A K-hop Zone-Based Broadcast Protocol in Mobile Ad Hoc Networks

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***Abstract*— Most proposed routing protocols in mobile ad hoc networks (MANETs) utilize neighbor set information to assist their routing decisions. 1-hop and 2-hop neighbor set information are the cases most commonly used. K-hop neighbor set, where $K \geq 3$, is seldom discussed in literature. In this paper, we discuss the broadcast problem in MANETs with the consideration of generic K-hop neighbor set. The proposed K-hop zone-based broadcast protocol is a simple, scalable protocol. The main purpose of this study is to provide a generic framework for a broadcast operation with K-hop information and to determine the potential performance improvement by increasing the value K.**[1]

I. INTRODUCTION

We consider a mobile ad hoc network (MANET) as a unit disk graph $G = (V, E)$, where the node set V represents a set of wireless mobile hosts (nodes) and the edge set E represents a set of bi-directional links between the neighbors. Each node has a unique identification (ID). Two nodes are considered neighbors if and only if their geographic distance is less than the transmission range. Broadcasting, as a fundamental operation, can be viewed as finding a *connected dominating set* (CDS) in a unit disk graph. A *dominating set* (DS) is a subset of nodes such that every node in the graph is either in the set or is adjacent to a node in the set. If the subgraph induced from a DS of the network is connected, the DS is a CDS. Finding a *minimum connected dominating set* (MCDS) in a given graph is NP-complete; in a unit disk graph, it has also been proved to be NP-complete. Therefore, only heuristic algorithms can be applied.

A node can utilize its neighbor set information for routing. 1-hop and 2-hop neighbor set information are the cases most commonly used. K-hop neighbor set, where $K \geq 3$, is seldom discussed in literature. In this paper, we consider the generic K-hop neighbor set problem and propose a simple K-hop zone-based broadcast protocol. When a source activates a broadcast operation, it selects a set of connected nodes in its K-hop neighbor set, called *forward node set*, to cover all the nodes in its K-hop neighbor set. The forward nodes are selected level by level, starting from the source to the nodes that are K-1 hops away from the source. In each level l, a set of nodes with the minimum size in level l is selected to cover all nodes in level $l+1$. The *border nodes*, which are the selected forward nodes exactly K-1 hops away from the source, become the new senders and they re-calculate their forward node sets in their corresponding K-hop neighbor sets. To reduce the coverage redundancy, the accumulative coverage area which is the union of the overlapped coverage areas, including the overlapped coverage area between the receiver and the sender, and overlapped coverage area between the receiver and any forward node with a smaller node ID than the receiver's, is excluded from the coverage area of the receiver. Thus, the number of forward nodes is greatly reduced. The objectives of this paper are twofold: (1) provide a generic framework for a broadcast operation with K-hop neighbor set information, and (2) determine the potential performance improvement by increasing the value K.

II. RELATED WORK

1-hop and 2-hop neighbor set information are commonly used in broadcast algorithms to assist the broadcast strategy. Guha and Khuller [1] provided a centralized algorithm that guarantees an *approximation ratio* of $O(\ln \Delta)$ to the MCDS under any random graph, where Δ is the maximum node degree of the network. In [2], Calinescu et al. proposed an algorithm proved to have a constant approximation ratio to the MCDS with location information. In [3], a generic localized broadcast scheme was proposed where broadcast-independent CDS approaches [4], [5], [6] and broadcast-dependent CDS approaches [7], [8], [9], are classified. All these algorithms pre-request that each node knows its 2-hop neighbor set information to construct its local view of the network.

The cluster-based schemes usually partition the network into non-overlapped regions. In [10], the network uses the node's 1-hop neighbor set information to form clusters. In [11], generic K-hop clustering is proposed: Each node gets its K-hop neighbor set information. A cluster is composed of all nodes within K hops from a given node. Each node belongs to one cluster. When a broadcast occurs, only nodes which are exactly K hops away from the sender, will relay the broadcast. A similar connectivity-based K-hop clustering algorithm is

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proposed in [12]. A node with the highest clusterhead priority, such as node ID or node degree, is selected as the clusterhead and all the nodes within a K-hop distance join in the cluster. In [13], a max-min D-cluster formation was proposed: A node u becomes a clusterhead if (a) u has the maximum ID within its K-hop neighborhood, or (b) u has the maximum ID in the K-hop neighborhood of another node v which is in u's K-hop neighborhood. Non-clusterheads choose their closest clusterheads to partition the network into clusters. Although clusters are not overlapped, two clusterheads may be adjacent. In [14], another K-clustering framework is proposed: The network is divided into non-overlapping subnetworks, and every two nodes in a subnetwork are at most K hops from each other. The proposed algorithm uses two phases to construct the K-clustering: a phase of constructing a spanning tree of the whole network and a phase of partitioning the spanning tree into several subtrees with bounded diameters. The special case of K-clustering ($K = 1$) is cliques [15].

