II, where we also introduce and describe the system model. In Section III, we present the codes we consider and provide a preliminary assessment of their performance under AWGN. Their error rate performance under jamming is assessed through Monte Carlo simulations and discussed in Section IV. Finally, we provide some concluding remarks and possible directions for future work in Section V.

II. Preliminaries and system model

In this section we introduce the necessary background regarding the communication channel with jamming and the family of SC-LDPC codes we consider.

The communication scenario analyzed in this work is schematically illustrated in Figure 1. Message bits are first partitioned into blocks and encoded with the selected error-correcting code. Each encoded block of q bits is then mapped by the modulator to a symbol from a 2^q-ary signal constellation and transmitted; optionally, a spreading operation may be applied to the encoded bits prior to modulation according to the Direct Sequence Spread Spectrum (DS-SS) approach. In this paper, we consider Binary Phase Shift Keying (BPSK) modulation, which means that we assume $q = 1$. The analysis can be obviously extended to other constellations.

During propagation, the transmitted signal is subject to two types of additive interference: thermal noise introduced by the channel and interference occupying the same frequency band. The latter may be either intentional (jamming originating from an adversary) or unintentional (for example, natural phenomena). The resulting disturbed waveform is received and may undergo an optional despreading operation (if spreading was used), followed by demodulation. Demodulation and subsequent detection can be performed with or without knowledge of the interference characteristics (i.e., with or without Jamming State Information (JSI)), which affects receiver performance. Finally, the soft or hard decisions produced by the detector are passed to the decoder to recover the transmitted data.

Spreading is generally effective against continuous, narrowband interferers while provides no benefit against pulsed, broadband jamming. Because this work focuses on the latter, we can omit spreading and despreading in the subsequent analysis, as will also be explained in Section II-B.

A. Terminated SC-LDPC codes

A binary linear block code $\mathcal{C}$ with length n is a k-dimensional linear subspace of $\mathbb{F}_2^n$. The code can be represented by a parity-check matrix $\mathbf{H}$, such that its null space is the code itself. Equivalently, $\mathcal{C} = \{\mathbf{c} \,|\, \mathbf{c}\mathbf{H}^\top = \mathbf{0}\}$, being $\mathbf{0}$ an all-zero vector, and $\mathbf{c}$ are codewords.

A bipartite graph $\mathcal{G}(\mathbf{H})$, referred to as a Tanner graph [17], can be constructed from the parity-check matrix $\mathbf{H}$. A protograph-based SC-LDPC code is obtained by coupling a sequence of small base Tanner graphs, known as *protographs* [18], over m_s+1 time units, where m_s is the code's syndrome former memory order. The base matrix $\mathbf{B}$ of a protograph is a small $r_0 \times n_0$ matrix with integer entries denoting the number of edges between the corresponding check and variable nodes. To form the spatially coupled structure, the edges of $\mathbf{B}$ are distributed across $m_s + 1$ component base matrices $\{\mathbf{B}_0, \mathbf{B}_1, \ldots, \mathbf{B}_{m_s}\}$ such that

$$\mathbf{B} = \sum_{i=0}^{m_s} \mathbf{B}_i.$$

These component matrices can then be arranged diagonally to form a terminated convolutional base matrix as follows:

$$\mathbf{B}_{\mathrm{SC}} = \begin{bmatrix} \mathbf{B}_0 & & & \\ \mathbf{B}_1 & \mathbf{B}_0 & & \\ \vdots & \mathbf{B}_1 & \ddots & \\ \mathbf{B}_{m_s} & \vdots & \ddots & \mathbf{B}_0 \\ & \mathbf{B}_{m_s} & \ddots & \mathbf{B}_1 \\ & & \ddots & \vdots \\ & & & \mathbf{B}_{m_s} \end{bmatrix}.$$

