Influence of the Channel Model in the Optimum Switching Points in an Adaptive Modulation System

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***Abstract*— Adaptive modulation techniques have been widely employed in order to improve the performance of wireless networks. The switching point between neighboring modulations is a key issue to define the performance of an adaptive modulation system. In this paper, we analyze in depth the influence of the fading channel model in the optimum switching points considering the maximum throughput as the criterion to determine the switching points.**

Keywords- Adaptive modulation; Nakagami-m fading; optimum switching points; maximum throughput criterion.

I. INTRODUCTION

Due to the growing demand for high transmission rates and the scarcity of spectrum in wireless networks, several studies have been developed to improve the performance and ensure Quality of Service (QoS) for such networks.

The adaptive modulation technique has been studied in order to improve the performance of time-varying conditions channels, maintaining the required performance [1]-[3]. This scheme consists of the dynamic adaptation of the modulation scheme as a function of the channel's state. The receptor makes an estimation of the channel state and sends this information back to the transmitter through a feedback channel. Based on this information, the transmitter changes the modulation order, choosing a modulation that better matches with the conditions of the channel at that time [1]-[5].

In general, the change of modulation order occurs between neighboring modulations (for a modulation with 2^n points in its constellation, the neighboring modulations has 2^{n-1} or 2^{n+1} points in its constellation). A key issue in adaptive modulation schemes is to define the best point to switch from one modulation to its neighboring modulation [4][5].

The switching points between neighboring modulations can be determined in several ways, and the most commonly used in the literature is to determine the switching as a function of a target for the bit error rate (BER) [2], or a target for the packet error rate (PER) in the channel [1]. However, in [4] the authors show that these criteria can't optimize some quality of service parameters, like throughput; thus, these authors propose the determination of the optimum switching points based on the maximum throughput criterion in the wireless channels. The analysis presented in [4] consider a memory-less channel, e.g., an AWGN channel. Then, in [5], the authors use the same criterion, but considering Rayleigh fading channels, and show that the model of the channel affects the optimum switching points.

In this paper, we analyze in depth the influence of the channel model in the optimum switching points of an adaptive modulation scheme. For this, we consider the more generic Nakagami-*m* channel model. We consider a wireless network over a Nakagami-*m* block fading channel with adaptive *M*-ary Quadrature Amplitude Modulation (*M*-QAM). Thus, this paper extends the analysis presented in [5] considering several different fading channels, besides the Rayleigh fading model considered in [5].

The remainder of this paper is organized as follows: In Section II, we introduce the channel model; in Section III, we present the calculation of the exact PER in the channel, necessary to compute the throughput; the maximum throughput criterion is shown in Section IV; Section V presents the numerical results, and finally we present our conclusions in Section VI.

II. CHANEL MODEL

We assumed that the transmissions occur over a slowly-varying flat-fading channel, modeled as a Nakagami-*m* block fading channel, where the choice of modulation in the physical layer is made on a frame-by-frame basis, so that the channel gain remains invariant on a single frame, but may vary between adjacent frames [1][3].

The signal-to-noise ratio (SNR) in the receiver can be statistically described by a general Nakagami-*m* model, with probability density function (pdf) given by:

$$p_{\gamma}(\gamma) = \frac{m^m \gamma^{m-1}}{\left(\bar{\gamma}\right)^m \Gamma(m)} \exp\left(-\frac{m\gamma}{\bar{\gamma}}\right). \quad (1)$$

where $\bar{\gamma}$ is the average received SNR, $\Gamma(m)$ is the Gamma function defined by $\Gamma(m) = \int_0^{\infty} x^{m-1} e^{-x} dx$, and m is the Nakagami fading parameter [1].

The Nakagami-*m* fading model is equivalent to a set of independent Rayleigh fading channels obtained by maximum ratio combining (MRC), with the diversity order of m [6].The Nakagami-*m* distribution is an approximation widely used in literature for representing a wide range of multipath

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channels [2]. For $m = 0.5$, the Nakagami fading model represents the unilateral Gaussian distribution (which corresponds to the highest amount of multipath fading scenario). When $m = 1$, it assumes a Rayleigh distribution model. For $m > 1$, there is a one-to-one mapping between the Nakagami fading parameter and the Rician factor and allows the Nakagami distribution to approach the Rice distribution [2]. Furthermore, reference [2] claim that the Nakagami-*m* distribution often gives the best fit to urban and indoor multipath propagation.

