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Providing Balanced Throughput and Fairness Using Random Ranks and Mini Slots at MAC Layer in Ad hoc Networks

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ABSTRACT

Ad hoc networks offer infrastructure free operation, where no entity can provide reliable coordination among nodes. Medium Access Control (MAC) protocols in such a network must overcome the inherent unreliability of the network and provide high throughput and adequate fairness to the different flows of traffic. In this paper, we propose a MAC protocol that can achieve an excellent balance between throughput and fairness. Our protocol utilizes control-message handshake similar to IEEE 802.11. The protocol makes use of granule time slots and sequence of pseudo random numbers to maximize spatial reuse and divide the throughput fairly among nodes. We have demonstrated the performance of this protocol using simulation with fixed topologies. Our simulation results include a detailed comparison between the proposed protocol and existing protocol that has been shown to excel in terms of throughput or fairness.

Categories and Subject Descriptors

C.2.1 [Advantage-Networks]

General Terms

Performance

Keywords

Distributed multihop wireless networks, ad hoc networking, medium access control, random ranks, mini slots, aggregate throughput, long-term fairness.

1. INTRODUCTION

As wireless technologies advance and become more popular, wireless protocols must evolve to meet the higher demands of these technologies. Ad hoc networks are an exciting approach to network design [1], [2]. Not relying on complex and expensive infrastructure, which is required by their traditional counterparts, ad hoc networks can operate in scenarios where traditional networks fail, such as disaster relief and military applications. Ad hoc networks are also particularly well suited for sensor networks and small scale temporary solutions (e.g. conferences). Efforts are also made to extend ad hoc networks to more general-purpose applications, such as wireless local area networks (WLANs) [3], [4], [5], and as extensions to centralized networks, such as future generation cellular networks [6], [7].

The benefits of an ad hoc network come at a significant cost. The wireless medium is shared among many nodes and is prone to collisions, and the lack of infrastructure requires protocols to be distributed. In general, the unpredictable and dynamic topology of ad hoc networks leads to each node possessing only partial knowledge of the network topology. This often results in an unfair allocation of throughput between different senders. Further the problem of fairness in wireless ad hoc networks is addressed in a classical approach inherited from wired network. The common assumption is that nodes/flows have pre-assigned fair shares. Wired networks have efficient means of allocating fair shares through admission control and additionally the fair shares remain constant throughout the session duration due to the static nature of the nodes. In ad hoc networks it is meaning less to assume statically pre-assigned fair shares because not only nodes move, but the, contention is also location dependent. Another problem in ad hoc networks is due to the limited transmission range of mobile stations called hidden terminal problem [8], which is known to degrade throughput significantly.

Several MAC protocols have been devised to address these problems. Among these, IEEE 802.11 Distributed Foundation Wireless Medium Access Control (DFWMAC) is a proposed standard for wireless ad hoc and infrastructure LANs [9]. DFWMAC is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and provides also RTS/CTS access method. The RTS/CTS access method is used to combat the hidden terminal problem by allowing stations to acquire the channel before they transmit the data packets. Although the RTS/CTS access method can alleviate the effects induced by the presence of hidden terminal. DFWMAC still suffers from fairness problem induced mainly by the intrinsic multihop nature of ad hoc network [10].

The lack of coordination in ad hoc networks leads to frequent collisions between nodes. This problem can only be overcome by introducing randomness into the MAC protocol. Many protocols, including those based on CSMA/CA, use random backoff periods. This solution has two distinct disadvantages. First, there is no optimal method to calculate the bounds of the random backoff period for multihop ad hoc networks, which leads to inefficient operation and, in some cases, extreme unfairness. Second, backoff periods are, by their very nature, waste time by waiting idly. The proposed protocol introduces new mechanisms to bring randomness into collision avoidance by utilizing pseudorandom number sequences over granule time slots resulting in maintaining the fairness in spectrum sharing.

The rest of this paper is organized as follows: section 2 Related work. Section 3 Discussion of RRMS operational prinicipal. Section 4 presents the performance evaluation of the proposed protocol in terms of throughput and fairness. Section 5 contains Simulation results. Finally the paper is concluded in section 6.