Outside the diagonal band formed by the component matrices $\mathbf{B}_0, \mathbf{B}_1, \ldots, \mathbf{B}_{m_s}$, all the remaining entries of $\mathbf{B}_{\mathrm{SC}}$ are zeros. The matrix $\mathbf{B}_{\mathrm{SC}}$ can then be *lifted* by a factor M, i.e., each non-zero entry is replaced by a sum of one or more $M \times M$ permutation matrices; zero entries are instead replaced by all-zero matrices. This produces the full binary parity-check matrix $\mathbf{H}$ of the terminated SC-LDPC code [19], describing a code with frame length LMn_0, where L is the number of spatial positions (i.e., replicas of the base matrices $\mathbf{B}_0, \mathbf{B}_1, \ldots, \mathbf{B}_{m_s}$) in $\mathbf{B}_{\mathrm{SC}}$. After lifting by a factor M, the parity-check matrix will be of size $(L + m_s)r_0M \times Ln_0M$. The design rate of the resulting SC-LDPC code is given by

$$R \geq R_\infty - \frac{m_s r_0}{n_0 L},$$

where $R_\infty = 1 - \frac{r_0}{n_0}$ denotes the asymptotic code rate. The inequality accounts for the fact that, in terminated SC-LDPC codes, the parity-check matrix does not necessarily have full rank. Finally, the code's syndrome former constraint length is defined as $\nu_s = Mn_0(m_s + 1)$.

B. Jamming model

Consistent with the jamming signal models found in the literature, in this work we consider a type of *pulsed jamming* that consists of a signal modeled as a sequence of Gaussian noise bursts separated by silent intervals [20].

More in detail, the jamming signal $j(t)$ is modeled as a Gaussian random process with band B, transmitted for a fraction $0 < \rho \leq 1$ of time. By denoting the jamming pulse duration by D and its period by T, we have that $\rho = D/T$. Clearly, if $D = T$, then $\rho = 1$ and the jamming signal is always present. Let us denote by P_J the average jamming power over time and by N_J the jamming signal power spectral density, which we assume to be constant. The pulsed jamming signal has no power for a fraction $(1-\rho)$ of time and a power $P'_J = P_J/\rho > P_J$ for the remaining fraction ρ of time. Therefore, for a given overall jamming power, if we decrease D, the amount of jamming power applied to the signals affected by jamming increases.

Let us consider its impact on a BPSK signal without DS-SS. At the receiver side, the received signal is projected on $\sqrt{\frac{2}{T_b}}\cos(2\pi f_0 t)$, where T_b is the bit duration and f_0 the carrier frequency. For each received bit, the added jamming signal, when present, can be modeled as a sample of the random variable

$$J = \int_0^{T_b} j(t)\sqrt{\frac{2}{T_b}}\cos(2\pi f_0 t)dt,$$

which is a Gaussian random variable with zero mean and variance $N'_J/2 = N_J/(2\rho)$. When instead the DS-SS signal is considered, the effect is the same, and we can show this as follows. DS-SS can be obtained by using a pseudonoise (PN) binary sequence $\{c_k\}$, $c_k \in \{-1,+1\}$, which is N times faster than the data sequence, i.e., it is characterized by a chip rate $R_c = NR_b$, with $R_b = 1/T_b$. With $T_c = 1/R_c = T_b/N$ we denote the chip time. By using a rectangular shaping filter of duration T_c, the spreading signal can be written as

$$c(t) = \sum_k c_k P_{T_c}(t - kT_c),$$

where $P_{T_c}(t)$ is a rectangular waveform with duration T_c. Then, the data signal $d(t)$ and the spreading signal $c(t)$ are directly multiplied over time. This way, each data symbol is multiplied by N chips of the PN sequence. Typically, N will be equal to the period of the PN sequence, but it can also be shorter, when a period is used for more than one bit. This is the case, for example, of coded transmission.

By considering DS-SS and working at bit time, we can project the received signal on $\sqrt{\frac{2}{T_b}}d(t)\cos(2\pi f_0 t)$ (bit time duration) and we obtain the same result as before. As an alternative, we can project it on $\sqrt{\frac{2}{T_c}}\cos(2\pi f_0 t)$ (chip time duration) and for each chip we obtain a Gaussian variable with zero mean and variance $N'_J/2 = N_J/(2\rho)$. At bit level we have:

$$J = \int_0^{T_b} j(t)\sqrt{\frac{2}{T_b}}\cos(2\pi f_0 t)dt = \sqrt{\frac{T_c}{T_b}}\sum_k J_k,$$

which gives the same result. This demonstrates that, for the specific type of jamming we are considering, it is irrelevant whether or not to include spreading and despreading blocks in the system.

