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A Non-Cooperative Game Theoretic Approach for Power Allocation in Intersatellite Communication

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***Abstract*—Static interference management techniques to enable multiple access intersatellite communication in small satellite networks can be inefficient noting the unpredictable variations in network conditions. Game Theory (GT) is a powerful mathematical tool to model the interactions among the cognitive small satellites to observe the network variations as well as actions of other satellites and make the best decisions to optimize their performance. In this paper, a network of multiple slave satellites that want to communicate with a single master satellite over an interference channel is considered. We propose a distributed power allocation mechanism using a non-cooperative game theoretic model to enable the slave satellites to select the optimal power strategy to reduce the interference level and maximize their utility functions. Using a pricing algorithm to control the aggressive behavior of the players of the game, the optimum pricing factor for the system and the optimal values of the power for slave satellites are defined. To the best of our knowledge, this paper is the first one to propose a decentralized power allocation mechanism in autonomous small satellite networks using a game theoretic model. The simulation results show the performance of this proposed model in enhancing the network sum-throughput.**

I. Introduction

The interest in using smaller satellites rather than the large ones in order to reduce the cost of the satellites has increased recently. Using smaller satellites reduces the development time and builds more launch opportunities for different types of missions. The potential of a system containing multiple smaller satellites in a constellation or cluster can be more efficient than using a large satellite in performing coordinated measurements of remote space in different space missions. Different configurations for small satellite such as clusters, constellations, and swarms have been utilized to perform scientific and technological missions. Supporting multiple signals and increasing data rates over reliable inter-satellite and ground links to Earth are part of the issues in such systems. Failure of nodes or potential changes in network topology because of the dynamic nature of the space environment may impose more issues [1].

Considering the dynamic and unpredictable environment of the space, networking multiple satellites could be difficult. Situations in which the master satellite loses its functionality is unavoidable and it requires autonomous decision making to take a proper action based on the current network topology. Autonomous transferring of data in different satellite missions for Earth observations and inter-planetary explorations and observations requires Inter-Satellite Communications (ISC) to be used for executing advanced functions with the minimum human intervention. ISC can eliminate the broad earth based relay system and maintain the distance between satellites. Limited power, mass, antenna size, on-board resources and computing capabilities impose some constraints at the transmitting and receiving ends of the system. High data rate communication is one of the most important requirements to be met in dynamic topology of small satellites. The growth of technology and the complexity of the space missions will need autonomous data transfer in a robust network of mobile elements. Developing a robust network of satellites having autonomous and reliable channel access and routing schemes requires a smart approach for suitable timing, positioning, and spacing among the satellites, in particular when the manual control of these factors from earth is impossible. New agent based computing platforms where the satellites have capabilities to perform intelligent improvements based on the network situations is a solution to get over these issues and game theory can be a very helpful approach to achieve the optimum system performance [2].

Game Theory (GT) is a class of mathematical optimization tools to model situations in which decision makers have to make specific decisions that have mutual and possibly conflicting consequences [3]. Decision-makers in GT are also called the players and may have conflicting or common goals which may lead to different types of cooperative or non-cooperative games. The achieved benefit or cost by each player of the game from available interactions is dependent on the player's own decisions as well as those taken by other players [4]. GT has two major differences with multi-objective optimization. In GT, each objective function is owned by a different agent, and the decision variables are partitioned into those controlled by the owner of each objective function. Optimization can be viewed as a special case of game theory with one player. On the other hand, the boundaries and constraints of the problem are less well defined in GT than in optimization.

The rest of the paper is organized as following: Section II includes an overview of the related work in inter-satellite communication techniques for small satellite networks. In section III, a brief review of non-cooperative game theory is provided. In Section IV, the problem of power control in a network of small satellites is formulated using a non-

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cooperative game theoretic approach. In section V, we suggested an algorithm that matches the limitations of our system and the simulation results are discussed in Section VI. Finally, Section VII includes the conclusion of the paper.

