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Approach of Data Broadcasting By Using Zigbee Network

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Abstract: This paper studies efficient and simple data broadcast in IEEE 802.15.4 based ad hoc networks (e.g., ZigBee). Since finding the minimum number of rebroadcast nodes in general ad hoc network is NP-hard, current broadcast protocols will either employ heuristic algorithms or assume extra knowledge such as position or two-hop neighbor table. The ZigBee network has characterized as low data rate and low cost. It will not provide position or two-hop neighbor information, but it requires an efficient broadcast algorithm that can reduce the number of rebroadcast nodes with limited computation complexity and storage space. This paper proposes self-pruning and forward node selection algorithms that exploit the hierarchical address space in ZigBee network. It is only needed one-hop neighbor information; a partial list of two-hop neighbors is derived without exchanging messages between neighboring nodes. The ZigBee will forward node selection algorithm finds the minimum rebroadcast nodes set with polynomial computation time and memory space. By using the proposed localized algorithms, it has been proven that the entire network is covered. In terms of the number of rebroadcast nodes, simulations are conducted to evaluate the performance improvement, number of duplicated receiving, coverage time, and communication overhead.

Keywords: Broadcast, IEEE 802.15.4, ZigBee, ad hoc network, RFD, FFD

I. Introduction

The IEEE 802.15.4 standard [1] was approved in 2003 as a multiple access control (MAC) and physical (PHY) layer standard for low data rate, low power and low cost wireless personal area networks (WPANs).The ZigBee2 Alliance [2] is a rapidly growing association of companies working together to enable reliable, cost-effective, low-power, wirelessly networked monitoring and control applications. The ZigBee specifications were ratified in December 2004. And the ZigBee network specification [3] is one of the first standards for ad hoc and sensor networks. In contrast to the intensive industrial activities on IEEE 802.15.4 and ZigBee, academic research on this subject is still at its early stage [4, 5], partly because the ZigBee specifications were not publicly available until June 2005 [2].

This paper addresses one of the most important research topics on ZigBee networks3: data broadcast. Due to the broadcast nature of wireless channels, a single transmission from a node is heard by all nodes within its transmission range.

A simple broadcast approach is to flood the whole network by rebroadcasting at every node. But this approach consumes too much communication bandwidth, causing broadcast storm problem [6].

Some local network topology information should be employed to reduce the broadcast redundancy. Most current approaches assume that the transmission power can be controlled, and that the position or 2-hop neighbor information is easily available. However, these assumptions are not practical for ZigBee network because a ZigBee device has limited computation and storage capacity. All the functionalities in MAC and upper layers are expected to be implemented in a single chip microcomputer, such as a 16-bit M16C [7]. So it cannot afford to conduct sophisticated algorithms based on data structures that take a large memory space.

A ZigBee device should be of small size low cost, so it cannot obtain accurate position information using extra hardware like GPS. ZigBee networks are targeting low data rate and low power applications, so they cannot provide large communication bandwidth and power for exchanging position or neighbor information among neighbors. Even if such information can be obtained by a ZigBee device, it may not even have enough memory space to store it when the network size is large. Given the above limitations, we are motivated to find a localized and light-weight broadcast algorithm for ZigBee networks.

II. THEORY

A. IEEE 802.15.4 and ZigBee

The IEEE 802.15.4 standard is for low-rate WPANs that require low power, low cost, and low complexity. An IEEE 802.15.4 device can be deployed in sensor networks, home automation, and industrial automation and monitoring etc. At the physical layer, IEEE 802.15.4 defines 27 channels of data rates 250 kb/s, 40 kb/s and 20 kb/s. At the MAC layer, IEEE 802.15.4 controls access to the radio channel using the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism.

IEEE 802.15.4 defines two types of devices: full function device (FFD) and reduced function device (RFD). An FFD can serve as a coordinator or a regular device. It can communicate with any other device. An RFD is a simple device that associates and communicates only with an FFD.