In addition to the jamming signal, the channel is also affected by additive white Gaussian noise (AWGN) with a constant power spectral density of $N_0/2$.

III. CODES SELECTION

In our simulations, we consider the (protograph-based) AR4JA LDPC code specified in [4], with a code rate $R = 1/2$. This code, which represents the lowest-rate LDPC option in the standard, has an information length of $k = 1\,024$ and is derived from a parent code having length $n = 2\,560$. Then, the last 512 symbols of the parent code are punctured and, therefore, the effective number of modulated and transmitted symbols reduces to $n' = 2\,048$. The code rate $R = k/n' = 1/2$ therefore accounts for the symbols actually sent over the channel. Further implementation details of this well-known code are omitted for brevity and can be found in [6].

Furthermore, we consider terminated protograph-based SC-LDPC codes drawn from the $(3,6)$ regular ensemble, where each variable node has degree 3 and each check node has degree 6. The (uncoupled) base matrix is $\mathbf{B} = \begin{bmatrix} 3 & 3 \end{bmatrix}$. To construct the spatially coupled version with memory $m_s = 2$, we define the component matrices as $\mathbf{B}_0 = \mathbf{B}_1 = \mathbf{B}_2 = \begin{bmatrix} 1 & 1 \end{bmatrix}$, so that $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1 + \mathbf{B}_2$. The full terminated convolutional base matrix $\mathbf{B}_{\mathrm{SC}}$ is

$$\mathbf{B}_{\mathrm{SC}}^{(3,6)} = \begin{bmatrix} \mathbf{B}_0 & & & \\ \mathbf{B}_1 & \mathbf{B}_0 & & \\ \mathbf{B}_2 & \mathbf{B}_1 & \ddots & \\ & \mathbf{B}_2 & \ddots & \mathbf{B}_0 \\ & & \ddots & \mathbf{B}_1 \\ & & & \mathbf{B}_2 \end{bmatrix}.$$

Then, to obtain the matrix $\mathbf{H}$, we perform the lifting of $\mathbf{B}_{\mathrm{SC}}^{(3,6)}$ as described in Section II. Specifically, each entry equal to 1 in $\mathbf{B}_{\mathrm{SC}}^{(3,6)}$ is replaced by a randomly selected $M \times M$ permutation matrix, whereas each entry equal to 0 is replaced by an $M \times M$ all-zero matrix.

We consider two different codes lifted from $\mathbf{B}_{\mathrm{SC}}^{(3,6)}$:

- $\mathcal{C}_1$ with frame length 199 728, code rate $R = \frac{1}{2} - \frac{2\cdot 1}{2\cdot 292} = 1 - \frac{100\,548}{199\,728} = 0.4966$, $M = 342$, $L = 292$, and constraint length $\nu_s = 2052$;
- $\mathcal{C}_2$ with the same value of $M = 342$ and $\nu_s = 2052$, but $L = 73$. Thus, the frame length is 49 932 and the code rate is $R = 0.4863$.

Note that the SC-LDPC codes' constraint length is comparable with the effective block length of the AR4JA code. Moreover, all the three codes are characterized by rate ≈ 0.5.

We have run Monte Carlo simulations of BPSK-modulated and coded transmissions to compare their performance without the influence of a jamming distortion, i.e., just considering a conventional AWGN channel. In both cases, the LDPC decoder is a flooding schedule decoder running the Sum Product Algorithm (SPA). The maximum number of iterations has been set to 100. The results shown in Fig. 2 indicate that the SC-LDPC-coded transmissions have a better performance than the AR4JA-coded one.

IV. Numerical assessment of error rate performance

In this section, we describe the setup of the Monte Carlo simulations performed on BPSK-modulated transmissions under jamming, and present the corresponding results.

As discussed in Section II-B, *pulsed jamming* is characterized by a *pulse period* T and by a *duty cycle* ρ. In the simulation settings, they have been set to $T = 1280$ and $\rho = 0.1$, respectively. This arbitrary choice, made for illustrative purposes (other values could also be considered), corresponds to a burst period of

$$D = T \cdot \rho = 1280 \cdot 0.1 = 128 \text{ symbol time intervals.}$$

In other words, the jammer is active for the duration of 128 modulated symbols within each period of 1280 symbol times.