II. Related Work

A. Background

Game theory is a powerful tool to analyze the interactions among decision-makers with conflicting interests and finds a rich extent of applications in communication systems to model network routing, load balancing, resource allocation and power control. GT has been used for signal processing applications in robust detection and estimation as well as watermarking problems. Finding the solution for networking issues, specially in distributed networks, is another application of game theory is signal processing. Some examples of using game theoretic models in communication networks include power control of radiated signals in wireless networks; beamforming problem for smart antennas; precoding in multiantenna radio transmission systems; data security; spectrum sensing in cognitive radio; spectrum and interference management; multimedia resource management; and image segmentation [4].

Generally, collision occurs when more than one slave satellite in a network transmit data to the master satellite at the same time and this leads to the loss of data. Several multiple access protocols have been proposed to address the problem of interference management in intersatellite communications [2]. Among different multiple access protocols, TDMA has a limited application for a system with large number of satellites though providing a high bandwidth efficiency. The half duplex CDMA limits the number of satellites and has the near far problem affecting the performance of the system. The Load Division Multiple Access (LDMA) protocol which is a hybrid of CSMA and TDMA, may present a poor performance in a large-scale network when the number of satellites in a system increases and has the issue of difficult time scheduling. They hybrid of TDMA and FDMA is not suitable for dense and heavily loaded networks. The hybrid of TDMA and CDMA has strict synchronization requirements [1].

The dynamic and unpredictable behavior of space environments would lead to delayed and disrupted communication links. The change in formation of the satellites in a cluster is unavoidable when they approach the perigee and apogee. Therefore the overall architecture should be flexible enough to adapt itself to the change in system dynamics. The available communication systems cannot meet these issues completely [1]. In this paper, we propose a power control mechanism based on non-cooperative game theory for interference management in an interference channel among multiple slave satellite and a common master satellite as the receiver. This model can enable the satellites to select the best power strategy considering the dynamic changes in the network. To the best of our knowledge, this paper is the first one to propose a decentralized power allocation mechanism in autonomous small satellite networks using a game theoretic model. This model can converge to an stable power allocation solution within a short time.

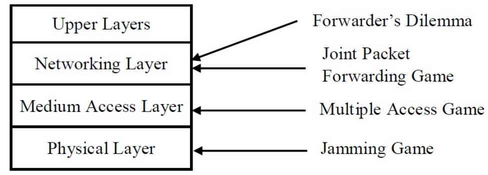

Fig. 1: The classification of the examples according to protocol layers.

B. Application of Game Theory in Routing and Channel Access

This sub-section provides few examples of the problems over different protocol layers (as shown in Figure 1) among a wide range of problems.

The games in wireless networks can be defined for two decision makers while the application of game theory extends far beyond two player games. Indeed, in most networking problems, there are several participants. Consider a two-source, two-destination network. Each source wants to send packets to its respective destination and each source is dependent to the other source to forward its packet. Without cooperation, neither source can deliver packets to the destination. This game is called the Forwarders Dilemma [5].

In another type of forwarding game, a sender wants to send a packet to its receiver in each time slot and needs the intermediate devices located between the sender and the receiver to forward the packet. This is called the Joint Packet Forwarding Game. If both players forward, then they each receive a reward (e.g., from the sender or the receiver) [3]. In networks with a central authority such as a military network, the assumption that intermediate devices will always forward packets for other players when requested to do so makes sense. However, in networks without a central authority, the autonomous devices may refuse to use their limited resources to forward packets for other players [6].

Multiple access game studies the problem of medium access in an interference channel, where multiple players want to send their packets to their receivers using a shared medium supposing that the senders and the receivers are in the power range of each other and their transmissions mutually interfere. The packet transmission will be successful if the other players do not transmit (stay quiet) in that given time slot, otherwise collision will occur and the packets will be corrupted. If there is no collision, the transmitter gets a reward from the successful packet transmission [3]. Jamming games study the scenario when malicious users intend to disturb the communication of legitimate transmitters.

A pricing scheme is suggested in [7] and the effect of non-cooperative routing behavior on network performance is studied in [8]. The pricing function design in the power control games in CDMA systems has been investigated in [5] and [9].