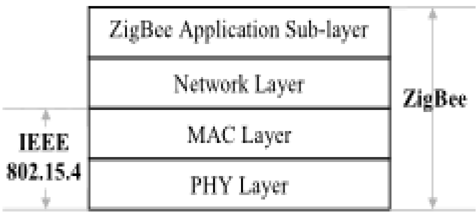


Figure 1. ZigBee protocol stack

Based on IEEE 802.15.4, the ZigBee Alliance specifies the standards for network and application sub-layer, as shown in Fig.1. The responsibilities of network layer [3] include joining/leaving a network, routing, security, discovering 1-hop neighbors and storing neighbor information. The ZigBee network layer assigns addresses and builds a hierarchical tree topology. A coordinator is responsible for starting a new ZigBee WPAN and setting network parameters such as the maximum allowable number of children nm of each device and the maximum level dm of the logical tree. The coordinator is the root of the tree with address 0. When a new device is willing to join a network, its MAC layer scans the available WPANs and notifies the network layer. After the upper layer selects a suitable WPAN, the network and MAC layer perform the association process with an existing device in the

selected WPAN. If the existing device has enough address space, it will assign a free network address to the new device and make it one of its children. In case a child loses the association with its parent, it can initiate a rejoining process, called orphaning, and its parent will respond to resume the association.

$$Cskip(d) = (1 - n_m^{d_m - d})/(1 - n_m)$$

At any level d of the logical ZigBee tree, the network addresses are evenly separate the ZigBee routing algorithm is a hybrid of tree forwarding and ad hoc on-demand routing. Any node can route frames to its parent or direct children on the tree. For example, assuming a device at level d with address A receives a packet with destination address D, it will select one of its children with address A+1+[(D-A-1)/Cskip(d)] .Cskip(d)4 as the next hop if A<D<A+Cskip(d-1) otherwise its parent is selected as the next hop. The RFDs are leaf nodes and can only forward the data packet to their own parents. If an FFD has enough computation capacity and storage space, it can be a router-capable FFD (RFFD) and store routes to devices other than its tree neighbors. An RFFD discovers a route by broadcasting a route request and waiting for replies from the destination or intermediate nodes, similar to the Ad hoc On-demand Distance Vector (AODV) routing protocol for general multi-hop ad hoc networks [8].

B. Broadcast in Ad Hoc Networks

Most research on ad hoc networks models the network topology as a unit disk graph in which each node has a unit transmission range. Ni et al. [6] introduced the broadcast storm problem when every node rebroadcasts a packet once. To reduce the broadcast redundancy and avoid collisions during rebroadcasting, they introduced some simple algorithms. For example, the counter based algorithm rebroadcasts a packet only if the number of duplicated broadcast packets received during a waiting period is less than a threshold. The location based approach only rebroadcasts when the additional coverage by the rebroadcast is larger than a threshold. In [9], the authors improved the above algorithms by adaptively choosing the threshold as a function of the number of neighbors. Both simulation comparison [10] and theoretical analysis [11] have been conducted. These approaches are simple to implement, but they cannot guarantee coverage of the whole network [10]. More complicated algorithms assume the knowledge of network topology in order to guarantee network coverage and reduce broadcast redundancy. When the global network information is available, the problem of selecting the minimum number of forward nodes is essentially the well-studied set cover problem, which is NP-hard [12]. But its solution can be approximated by a greedy algorithm [13] with an approximation factor of log(n), where n is the maximum number of neighbors. Since global network topology is not practically available, localized algorithms which only need the information of 1-hop and 2-hop neighbors are preferred. However, selecting a minimum subset of 1-hop neighbors to cover all 2-hop neighbors is still a set cover problem. For the special case when the network topology is a unit disk graph, the complexity of the corresponding forward node selection problem is not known, but it can be approximated by sophisticated algorithms with a constant factor [14]. Many heuristic algorithms have been proposed to decide if a node needs to rebroadcast. A Scalable Broadcast Algorithm (SBA) was proposed by Peng and Lu [15], which checks if a receiving node's 1-hop7 neighbors are all covered by previous transmissions from other nodes. If so, the receiving node need not rebroadcast the packet. Lim and Kim [12] and Stojmenovic et al. [16] proposed independently the same approach which is called self pruning and neighbor elimination, respectively. This paper will use self pruning to represent this idea. Peng and Lu [17] also proposed an efficient Ad Hoc Broadcast Protocol (AHBP), which greedily selects forward nodes from a node's 1-hop neighbors to cover all its 2-hop neighbors; all previously selected nodes on the same route need not be selected again and the node with the most uncovered neighbors is first selected. Other algorithms based on the similar greedy forward node selection idea include the dominant pruning [12] and the multipoint relaying [18]. This paper will use forward node selection to represent this idea. The size of the candidate forward node set can be further reduced by neighbor designation approaches in [19]. These localized forward node selection algorithms guarantee the coverage of the whole network, but informing 1-hop neighbors that who will be a forward node introduces a communication overhead. A detailed overview of broadcasting in ad hoc networks can be found in [20]. Research on energy efficient broadcast protocols is usually coupled with topology control, which tries to maintain a connected network topology with the minimum total transmission power [21]. But finding a minimum energy broadcast tree is NP-hard [22]. Many heuristic protocols have been introduced [23], which can approximate the optimal solution with a constant factor when the global network information is available. Some localized protocols have recently been proposed [24], but they need location or distance information and introduce extra communication overhead to exchange such information among nodes. Due to the resource constraints in IEEE 802.15.4 and ZigBee networks, we make following assumptions in this paper:

- The distance between nodes and the position of nodes are not available.

- The transmission power of nodes is fixed and the same.
- The network topology is not necessarily modeled as a unit disk graph. But the symmetry of neighborhood is assumed. That is, if A is a neighbor of B, then B is also a neighbor of A.
- Addresses are hierarchically assigned. Hence, given the network address of a device, the addresses of its parent and children can be derived without information exchange.
- Every device maintains a table of only 1-hop neighbors. Each neighbor table entry consists of a neighbor's network address and the number of its children.

To facilitate the description, some notations are listed in Table 1, where A and B represent a set of nodes or a single node.

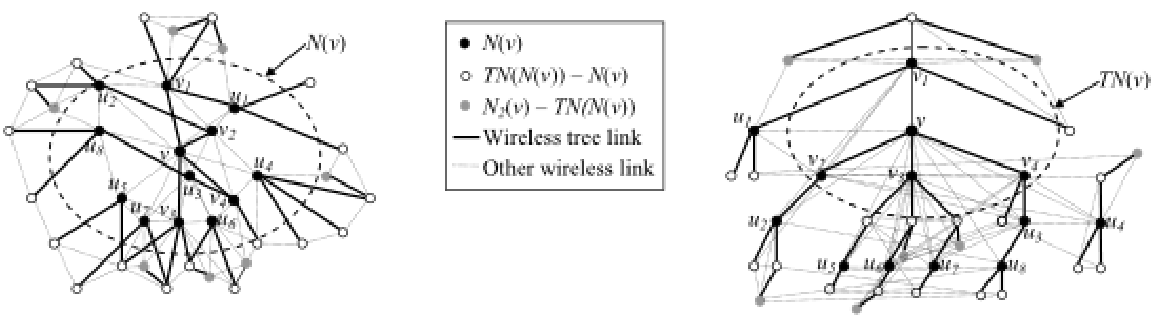
Table 1. Notations

$N_0(A)$ or $TN_0(A)$	A
$N_1(A)$ or N(A)	1-hop neighbors of A, including A
$N_K(A)$ (K≥2)	$N(N_{K-1}(A))$, k-hop neighbors of A
A covers B	B⊆ N(A)
$TN_1(A)$ or TN(A)	1-hop tree neighbors of A, including A
$TN_K(A)$ (K≥2)	$TN(TN_{k-1}(A))$
A on -tree covers B	B⊆ TN(A)
A – B	$A \cap \overline{B}$
S(A)	Candidate forward nodes of A
C(A)	To-be-covered nodes of A
F(A)	Forward nodes of A

III. ALGORITHM AND CODING

Zigbee On-Tree Self-Pruning Algorithms

The self-pruning broadcast algorithm would perform poorly when applied to ZigBee networks where the 2-hop neighbor information is not available. On the other hand, by exploiting the tree structure of ZigBee address space, a node can find addresses of a partial list of 2-hop neighbors without introducing any communication or storage overhead. In other words, given the address of a 1-hop neighbor in N(v) and its number of children, one can determine the addresses of all its tree neighbors in TN(N(v)).