The error-rate performance under jamming is evaluated in terms of E_b/N_0 for several values of the ratio E_b/J_0 between the energy per bit and the one-sided jamming spectral density. Monte Carlo simulations have been conducted for transmissions encoded with the codes described in Section III, considering both the presence and absence of JSI at the demodulator. The values of E_b/J_0 have been set to 5, 10, and 15 dB, representing progressively weaker jamming conditions. As expected, the results show that increasing E_b/J_0 reduces the impact of jamming and leads to improved system performance.

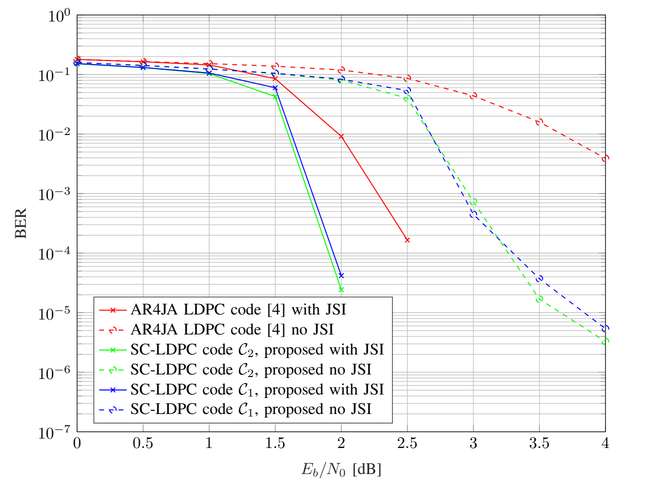

Fig. 3. Comparison between AR4JA and SC-LDPC codes at $E_b/J_0 = 5$ dB, with and without JSI

The trends discussed above are clearly illustrated in Fig.s 3-5, which indeed report the simulated error-rate performance of the considered coding schemes under pulsed jamming for different values of E_b/J_0, and for both cases with and without JSI. Across all scenarios, the SC-LDPC-coded transmissions exhibit a consistent performance advantage over the AR4JA-coded ones, confirming the increased robustness provided by spatial coupling. This improvement is particularly evident at

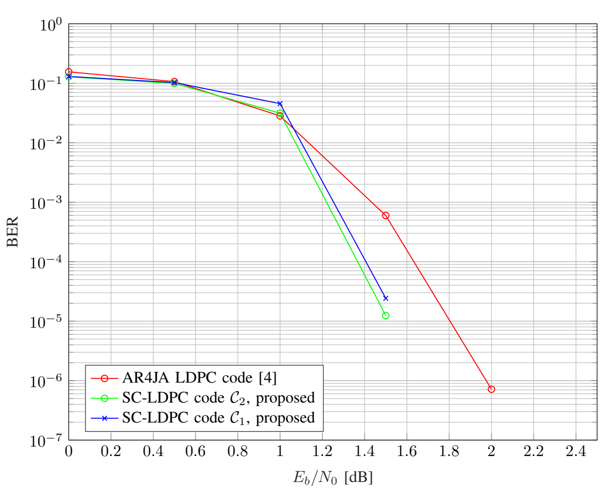

Fig. 2. AR4JA and SC-LDPC codes comparison over the AWGN channel (no jamming)

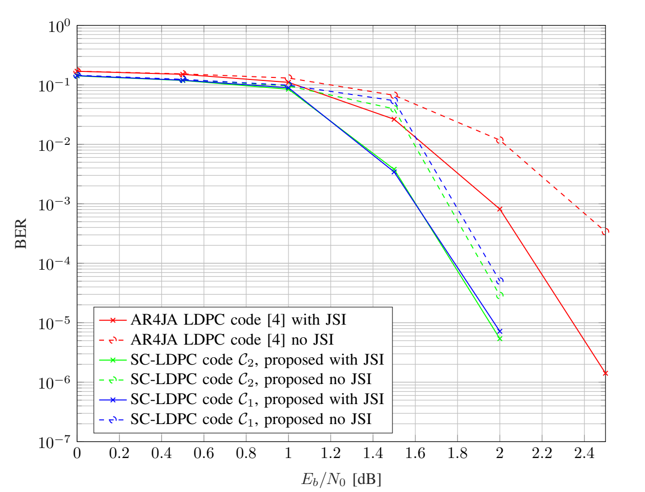

Fig. 4. Comparison between AR4JA and SC-LDPC codes at $E_b/J_0 = 10$ dB, with and without JSI