III. Introduction to Non-cooperative Game Theory

In essence, for a set of players, denoted by $N = \{1, ..., K\}$, a game in strategic (i.e. normal) form is represented by a family of multivariate functions $u_1, ..., u_K$; $K \geq 1$ called the utility (i.e. payoff) function of the players. The strategic form assumes that u_k can be any function of the following form:

$$u_k : \mathcal{S}_1 \times ... \times \mathcal{S}_K \rightarrow R$$

where $\mathcal{S}_k$ is called the set of strategies of player k. The strategic-form game is referred by using the compact triplet notation of $(N, \mathcal{S}_k, u_k)$ where $k \in N$. The notation $\mathcal{S}_{-k}$ is used to denote the strategies taken by all other players, except player k. There are a couple of game theoretic concepts needed as preliminary definitions which are described in following subsections.

A. Nash Equilibrium

The Nash Equilibrium (NE) is a basic solution concept for a strategic-form game, on which many other concepts are built. Nash proposed a simple but powerful solution concept, which is now known as an NE (equivalently, Nash point).

An NE of the game $G = (N, \mathcal{S}_k, u_k)$ has the strategy profile $\mathcal{S}^{NE} = (\mathcal{S}_1^{NE}, ..., \mathcal{S}_k^{NE}) = (\mathcal{S}_k^{NE}, \mathcal{S}_{-k}^{NE})$ such that

$$\forall k \in N,\ u_k(\mathcal{S}_k^{NE}, \mathcal{S}_{-k}^{NE}) \geq u_k(\mathcal{S}_k, \mathcal{S}_{-k}^{NE})$$

NE presents an stable strategy set, where no player has incentive to unilaterally change its strategy if the strategies of other players remain unchanged. Given above, it can be seen that $\mathcal{S}^{NE}$ represents a strategy profile in the broad sense. For example, it may be a vector of actions, a vector of probability distributions, or a vector of functions [4].

B. Best Response

Player $k's$ Best response (BR) denoted by $BR_k(s_{-k})$ to the vector of strategies s_{-k} is the set of valued function as

$$BR_k(s_{-k}) = arg\ max_{s_k \in \mathcal{S}_k}\ u_k(s_k, s_{-k})$$

which means a strategy chosen by player k that maximizes its utility based on the strategies of other players.

Considering the notion of the composite BR, the NE can be characterized.

$$BR : \mathcal{S} \rightarrow \mathcal{S}$$

$$s \mapsto BR_1(s_{-1}) \times ... \times BR_K(s_{-K})$$

C. NE Characterization

In a strategic form game of $G = (N, (\mathcal{S}_k)_{k\in N}, (u_k)_{k\in N})$ a strategy profile s^{NE} is considered an NE if and only if

$$s^{NE} \in BR(s^{NE})$$

1) Definition: A utility function meets the Diagonally Strict Condition (DSC) if there is a vector r such that

$$\forall\, (s, s') \in \mathcal{S}^{\in}, s \neq s' : (s - s')(\gamma_r(s') - \gamma_r(s))^T) > 0$$

where $\gamma_{r(s)} = [r_1(\frac{\partial u_1}{\partial s_1}), ..., r_K(\frac{\partial u_K}{\partial s_K})]$ [4].

Lemma 1 The existence and uniqueness of a pure NE is guaranteed for a game with a continuous concave utility function meeting DSC [4].

D. Pricing Algorithms

Changing the utility function in a way that the game structure is maintained is one of the simplest and most routine ways of improving the efficiency of the NE. This approach may be done by introducing some form of externalities to the game. In noncooperative games that the selfish players try to maximize their own utility by increasing some factors, charging them for the increment of those factors by a pricing factor such as α leads to the players being discouraged from behaving in an aggressive way.

$$\widetilde{u}_k(s) = u_k(s) - \alpha s_k$$

IV. System Model and Problem Formulation

In this paper, we consider a network of small satellites which consists of a master satellite and multiple slave satellites. The master satellite is assumed to be a larger satellite with higher computation and communication capabilities to perform the data processing and information communication with other master satellites as well as the Earth Station. The slave satellites capture the needed data of the mission and send them to the master node in order to be sent to ground station or other cluster heads. Satellites should go through a computationally intensive processing as well as the inter-satellite communication. Noting the limited available power at these small satellites, optimizing the transmission power for communication system to meet the required expectations for a reliable communication while not overspending this resource is an important design factor in such systems.

There are different formation scenarios, such as triangular and circular clusters. A routine formation considers a master satellite at the center of the cluster which acts as the access point, while the slave satellites surround it acting as the mobile nodes [10]. The inclination, eccentricity, angle of perigee and semi-major axis of the satellites in the formations are the same. The shape of formations change when a triangular formation reaches to the poles or the circular formation approaches the perigee and apogee.