a. Physical topology b. Logical ZigBee tree topology

Figure 2. A ZigBee network topology

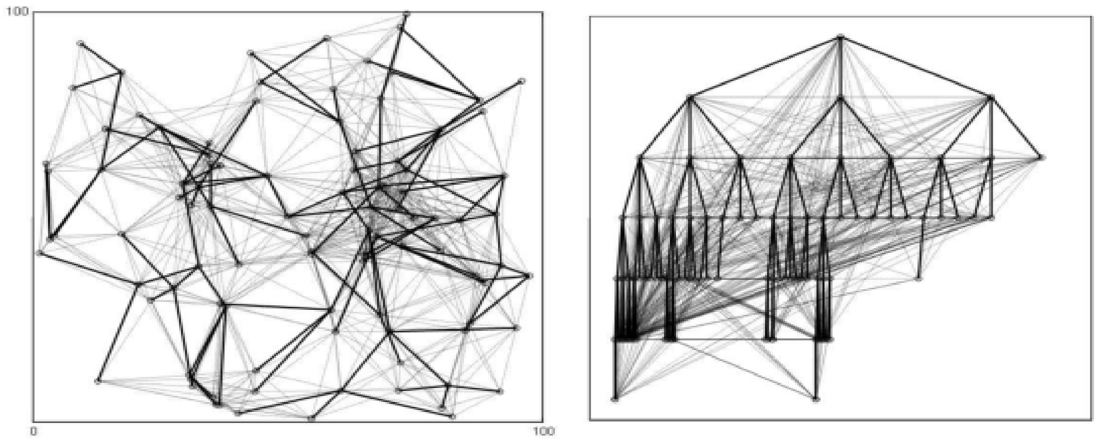
Fig. 2 displays a ZigBee network when nm = 3, including both physical topology and logical tree topology. For node v at the center, all its 1-hop neighbors N(v) (black dots) are located within its transmission range as shown in Fig. 2a. Among these 1-hop neighbors, four tree neighbors belong to 10 located anywhere on the logical ZigBee tree in Fig. 2b. Assuming the address of node v is Av, the depth of node v in the logical ZigBee tree is d, and it is the k^{th} child of its parent v1, then the address of its parent would be A_V - (k-1)Cskip(d)-1 and the address of it i^{th} $(1<=i<= n_m)$ child is A_V +1+(i-1)Cskip(d+1). More details of address assignment in ZigBee networks can be found in. Similarly, given the network addresses of v1 to v4 and u1 to u8, node v can further identify their parent and children, which form TN(N(v)) represented by white dots in Fig. 2. For any 1-hop neighbor of node v, for example node v1, it may have its own 1-hop neighbors other than its tree neighbors, which are not known by node v. Therefore, TN(N(v)) is only a subset of N2(v).

The gray dots in Fig. 2 represent all nodes in N2(v) – TN(N(v)). The tree neighbors are connected by solid lines in Fig. 2, while any two nodes that are not tree neighbors but are within transmission range of each other are connected by dotted lines.

According to the self-pruning algorithm for general ad hoc networks, node v in Fig. 2 needs to receive the duplicated broadcast packet from all its twelve 1-hop neighbors before it can prune itself; whereas with the on-tree self-pruning algorithm we propose, node v can prune itself once it learns that its four tree neighbors, v1 to v4, have been already covered. The coverage information can be acquired by receiving the duplicated broadcast packet from either v1 to v4, or their tree neighbors.

The proposed broadcast algorithms for ZigBee networks are evaluated by using an event-driven simulator we developed in MATLAB, which includes a ZigBee network generator. We assume an ideal case when there is no packet loss in MAC and physical layer.

The reliability issue is recently studied in. The network topology is generated within a 100 m × 100 m sq. area. The location 18 of each node is randomly generated. In addition to the proposed OSR and ZOS algorithms, four other algorithms are simulated for comparison.



a. Physical topology **b. ZigBee logical topology**

1) The SBA [15] in which a node is self-pruned only if all its physical 1-hop neighbors are covered;

2) The AHBP algorithm [17] in which a greedy algorithm is employed to select forward node from N(v) to cover TN(N(v)).

3) The ZigBee broadcast algorithm currently used by the ZigBee specification, in which only tree neighbors rebroadcast.

4) The Global algorithm in which greedy algorithm is applied to the whole network, assuming the global network topology is known. Although the global information is not available for each ZigBee device, this Global algorithm gives an approximation of the global optimal solution of finding the minimum number of nodes to rebroadcast.