Thus, in this paper, we study the impacts of the variation of the parameter *m* in the optimum switching points in an adaptive modulation scheme.

III. Calculation of the Exact PER

A. Instantaneous PER

We employed several *n*-mode modulation schemes in our analysis: *M*-QAM with *M* = 8, 16, 32, 64, 128 and 256. Each *M*-ary modulation scheme has R_n bits per symbol, where and *n* = 1, 2… 6 the modulation mode (one of the six considered modulations).

The data is transmitted in packets containing a fixed number of bits, called n_p. Therefore, in each modulation mode each packet is mapped in n_p / R_n symbols [1].

For a system where the bits inside a packet have the same BER and the bit-errors are uncorrelated, the PER can be calculated as a function of the BER, as in [1]:

$$PER = 1 - \left(1 - BER\right)^{n_p} . \tag{2}$$

However, the author of [1] claims that the PER calculation through BER in (2) isn't accurate for large-size QAM constellations because the information bits of the same packet incurs different error probabilities for such constellations.

In this paper, we use the approach proposed in [1] to compute the PER in the system, which, in turn, is based on the methodology proposed in [7] to compute the exact BER for an arbitrary rectangular *M*-QAM modulation.

To compute the BER, following [7], we consider that a rectangular *M*-QAM modulation can be modeled as two independent pulse amplitude modulation (PAM), *I*-ary and *J*-ary, where $M = I * J$. The exact BER expression is obtained by observing regular patterns that occur due to the characteristics of Gray code bit mapping. The error probability of the *k*th bit in-phase components of the *I*-ary PAM, where $k \in \{1, 2, ..., \log_2 I\}$, is given by [7]:

$$P_I(k) = \frac{1}{I} \sum_{i=0}^{(1-2^{-k})I-1} \left\{ (-1)^{\left\lfloor \frac{i \cdot 2^{k-1}}{I} \right\rfloor} \left[2^{k-1} - \left\lfloor \frac{i \cdot 2^{k-1}}{I} + \frac{1}{2} \right\rfloor \right] \times \operatorname{erfc}\left((2i+1) \sqrt{\frac{3 \log_2 (I \cdot J) \cdot \delta}{I^2 + J^2 - 2}} \right) \right\} \tag{3}$$

where δ denotes the SNR per bit, and $\lfloor x \rfloor$ denotes the largest integer to *x*.

The error probability of the *l*th bit in the quadrature components of the *J*-ary PAM, where $l \in \{1, 2, ..., \log_2 J\}$, is obtained from [7]:

$$P_J(l) = \frac{1}{J} \sum_{j=0}^{(1-2^{-l})J-1} \left\{ (-1)^{\left\lfloor \frac{j \cdot 2^{l-1}}{J} \right\rfloor} \left[2^{l-1} - \left\lfloor \frac{j \cdot 2^{l-1}}{J} + \frac{1}{2} \right\rfloor \right] \times \operatorname{erfc}\left((2j+1) \sqrt{\frac{3 \log_2 (I \cdot J) \cdot \delta}{I^2 + J^2 - 2}} \right) \right\}. \tag{4}$$

In [1], the authors use the results given by (3) and (4) and derive an exact closed-form to compute PER. The exact instantaneous PER for each modulation mode as a function of the received SNR in a system with rectangular QAM symbols is given by [1]:

$$PER_n(\gamma) = 1 - \left\{ \prod_{k=1}^{\log_2 I} [1 - P_I(k)]^{(n_p / \log_2 (I \cdot J))} \times \prod_{l=1}^{\log_2 J} [1 - P_J(l)]^{(n_p / \log_2 (I \cdot J))} \right\}. \tag{5}$$

To compute $P_I(k)$ and $P_J(l)$ we considered $I = J = \sqrt{M}$ for square QAM modulations (256, 64 and 16-QAM), $I = 8$ and $J = 16$ for 128-QAM, $I = 4$ and $J = 8$ for 32-QAM, and finally $I = 2$ and $J = 4$ for 8-QAM.