The limited source of power in space missions and the intensive needed computations make the choice of the type of the game so critical. The games which need intense computations may be accepted in cellular networks on earth, though considering them in space missions may lead to the failing of the mission because of the limited resources of power.

Therefore our problem should consider the possible change of the distance between the satellites in a cluster to match with the possible changes. The considered system specifications are as Table I. We have supposed that the satellites have a full Channel State Information (CSI) knowledge of the network.

If the satellites in a cluster are considered in an equidistance configuration with respect to the master satellite, a multiple access game can be considered. There are two players P1 and P2 that want to send their packets to the receiver using a shared medium. It is assumed that the players have a packet to send in each time slot and can decide whether to transmit it or not. It is supposed that P1, P2, and the destination are in the power

TABLE I: System Specifications

System Parameters	Value
Size of cubesats	1 U
Number of satellites	3 (2 slave, 1 master)
Maximum power	5 W
Orbital altitude	Lower Earth Orbit, 300 km
Number of bits per packet	20

range of each other and their transmissions mutually interfere. If player P1 transmits the packet, it causes a transmission cost as a function of power. The packet transmission will be successful if P2 does not transmit (stays quiet) in that given time slot, otherwise there is a collision. If there is no collision, player P1 gets a reward of t from the successful packet transmission. In multiple access game, the stable strategy set in which the players get the highest utility values is when one of the players transmits its packet and the other player does not transmit. Using the concept of Nash Equilibrium, there are two Nash equilibria for the game that are (Q,T) and (T,Q) where T represents Transmission and Q stands for Quiet as shown in Table II. Note that both of the players are supposed to have an identical fixed cost to send a packet to the destination, denoted as $0 < c < t$, and a fixed reward for having a packet successfully delivered to its destination [5]. The goal for this problem is finding an optimal power that the slave satellites send their packets in the case that both of the slave satellites have a packet to transmit.

TABLE II: Multiple access game with two players.

p_1/p_2	Q	T
Q	(0,0)	(0,t-c)
T	(t-c,0)	(-c,-c)

In this paper, a decentralized small satellite network is considered, where multiple slave satellites opportunistically want to communicate with the master one. The objective of the proposed game theoretic model is to find the optimum power allocation strategy for the slave satellites to mostly improve performance of the system and maximize the payoff function of the individual slave satellite. This game is possible to be utilized on CDMA level 2 protocol. For sure there will be mutual interference between the multiple transmitters and the specific receiver. Here, it is assumed that that instant channel state information is available to the users [11].

As mentioned earlier in this section, the game that is considered here is a Multiple Access Game. A typical strategic power control game model is a three-tuple defined as $G = \{N, S, U\}$, where N is the player set, $S = \prod_i S_i$ is the action set, and U denotes the utility function which shows the preference relationship of the various players in the game model. The action set can be shown with (p_i). Having a large SINR, low power consumption and high transmit rate are interconnected. Supposing that the SINR (λ_i) and the transmission rate (R_i) are fixed, increasing power will not increase the utility function (U_i). Reaching to the SINR threshold, a player cannot make its performance better by increasing power, however it will be worsened by this approach. Choosing a suitable utility function is always a critical factor in game theory.

Successful receiving of a signal in a multiple access game, depends on SINR which is a measure of the useful received signal power to the undesired power collected at the master satellite and the SINR denoted by λ_i will be as

$$\lambda_k = \frac{\Gamma p_k g_k}{\sum_{i=1,i\neq k}^{N} p_k g_k + \sigma^2}$$

The terms Γ, p_k, g_k and N represent the processing gain, the transmit power, the channel gain, and the slave satellite number respectively, where σ^2 is the power density of background noise, and $\sum_{i=1,i\neq k}^{N} p_k g_k$ represents the total interference power perceived by the slave satellite i, which is introduced by the other players who are sharing the same spectrum slot. The transmission will be successful if λ_k is bigger than a required SINR that depends on the system parameters.