2. Related Work

In the above context it is pertinent to discuss relevant research done so far in this area.The first well-known effort to deal with the fairness problem at the MAC layer was the MACAW protocol [11]. MACAW incorporated several innovations to address the issues of fairness and better collision avoidance, including in particular, a Multiplicative Increase Linear Decrease (MILD) backoff algorithm, which resulted in more subtle adjustments to the backoff window size. This work provided a starting point for a considerable amount of research into fairness in ad hoc networks. Ozugur et al. [12] proposed that nodes should exchange information on the number of connections they have with other nodes, or the average time they have to wait before sending an RTS. They show how this information can be used to calculate the transmission probability for each flow. Bononi et al. proposed that each node should monitor the channel to determine what fraction of time the channel is in use [13]. They use this parameter together with the number of retry attempts to compute the transmission probability of each flow. Haas and Deng further extended these results and studied how the backoff window size should be dynamically adjusted [14].

The fair queuing techniques is another approach to achieve fairness in ad hoc networks [15], [16], [17]. It requires the labeling of data packets with start tags and finish tags to keep track of the priority of each packet. Nodes must then estimate when to send a packet of a given priority. This estimate can be based on an approximation or can be calculated by monitoring the traffic sent by other nodes [18]. Fairness can be achieved by directly exchanging between nodes the priorities of the packets waiting to be transmitted at each node. One protocol that uses this approach is DWOP [19], [20], proposed by Kanodia et al. This protocol achieves First-In-First-Out (FIFO) fairness by maintating a schedule of packets that are waiting to be sent or received by all neighbors together with their priorities at every node. A node would only send its own packet if this packet has a higher priority than all other packets in its schedule. To update neighbors schedules on newly arriving packets, information on the current packet sent and the next packet (its id and priority) is inserted into the RTS and CTS. So that neighbors can add an entry to their schedule and information on the current exchange is inserted into the DATA and ACK packets so that nodes can delete this entry from their schedule.

Another class of contention resolution schemes are based on pseudorandom priorities. In the Neighborhood aware Contention Resolution (NCR) algorithm by Bao and Garcia-Luna-Aceves [21], each node maintains a sequentially updated pseudorandom rank in each data transmission time slot. The ranks of all contenders like one-hop neighborhood for node-based NCE or two-hop neighborhood for link-based NCR are recorded. A node or a link, depending on the particular channel access flavor of NCR, is activated and allowed to participate in data transmission if it has the highest priority among its contenders. In the SEEDX protocol by Rozovsky and Kumar [22], each node generates a pseudorandom number sequence using a random seed. The time axis is slotted. Each slot is labeled “L” for Listen or PT for Possibly Transmit based on the random sequence. Periodically, nodes must broadcast their own seed and the seed of all their one hop neighbors. This allows every node to keep track of the schedules of every other node in its two-hop neighborhood. In order to send a packet, the sender must wait for a slot that is labeled “PT” for itself and “L” for its receiver. In this slot, a number of the receiver’s neighbors will also be in the “PT” state. The authors calculated the packet transmission probability in order to minimize the probability that more than one neighbor of the receiver will transmit in this time slot.

Towards the goal of fair and efficient spectrum sharing in distributed multihop wireless networks, we introduce a new medium access control protocol termed Randomly Ranked Mini Slots (RRMS). RRMS utilizes a pseudorandom sequence specific to each node. However, unlike the previously proposed schemes, RRMS includes new random access mechanisms where the time slots for the rank sequence, termed mini slots, can have a scale much smaller than the data packet transmission duration.

3. RRMS Operational Principle

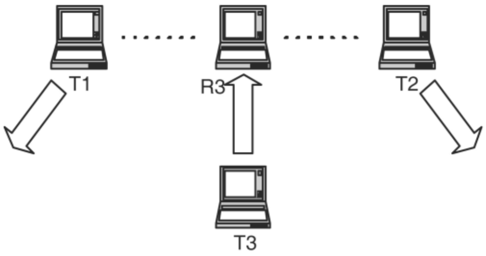

Fig. 1 RRMS and spatial reuse. T_i and R_i denote potential transmitters and receivers, respectively.