B. Average PER

As stated earlier, in this system the packets are transmitted over a block-fading channel and, to determine the average PER, it is necessary to consider the influence of the fading. So, the average PER for each modulation mode is equal to the integral of the instantaneous PER for the current modulation *n*, multiplied by the probability density function of the received SNR (in this case, the pdf of a Nakagami-*m* distribution)[1][8][9]. Therefore, the average PER is:

$$PER_n(\bar{\gamma}) = \int_0^\infty PER_n(\gamma) p_\gamma(\gamma) d\gamma. \tag{6}$$

IV. The Maximum Throughput Criterion

Since we considered an adaptive modulation scheme without coding, all transmitted bits will be information bits. We consider only correct packets to compute the throughput (some authors refer to this as goodput). Thus, to compute the normalized throughput of the current modulations, we consider the following factors [4]:

- The ratio between the maximum numbers of transmitted bits and the maximum number of possible bits. In other words, the number of bits per symbol of the current modulation over the number of bits per symbol of a reference modulation (in our case, 256-QAM);
- The percentage of packets correctly transmitted.

The normalized throughput of the current modulation is given by:

$$\eta = \frac{\log_2 M_i}{\log_2 M_r} \cdot P_c \tag{7}$$

where M_i is the number of points in the constellation of the current modulation, M_r is the number of points in the constellation of the reference modulation and P_c is the probability of a packet being correctly transmitted, given by, $P_c = (1 - PER)$.

V. NUMERICAL RESULTS

In this section, we present numerical results for the optimum switching points using the maximum throughput criterion. We considered 256-QAM as the reference modulation and we set the packet length, following [5], n_p = 424 bits. We analyze the influence of the fading on the optimum switching points by varying the diversity order m of the fading Nakagami considering m = 0.5, 1, 2, 3 and 10 (this value was used in order to consider an AWGN-like channel).

To compute the throughput, for a given modulation and a given average SNR, we compute the PER using (3), (4), (5) and (6), then we compute the throughput using (7). All computations were done using Mathcad software.

Figures 1, 3, 5, 7 and 9 show the throughput curves, as a function of the average SNR, for m = 0.5, 1, 2, 3 and 10, and modulations 256, 128, 64-QAM, respectively. Figures 2, 4, 6, 8 and 10 show the throughput curves, as a function of the average SNR, for the same m = 0.5, 1, 2, 3 and 10, but now considering the modulations 64, 32, 16 and 8-QAM, respectively.

The optimum switching point between two neighboring modulations is obtained by the crossing point of the corresponding throughput curves.

Table I shows the optimal switching points and the throughput in these points. We can observe that the throughput in the switching points increases with the increasing of the diversity order m. So, in a system with adaptive modulation at the physical layer, if the diversity order increases, i.e., the channel becomes less severe in terms of fading, the throughput in the switching points improves.

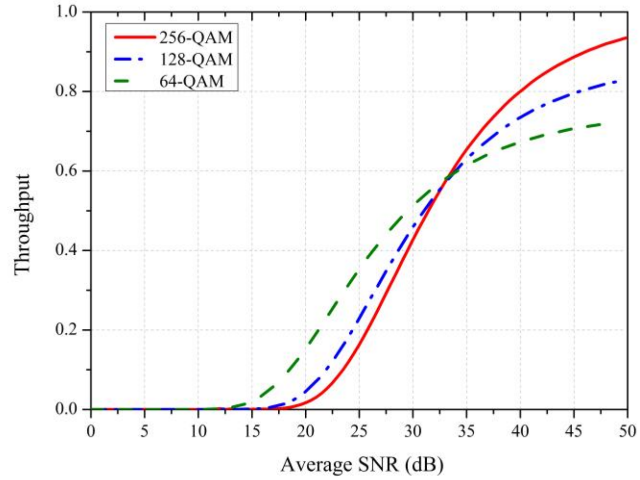

Figure 1. Throughput for m = 0.5 and 256, 128 and 64-QAM.