The utility function should consider an outcome of $t_k(s)$ as a measure of the degree of the player's satisfaction because of the successful transmission. On the other hand the cost of the transmission $c_k(s)$ should be taken into account. The utility function will be defined as

$$u_i = t_k(s) - c_k(s)$$

Considering $t_k(s) = t$ where t is a dimensionless outcome as a measure of the throughput achieved at destination and $c_k(s) = c$ as the cost of transmission with the strategy space of $S_k = \{0, p\}$ for a two player game leads to the multiple access game of Table I.

V. Proposed Game-Theoretic Solution

The binary strategy space of $S_k = \{0, p\}$ caused the multiple access game in Section IV to have two Nash equilibria. One of the ways to overcome this dilemma caused by the binary strategy space is considering the game as a continuous power game. Strategy space for the players will be set to $S_k = \{s_k \in \mathbb{R} : 0 \leq s_k \leq p\}$.

A good approximation for the throughput in a system with transmission of data packets can be as $t_k(s) = t(1-e^{-\lambda_k(s)})^L$ where L shows the number of bits per packet and t is the communication rate in bits per second.

There are different choices for the utility function. The utility function is defined as data received properly at the master satellite per unit of energy.

$$u_k(s) = t_k(s)/s_k$$

This definition combines three important criteria of wireless data communication, i.e. throughput, transmission power, and battery life into one utility function [12] and is shown in Figure 2.

If the players transmission power is too low, then the users received power at the master satellite will be lower than the received powers of other players. This will cause the players SINR to be low, and degrade the users performance. This is reflected by the drop in the utility function as SINR approaches to zero. If the players transmit power is too high, it means that

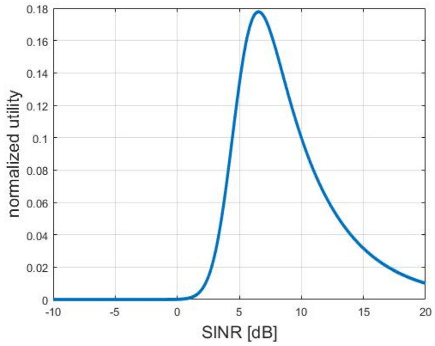

Fig. 2: Utility as a function of the SINR.

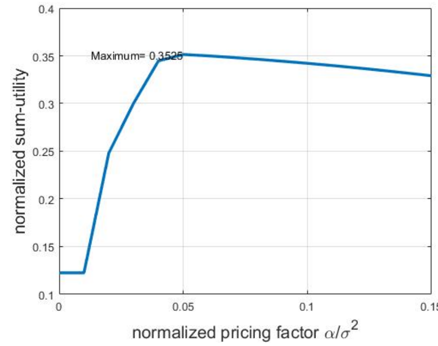

Fig. 3: Continuous power game with pricing for equal channel gains.

the slave satellite is wasting the battery power while having low impact on bit error rate. This is reflected by the drop in the players utility function as SINR is approaches infinity. Supposing that each satellite can decide how much power to spend for transmitting data, the outcome for each satellite is a function of its own decisions as well as the decisions of the other players. The players will attempt to make the best possible choices. Then, according to game theory, the players will choose an operating point which is a Nash Equilibrium [13].

Small satellites have very limited resources in terms of power, processor speed, and memory. It is not applicable to perform intensive computations methods such as multi-objective optimization on a single satellite [14]. Therefore the approach of finding the best responses of the players with respect to the actions of other ones considering a pricing algorithm can be a good solution to this noncooperative game.

The selfish players try to maximize their own utility in response to the actions of other players, and charging them by a pricing factor α discourages them from behaving aggressively.

$$\widetilde{u}_k(s) = u_k(s) - \alpha s_k = t_k(s)/s_k - \alpha s_k$$

The algorithm of the best response approach is simplified and sketched as BR Algorithm in Table III.

TABLE III: Best Response Algorithm for a Two-Player Game.