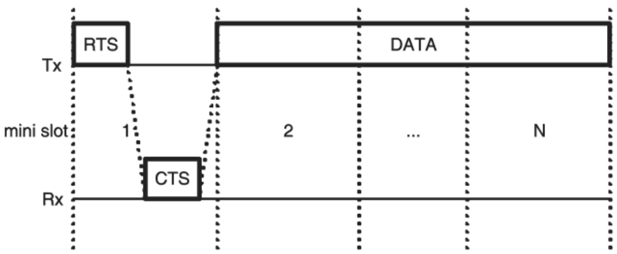

Fig. 2 RRMS exchange mechanism.

Each node generates a new term in the random sequence for each new time slot. The number generated in the current slot is called the rank. The rank is generated by using random function. The node will begin to send in the current time slot if the channel is idle and its own rank is higher than the ranks of all the potential senders that interfere with it. One main feature that distinguish the protocol from NCR or SEEDEX [21],[22] is that the rank sequence time slots in the protocol are much smaller than the data transmission duration. Therefore, a single data exchange is sent over multiple time slots. We refer to these granule time slots as mini slots. The disadvantage of having time slot size equal to the data transmission duration is best explained in a sample topology as shown in Fig. 1. This figure shows a common scenario where three flows line up. Given independent rank sequence, it is clear that the event $E_{monotone} = \{R_{T1}<R_{T3}<R_{T2}\} \cup \{R_{T2}<R_{T3}<R_{T1}\}$ occurs in any time slot with probability.

$$P(E_{monoton}) = 2/3! = 1/3$$

However, this event is highly undesirable if the rank-sequence time slot size equals the data transmission duration since, in the first case, only T2 is allowed to send in the current slot and , in the second case, only T1 is allowed to send in the current slot. Ideally, we would like to send T1 and T2 simultaneously (i.e. to take the advantage of spatial reuse). We further quantify the advantage of using mini slots that are much shorter than the data transmission duration in section 3.1, such that T1 and T2 are allowed to transmit nearly simultaneously.

Since the data exchange takes place over multiple random-rank time slots, the RTS-CTS handshake is needed to reserve the channel. Without channel reservation, one node may begin to send in one slot because it has the highest rank in this slot and an interfering node may begin to send in the following slot because it has the highest rank in that slot. The packets would then collide. The exchange mechanism is shown in fig. 2 solves this problem.

The exchange begins with the sender sending an RTS in the first slot. The receiver, if it is ready to receive, will reply with CTS in the same slot. The sender will then begin to send a DATA packet in the second slot for as many slots as are needed. The RTS and CTS serve the same purpose as they do in DFWMAC [9], namely, they announce to neighboring nodes that can exchange of a stated duration is about to take place and that all interferers should defer their transmissions. Neighbors that hear the RTS or CTS set up a Network Allocation Vector (NAV) for the duration of the exchange, which prevents them from transmitting during this time. A sender only begins an exchange in a slot in which it has a higher rank than all of its interfering senders and if it does not have its NAV set.

Note that there is no need for backoff. If the sender of an RTS does not receive a CTS from the receiver by the end of the mini slot, the transmission is aborted. Then, the sender just needs to wait for the next slot in which it has the highest rank. If the CTS is received in time, the DATA packet is sent at the beginning of the next mini slot and continues for as many slots as needed.The following pseudocode summarizes the general operation of the protocol in each time slot for a node attempting to transmit:

```
if NAV is set
        Wait for next CTS slot
    else if self rank is not maximum among contenders
        Wait for next slot
    else
        Send RTS
        Wait for CTS from receiver
        if CTS is not received
            Wait for next slot
    else
        Send DATA
```

3.1 Mini Slots and Spatial Reuse

Now we illustrate that using mini slots can lead to significant improvement in the spatial-reuse of the wireless medium, while maintaining fairness in spectrum sharing.

In this section, we quantify the spatial-reuse efficiency of protocol through random-rank mini slots. We use the common scenario as shown in fig. 1. with out loss of generality, we consider one of the outcomes in the event Emonotone, $R_{T1} < R_{T3} < R_{T2}$, at the current mini slot. Then, T2 alone, will send in this mini slot. In the next mini slot, T1 will begin to send if $R_{T3} < R_{T1}$, which will occur with probability ½. On the other hand, if T3 has the highest rank in the second mini slot, then nothing will happen, since T3 will send an RTS but R3 will not receive it. Then, in the third mini slot, T1 will again begin to send with probability ½ , and so on.