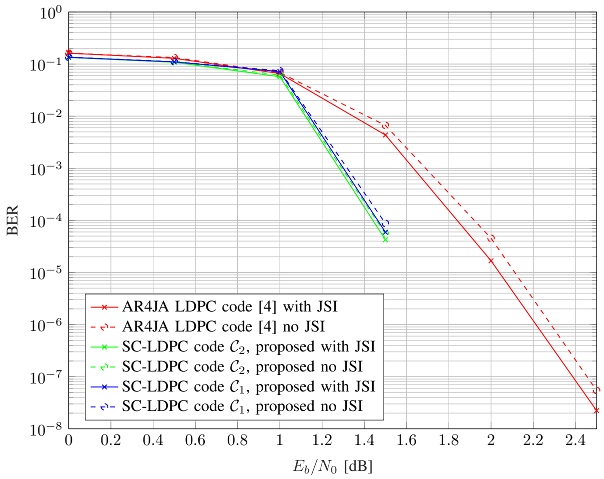

Fig. 5. Comparison between AR4JA and SC-LDPC codes at $E_b/J_0 = 15$ dB, with and without JSI

lower E_b/J_0 values, where the interference power is stronger and the system operates under harsher channel conditions. The availability of JSI at the demodulator further enhances detection performance for both code families, though the relative gain remains larger for the spatially coupled ensemble, indicating that the decoding process benefits more from accurate interference estimation when the underlying code structure is coupled.

A quantitative comparison highlights the extent of these improvements in terms of the E_b/N_0 required to achieve a given target error rate. At $E_b/J_0 = 5$ dB, corresponding to a strong jamming regime, when JSI is available, the SC-LDPC codes gain more than 0.5 dB in terms of E_b/N_0 with respect to the reference AR4JA code to reach a $\text{BER} \approx 10^{-4}$. Without JSI, all curves shift to higher E_b/N_0 values, yet the relative gain of the spatially coupled ensemble remains significant, confirming its robustness to impulsive interference. At $E_b/J_0 = 10$ dB, where the jamming effect is moderate, the E_b/N_0 gap between the two code families reduces to nearly 0.4 dB for both available and not available JSI. In the mild-jamming regime ($E_b/J_0 = 15$ dB), all codes approach their nominal AWGN performance, but the SC-LDPC schemes still exhibit a consistent gain of approximately 0.35 dB at $\text{BER} = 10^{-4}$.

V. Conclusion and Future Works

This work has examined the error-rate performance of modern protograph-based LDPC-based coding schemes for telemetry transmissions affected by additive interference, with particular attention to pulsed jamming. The study followed the CCSDS Telemetry recommendations and included simulations of the reference AR4JA code of rate $R = 1/2$ with $k = 1024$ information symbols, alongside our proposal: terminated protograph-based spatially coupled LDPC codes drawn from the $(3, 6)$ ensemble.

Monte Carlo results highlight a marked improvement in performance when spatial coupling is introduced. Thanks to the stronger connections between code nodes, the spatially coupled structure allows the decoder to recover more reliably under jamming. The results point to the potential of spatially coupled constructions to enhance the reliability of telemetry communications in the presence of interference.

Future investigations will focus on evaluating a wider range of coding rates for the AR4JA and the SC-LDPC code families, aiming to provide a more comprehensive characterization of their performance in jamming environments. Moreover, in [4], along with the LDPC codes, other codes, like conventional convolutional codes, $(255, 223)$ and $(255, 239)$ RS codes and a series of turbo codes of different rates and block sizes, are presented. We intend to study their performance and compare it with that of AR4JA LDPC codes and SC-LDPC codes.

Finally, we believe it could be interesting to extend this study to the case of continuous-wave jamming. This type of interference differs substantially from the broadband noise-like jamming considered here, as it consists of a narrowband, continuous signal that persists over time and overlaps spectrally with the useful transmission. Analyzing the behavior of both recommended and spatially coupled LDPC codes under such conditions would provide further insight into their robustness against different classes of interference.

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