BR Algorithm
0 Input maximum power (p) and number of slave satellites (K)
1 Initialize k=0
2 Break the interval of $[0, p]$ to M intervals
3 $k = k + 1$
4 For $m = 0$ to $m = M$
5 Calculate SINR and the utility of Player k for $s_k(m)$
6 Save the MAX of the utility as BR of the player k
7 If $k = K$ go to 8, else go to 3
8 Find the fixed points of the BRs

As shown in the BR Algorithm, we consider the strategy space as $S_k = \{s_k \in \mathbb{R} : 0 \leq s_k \leq p\}$ and the interval of $[0, p]$ will be divided into M steps. The higher the M, the more accurate and efficient the result will be, but on the other hand increasing the number of the steps increase the run-time and the simulation will be slower. In the next step, the best response of the Player 2 will be its maximum utility among all the calculated utility function values to $s_1(m)$ where $m = 0\ to\ M$ shows the number of the steps. All the other slave satellites should go through the same procedure and maximize their utility function. Therefore we should choose the fixed points of the BR values vector for all the players. Since the proposed utility function has the conditions mentioned in Lemma 1, the NE of the game is unique.

VI. Simulation Results

The maximum power value for our system is considered as $p = 5\ W$ and the number of steps in the interval of $[0, p] = [0, 5]$ was considered as $M = 10000$. Therefore, in each iteration, the algorithm searches 10000 points in the strategy space and finds the final solution. Higher values of M increases the runtime and it takes longer to find the solution. The processing gain was set to $\Gamma = 4$. We set the channel gains to $g_1 = 0.50$ and $g_2 = 0.50$. The number of bits per packet was set to $L = 20$. Note that the BR approach code is run based on a pricing algorithm for different values of the pricing factor α. Therefore the best pricing factor that should be considered for the system will be defined and in our simplified system of one master satellite and two slave ones, the pricing factor of $\alpha = 0.0.0420\ t/\sigma^2$ gives us the highest normalized utility of 0.3525 as shown in Figure 3; which yields $\widetilde{s}_1^\star/\sigma^2 = 0.0005$ and $\widetilde{s}_2^\star/\sigma^2 = 2.1140$ as the unique solution of the considered game. The utility values for the slave satellites were $u_1 = 0.9723$ and $u_2 = 1.9995$ which were found after 5 iterations of searching through the strategy space of 10000 potential solutions.

As some formation of satellites may change because of the non-symmetric formation, the channel gains may not be equal for different slave satellites. For the same system but considering the channel gains as $g_1 = 0.75$ and $g_2 = 0.50$ the pricing factor of $\alpha = 0.0.0390\ t/\sigma^2$ gave us the highest normalized utility of 0.5330 as shown in Figure 4; which yields $\widetilde{s}_1^\star/\sigma^2 = 1.5105$ and $\widetilde{s}_2^\star/\sigma^2 = 0.0005$ as the unique solution of this game. The utility values for the slave satellites were $u_1 = 2.9993$ and $u_2 = 0.9377$ which were found after 4 iterations of searching through the strategy space of 10000 potential solutions.

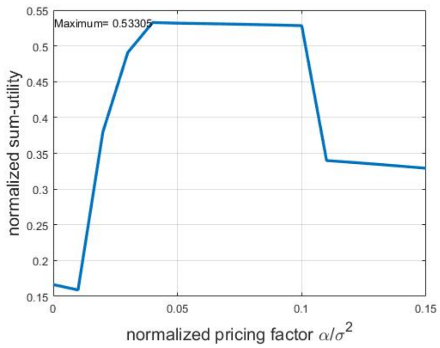

Fig. 4: Continuous power game with pricing for different channel gains.

VII. Conclusion

Interference management in multiple access intersatellite communication in small satellite networks is of great importance due to the unpredictable variations in network conditions. We considered a decentralized small satellite network where two slave satellites opportunistically want to communicate with the master satellite. A bigger network of small satellites and more number of slave satellites will be considered in future work. The objective of the proposed game theoretic model was to find the optimum power allocation strategy for the slave satellites to mostly improve performance of the system and maximize the payoff function of the individual slave satellite. Considering a binary strategy space for the power of the satellites leads to two Nash equilibria. We considered a distributed scenario and defined the strategy space as continuous rather than binary to overcome this dilemma. Considering the limited source of power for small satellites we used the best response algorithm including less computations beside a pricing algorithm to control the aggressive behavior of the players. Since the formation of satellites may change because of the non-symmetric essence of the formation and the channel gains may not be equal for different slave satellites, we simulated the system for two cases of the equal channel gains and different ones. The optimum pricing factor for the system and the optimal values of the power for slave satellites were calculated for both cases.

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