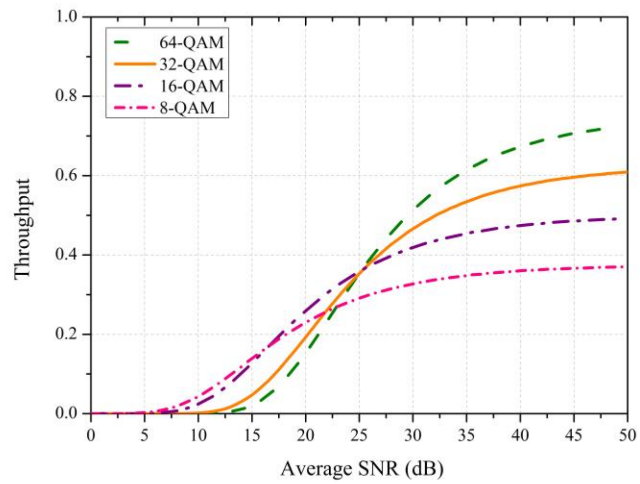

Figure 2. Throughput for m = 0.5 and 64, 32, 16 and 8-QAM.

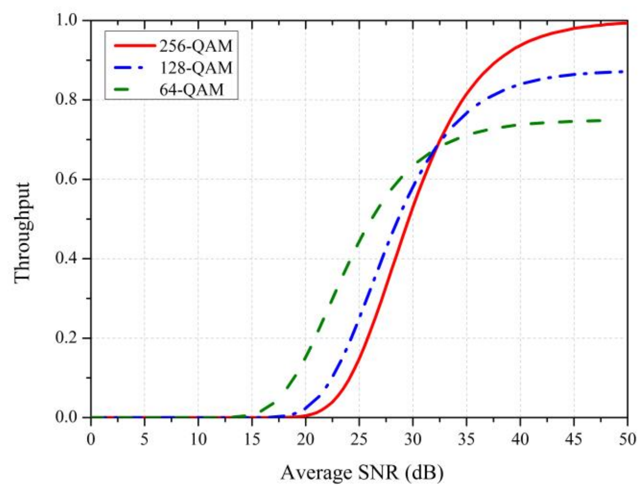

Figure 3. Throughput for m = 1 and 256, 128 and 64-QAM.

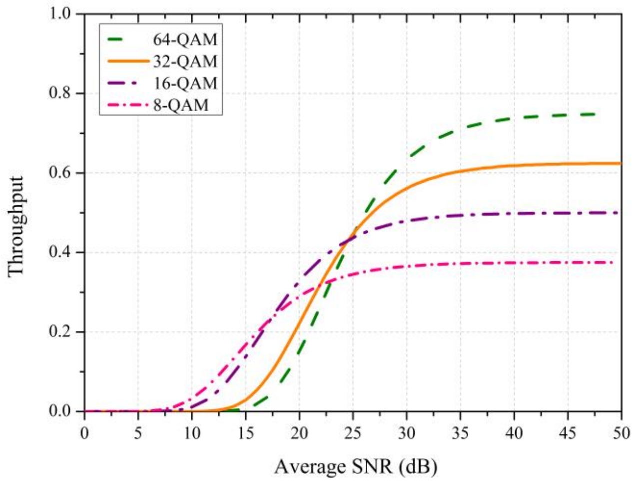

Figure 4. Throughput for m = 1 and 64, 32, 16 and 8-QAM.

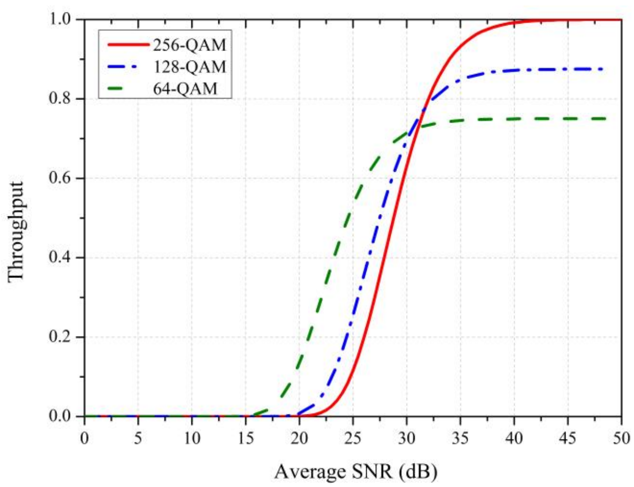

Figure 5. Throughput for m = 2 and 256, 128 and 64-QAM.