Obviously, the smaller is the mini slots, the sooner will T1be allowed to send. More precisely, the slot in which T1 will send is a geometrically distributed random variable with parameter ½, whose mean wait time is two mini slots. This means that we can expect that, on an average, only two mini slots will be wasted by T1. This illustration clearly demonstrates the spatial-reuse advantages of mini slots. Therefore, in general, we should try to minimize the duration of the mini slots.

The minimum allowable size of the mini slot is limited to the duration of an RTS packet and a CTS packet plus overheads because the highest -ranked sender must send RTS and receive CTS in the same mini slot to reserve the channel before an interferer begins to send. If the size of RTS and CTS packets could be made smaller, less bandwidth would be wasted. Ideally, the control packets size to data packet size ratio should approach zero, and then spatial reuse would be perfect; that is, all nodes that can send simultaneously without interfering with other.

4. Performance Evaluation

We evaluate the performance of our protocol by comparing them with DFWMAC (802.11). Comparisons are made in two categories: throughput and long term fairness.

4.1 Throughput

Throughput comparison is based on straight forward examination of the aggregate throughput of all flows in the network. It should be kept in mind, that throughput and fairness are a trade-off. The highest possible aggregate throughput for any given scenario is usually extremely unfair and, therefore, undesirable.

For example, in the three flows topology shown in Fig.1, maximum aggregate throughput will be achieved if flows T1-R1 and T2-R2 transmit continuously and the flow T3-R3 does not transmit at all. This will result in a throughput of two times the channel capacity. This situation is clearly unacceptable. A more fair solution would be to alternate transmissions by letting flows T1-R1 and T2-R2 transmit, then flow T3-R3, and then flows T1-R1 and T2-R2 again. This would result in an aggregate throughput of only 3/2 times the channel capacity, but each flow would receive an equal share of throughput.

One could also argue that flow T3-R3 is in a denser part of the network since it is competing with two other flows, whereas flows T1-R1 and T2-R2 are competing with only one flow and, therefore, flow T3-R3 should receive a smaller share of throughput. In any case, we emphasize that throughput results must be considered in light of fairness results and not as an independent evaluation.

4.2 Long-Term Fairness

We have also compared the simulation results in terms of long-term fairness. We first present the following example as a guideline for qualitative comparison: In Fig. 1, one could argue that flow T3-R3 should receive 1/3 of the channel capacity because it is competing with two other flows, and flows T1-R1 and T2-R2 should receive ½ of the channel capacity, since each of them is competing with only one flow. However, the throughput values (1/2, 1/3, ½) do not take full advantage of spatial reuse. For example, if flow T3-R3 receives 1/3 of the channel capacity, then flows T1-R1 and T2-R2 could each receive 2/3 of the channel capacity. Clearly, a protocol should not be penalized for giving two flows an extra 1/6 of channel capacity in throughput. Alternatively, the extra 1/6 of channel capacity could be given to flow T3-R3, resulting in each of the three flows getting ½ of channel capacity in throughput. It is impossible to say which result is more fair. We may therefore state that a protocol will be considered fair in the long-term if every flow that has n interfering flows receives a minimum share of 1/n+1 of channel capacity in throughput. Given that such basic fairness is satisfied, a larger throughput value is, of course, more desirable.

We also observe that qualitative judgments cannot be made when the topology is very large since it is impossible to keep track of the performance of each flow. For these topologies, we use a quantitative measure of long-term fairness, which has been denoted by Flow RMSE. The Flow RMSE is found by carrying out a long-term fairness comparison between the resultant transmission sequence of a given MAC protocol and that of the ideal sequence Sl, which is the transmission sequence that would result if a central coordinator was available and would have instructed nodes to transmit in FIFO order while utilizing spatial reuse.