In the greedy algorithm adopted by the above AHBP and Global algorithms, every node counts its neighbors that are not yet covered. The node with the maximum number of uncovered neighbors is selected first. Figure 3 illustrates a ZigBee network of 100 nodes and the rebroadcast nodes resulted from the above six algorithms. Both the physical topology and logical ZigBee topology are displayed, in which the wireless link between each pair of tree neighbors is represented by a solid line, while the other wireless links are represented by dash lines. The number of rebroadcast nodes is 100, 85, 51, 36, 31, and 10 for ZigBee, SBA, OSR, AHBP, ZOS, and Global algorithms, respectively, which is in decreasing order and reflects the increase of broadcast efficiency.

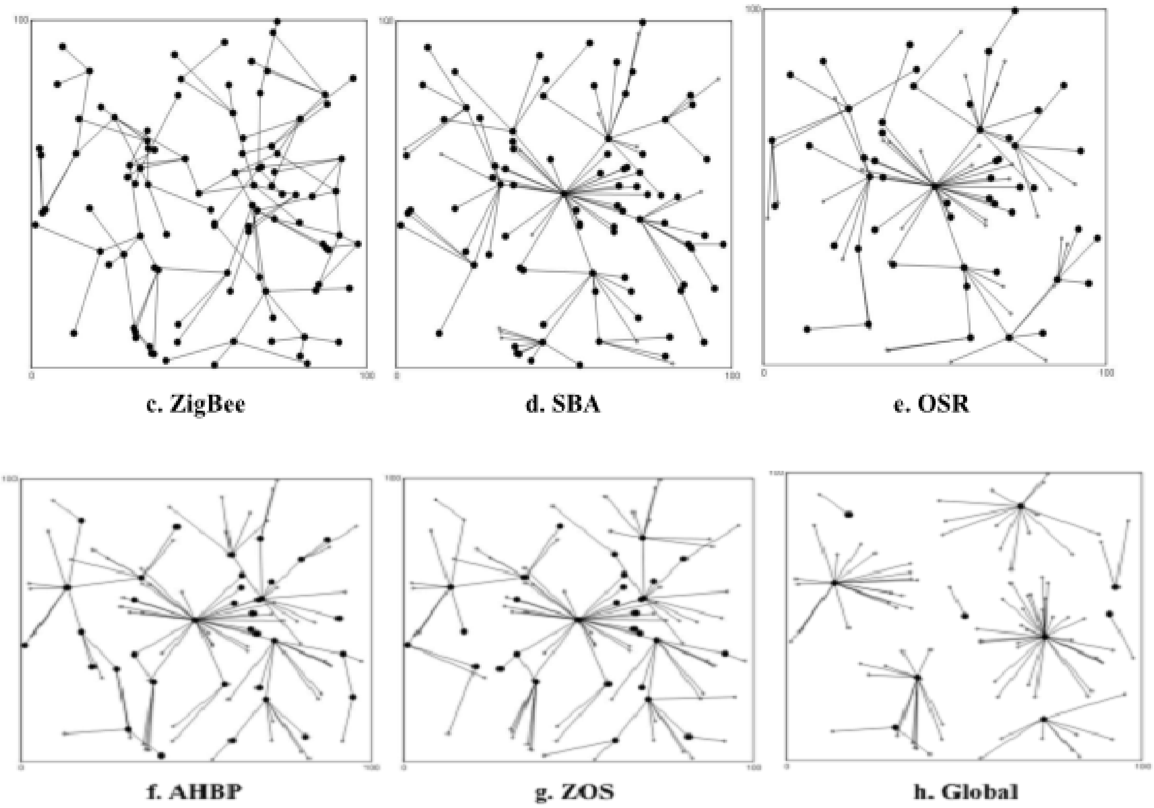


Fig. 3 ZigBee topology and rebroadcast nodes selected by six alorithms. Rebroadcast nodes are represented by big black dots in c to h. For alorithms zigBee, SBA,OSR,AHBP,ZOS and Global, the number of rebroadcast nodes is 100, 85,51,36,31,and10; the average number of duplicated packets is 17.6, 15.3, 9.42, 7.06, 6.39 and 1.89; the coverage time is 4.23ms, 1.23ms, 1.09ms, 1.73ms, 1.34ms and 0.954ms.