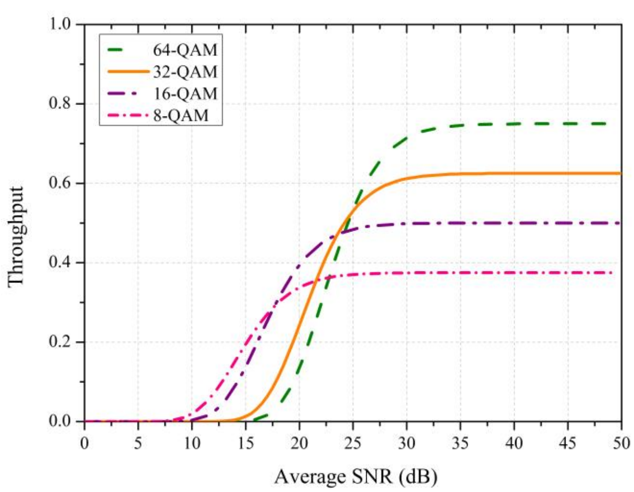

Figure 6. Throughput for m = 2 and 64, 32, 16 and 8-QAM.

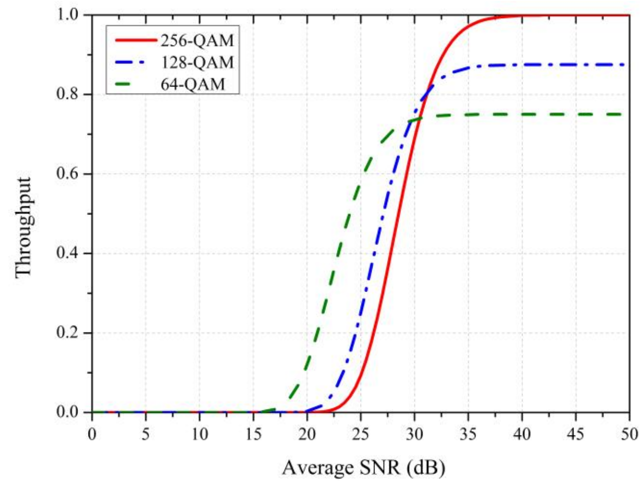

Figure 7. Throughput for m = 3 and 256, 128 and 64-QAM.

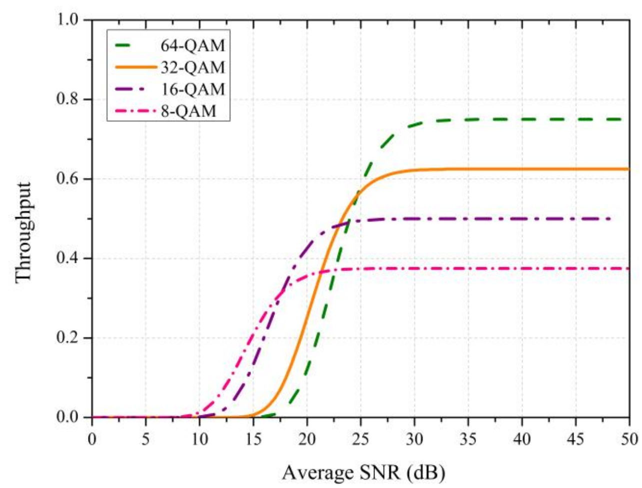

Figure 8. Throughput for m = 3 and 64, 32, 16 and 8-QAM.

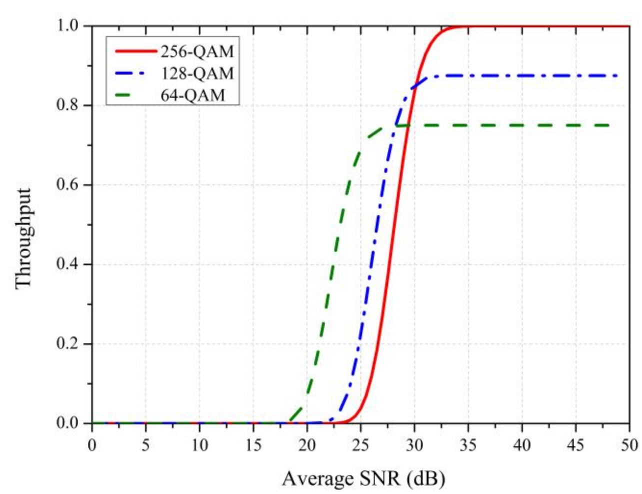

Figure 9. Throughput for m = 10 and 256, 128 and 64-QAM.