Once Sl is obtained, we find the transmission sequence Ssim, for each protocol via simulation. A comparison between Sl and Ssim must be made to evaluate how closely the simulated sequence resembles the ideal sequence. Suppose that a given scenario has m flows, labeled 1 to m. Let T^{i}_{l} and T^{i}_{sim} represent the throughput achieved by the ith flow in the ideal sequence and simulated sequences, respectively. We define the measure of long term fairness as

$$\text{Flow RMSE} = \sqrt{\sum_{i=1}^{m}\left(\frac{T_I^{i}}{T_I}-\frac{T_{Sim}^{i}}{T_{Sim}}\right)^{2}} \qquad (1)$$

Since the flow RMSE represents the root mean square error between the normalized flow rates of the ideal sequence and the actual sequence, a flow RMSE indicates the results of protocol are close to the ideal results. It is important to note that the throughput of each flow in this formula is normalized by the total throughput of the relevant sequence. This is because we wish to compare the fraction of total throughput achieved by each flow and not the absolute throughput value. If we did not do so, then protocols that achieve high throughput might achieve lower Flow RMSE since the ideal sequence achieves relatively high throughput also. By normalizing each flow's throughput by the total throughput, we ensure that Flow RMSE is a measure of long-term fairness alone and is independent of throughput performance.

5. Simulation Results

We begin by presenting simulation results for a fixed topology scenario with two protocols: DFWMAC and RRMS MAC protocol. Our simulation used a 11 Mbps channel with packet length listed in the following table. The RTS, CTS and ACK parameters are taken directly from the IEEE 802.11 standard [9]. The data length is a nominal value within the bounds of the standard specification.

TABLE1

Packet	RTS	CTS	Data	ACK
Length (bytes)	20	14	1470	14

The network under consideration is shown in Fig. 1. The simulation was carried out for 20 µsec and backlogged traffic arrival was assumed at every sender. The RRMS protocol with randomness work on granule time slots. The values of time slots taken in RRMS MAC protocols are 50.12 µsec, 55.72 µsec, and 60.72 µsec, which have been calculated. The per node throughput results for this scenario are shown in table 2. The results in table2 and Fig.6 demonstrate the throughput performance, long-term fairness and effect of mini slots. The DFWMAC achieves higher throughput, however cost in terms of fairness is greater. Thus by not using an effective fairness mechanism, they allow only maximal independent set of flows (flow1 and flow2) to transmit and choke other flow (flow3).

TABLE 2

Throughput results for each flow in megabyte/sec

protocol		Node1	Node2	Node3
DFWMAC		249.89	243.56	75

RRMS	Mini slot size in µsec			
	60.72	173.56	183.67	156.89
	55.72	185	208.72	175.56
	50.72	273.33	209.44	176.22

In contrast, the performance advantage of RRMS comes from random ranking over granule time slots. Table 2 shows that the proposed protocol yields superior results in both long-term fairness and throughput. The observations confirms our discussion in section 3.1, where we quantify spatial reuse efficiency of proposed protocol. The table 2 demonstrates a consistent increase in throughput with smaller size mini slots, showing that smaller mini slots can significantly increase in special reuse. Table 2 shows that fairness also increases with smaller sized mini slots, since smaller mini slots take greater advantage of spatial reuse and the ideal sequence also takes advantage of spatial reuse to achieve the best possible performance.

Fig. 3, 4, 5 shows the throughput of nodes 1,2,3 respectively. Graphs shows that throughput improves in RRMS with change in mini slots. Fig. 7 shows the fairness of topology of fig. 1, which is calculated with the help of equation 1. The Graph shows that fairness reaches to ideal values with RRMS.

For simulation NCTUns-4.0 network simulator is used.