IV. RESULT

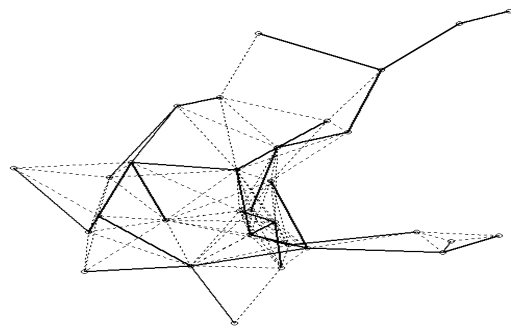
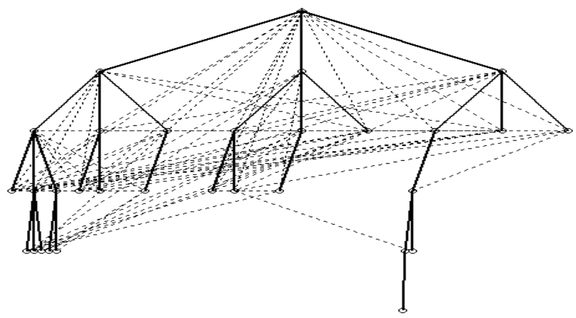
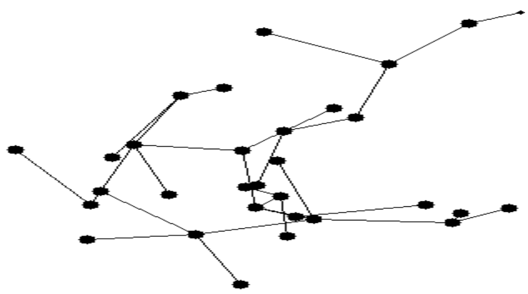


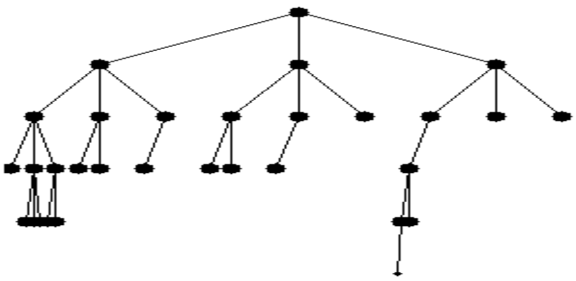
Fig.(i): Physical Network Topology



Fig(ii): Logical Network Topology



Fig(iii): Broadcast on ZigBee Physical Network Topology



Fig(iv): Broadcast on ZigBee Logical Network

V. FUTURE SCOPE

Chipcon is using ZigBee to produce a road map product that reduces the chip and system costs and increases integration level with low power consumption. Sensors are currently being used in environmental and agricultural applications, but the main target - home automation. ZigBee technology is also being used and tested in applications related to health monitoring.

VI. CONCLUSION

Given the fact that only physical 1-hop neighbors and logical tree neighbors are known in ZigBee networks, this paper has proposed two broadcast algorithms for IEEE 802.15.4 and ZigBee networks: on tree self-pruning rebroadcast algorithm OSR and ZigBee on-tree selection algorithm ZOS. The ZOS algorithm selects less number of rebroadcast nodes than the OSR algorithm, but it introduces an extra communication cost to carry the list of selected forward nodes. The proposed OSR and ZOS algorithms outperform the flooding based ZigBee broadcast algorithm, and the self-pruning algorithm SBA and forward node selection algorithm AHBP for general ad hoc networks. The proposed broadcast algorithms are feasible in terms of both computation complexity and memory space complexity.

In the real ZigBee networks, in addition to minimizing the number of rebroadcast nodes, we need to consider the robustness of the broadcast algorithm, which means that the broadcast algorithm should allow some kind of redundancy in order to cover the whole network even if the 1-hop neighbor information is not up-to-date or the nodes are moving. The trade-off between broadcast efficiency and reliability is studied in [25]. Future works include investigating the relationship between system performance and the ZigBee network parameters, the impact of dynamic network topology and power constraints on the broadcast algorithm.

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