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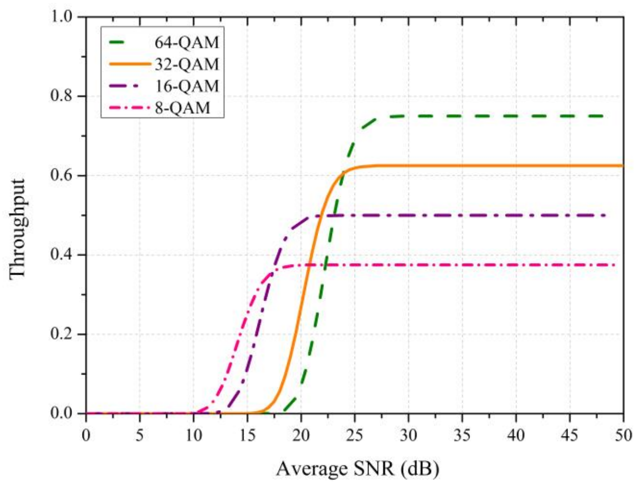

Figure 10. Throughput for m = 10 and 64, 32, 16 and 8-QAM.

TABLE I. OPTIMUM SWITCHING POINTS AND THROUGHPUT

Switch from	***m***	**Average SNR (dB) Switching points**	**Throughput (η)**
256 to128-QAM	0.5	32.7	0.559
	1	32.3	0.685
	2	31.6	0.77
	3	31.2	0.806
	10	30.1	0.846
128 to 64-QAM	0.5	33.7	0.592
	1	31.9	0.671
	2	30.4	0.718
	3	29.6	0.729
	10	28.2	0.746
64 to 32-QAM	0.5	25.1	0.353
	1	25.1	0.449
	2	24.9	0.527
	3	24.6	0.553
	10	23.9	0.603
32 to 16-QAM	0.5	25.4	0.364
	1	24.5	0.429
	2	23.5	0.469
	3	23	0.484
	10	21.8	0.492
16 to 8-QAM	0.5	16.5	0.168
	1	17.3	0.231
	2	17.6	0.289
	3	17.6	0.311
	10	17.3	0.353

Also, we can see that the optimum switching points vary with the channel model (represented by the parameter m of the Nakagami model). Also, for a particular value of m, we can observe that the SNR at the switching points is not a fixed value, but varies with the neighboring modulations.

Finally, we can observe that the switching points between some neighboring modulations are close to each other. For example, the switching point between the neighboring modulations 256-QAM to 128-QAM is close to the switching point between the neighboring modulations 128-QAM to 64-QAM, for m = 1, 2, 3 and 10. The switching point between the neighboring modulations 64-QAM to 32-QAM is also close to the switching point between the neighboring modulations 32-QAM to 16-QAM, and, therefore, their throughput is close as well, for all considered m. Based on this result, we can conclude that some modulations (like 128-QAM and 32-QAM) can't be considered in the implementation of an adaptive modulation system.

Furthermore, for $m = 0.5$ the switching point from 128 to 64-QAM occurs before the switching point from 256 to 128-QAM, similarly, the switching point from 32 to 16-QAM occurs before the switching point from 64 to 32-QAM. Thus, 128-QAM and 32-QAM should not be used in the adaptive modulation system in this case.

VI. CONCLUSION

In this paper, we considered a system with an adaptive modulation technique, considering a Nakagami-m fading channel model, and we analyzed the optimum switching points between neighboring modulations by using the maximum throughput criterion. We considered M-QAM modulations, with M = 8, 16, 32, 64, 128 and 256, and we set the diversity order to m = 0.5, 1, 2, 3 and 10.

We observed that if we modify the diversity order m of the Nakagami fading model, the optimum switching points, and the throughput in the switching points changed. So, the higher is the parameter m, higher is the throughput.

We also observed that some switching points between neighboring modulations are close to each other, indicating that some modulations (like 128-QAM and 32-QAM) can be neglected in the implementation of a practical adaptive modulation scheme.

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