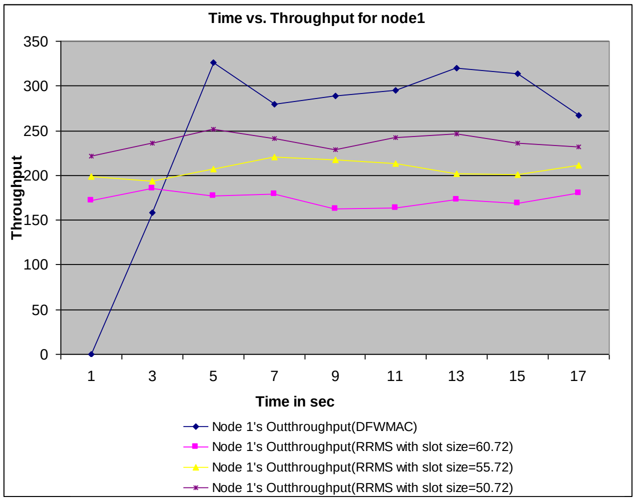

Fig.3 Effect of RRMS for node1

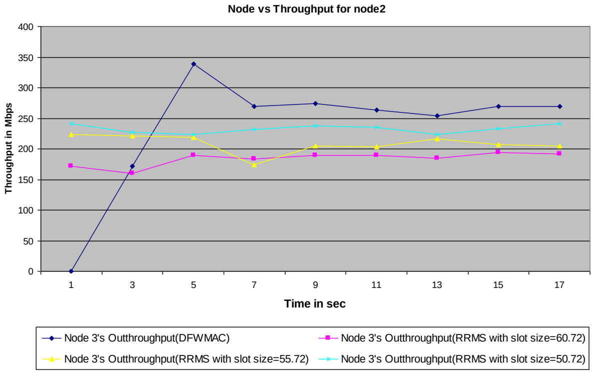

Fig. 4 Effect of RRMS for node 2

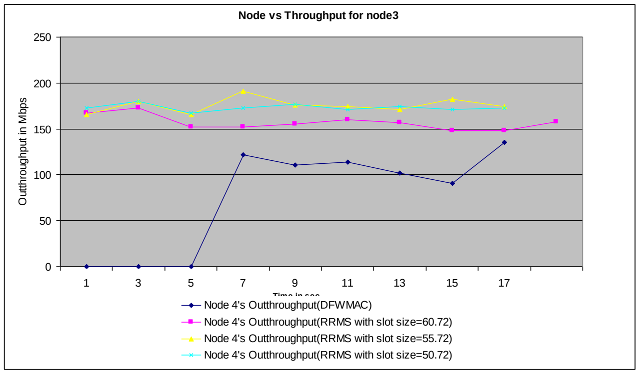

Fig. 5 Effect of RRMS for node 3

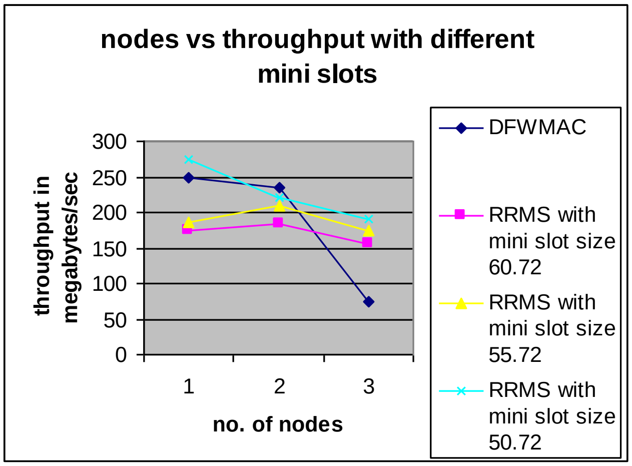

Fig. 6 Effect of mini slots

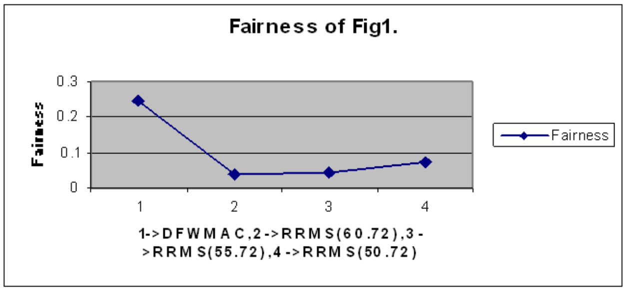

Fig. 7 Fairness

6. Conclusion

The MAC layer of an ad hoc network is an uncoordinated dynamic environment which presents sever difficulty for reliable communication. The problem of fairness particularly is a real hurdle since the shared medium is prone to collision. The future success of ad hoc network relies on finding fair, efficient and robust MAC layer algorithm and protocols.

In this paper, we have presented the new MAC protocol and provided a detailed evaluation of their throughput and fairness performance. The RRMS utilizes control message handshake similar to IEEE 802.11, which allows it to be implemented easily. The RRMS yielded balanced throughput and fairness results that were close to the ideal results that can only be achieved by a centralized network. We have also investigated the performance of RRMS with varying mini slots sizes. Our results showed that both throughput and fairness can be improved with smaller sized mini slots.

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