The zone routing protocol (ZRP) [16] also assumes that each node gathers K-hop neighborhood information in its zone. Nodes in the zone periodically update their existence information so that each node can construct its *bordercast tree*, which is a multicast tree that spans all nodes within the routing zone. When broadcasting a query packet, the source applies the bordercast resolution protocol (BRP) [17] to deliver the packet to its destination. If the query destination is not in the routing zone, the packet is transmitted along the source's bordercast tree. Nodes on this tree will construct their own bordercast trees to forward the packet when they receive the packet. By pruning the branch where the packet was from on the tree, the bordercast tree includes only the uncovered nodes in the routing zone and saves many redundant transmissions. The algorithm requires each node on a bordercast tree to compute its own bordercast tree. It is not necessary since only border nodes that are K hops away from the source need to reconstruct their bordercast trees.

The proposed K-hop zone-based broadcast approach differs from cluster-based approach or ZRP (with BRP) in the following aspects: (1) In cluster-based approaches, cluster heads are not connected. Special nodes such as gateways need to be selected separately to connect clusterheads. K-hop zone-based approach generates a CDS of forward nodes. (2) In the ZRP approach, interzone routing protocol uses K-hop border nodes to disseminate a broadcast packet. But the K-hop zone-based broadcast approach uses (K-1)-hop border nodes to disseminate a broadcast packet. Also, the broadcast redundancy control mechanism is also different. In the ZRP, when a sender needs to broadcast a routing query outside the zone, it applies the BRP to construct its bordercast tree; each node on the tree needs to construct its own bordercast tree which only prunes the overlapped coverage area of the sender. In contrast, our approach does not require that every forward node but rather that only border nodes construct their broadcast trees. Besides extracting the overlapped coverage area of the sender, a border node also extracts the overlapped coverage areas of other border nodes with smaller IDs.

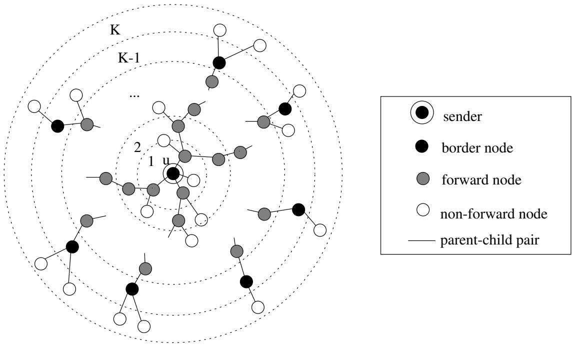

Fig. 1. Forward node set selection process.

III. A GENERIC K-HOP ZONE-BASED BROADCAST PROTOCOL

A. K-hop zone

In most of the current broadcast protocols, a node utilizes its neighbor set information to assist its routing strategy. A node's *K-hop zone* includes all the nodes within K hop distance from the given node. The hop count K is the *radius* of the zone. The value of K can range from 0 to the diameter of the network. In one extreme case where K's value is 0 (i.e., nodes in the network have no neighborhood information), the only possible strategy for a node to route the packet is to flood the packet to all its neighbors. In the other extreme case where K's value is the diameter of the network (i.e., each node knows the global information of the network), optimum solutions can be found in this circumstance. Since it is too costly and almost impossible for each node to get the global information in the MANET, centralized algorithms based on the global information are often used for getting theoretical boundaries. One required property for any practical routing protocol is its computational locality or distributivity. This requires that each node knows just its neighborhood information within a small hop distance to make routing decisions. Most of the current protocols assume that each node knows its 1-hop and 2-hop neighbor set information. The general case of K-hop neighbor set where $K \geq 3$ is discussed in this paper. It is assumed that K-hop neighbor information does not include any position information.

B. Forward node set selection process

$N_k(u)$, the *k-hop neighbor set* of u, consists of all nodes within k hops from u, and u's *k-hop node set* $H_k(u)$ consists of all nodes that are exactly k hops away from u. $N_k(u)$ and $H_k(u)$ have the following relationships:

1. $N_k(u) = N_{k-1}(u) \cup H_k(u)$
2. $N_{k-1}(u) \cap H_k(u) = \phi$

A sender u computes its forward node set level by level, starting from u to the nodes that are K-1 hops away from u, to cover all the nodes in its K-hop zone. In each level, u heuristically selects a forward node set $F_k(u)$ with a minimum number of nodes in $H_k(u)$ to cover all the nodes in $H_{k+1}(u)$, where $0 \leq k \leq K-1$. Specifically, $F_0(u)$ (u itself) covers

TABLE I

(0/1/2/3)-HOP NODE AND NEIGHBOR SETS OF NODE 6

k	$H_k(6)$	$N_k(6)$
0	6	6
1	2,5,7,11,12	2,5,6,7,11,12
2	1,3,4,8,10,13	1,2,3,4,5,6,7,8,10,11,12,13
3	9	1,2,3,4,5,6,7,8,9,10,11,12,13

all nodes in $H_1(u)$, $F_1(u)$ covers all nodes in $H_2(u)$, ..., this process repeats until $F_{K-1}(u)$ covers all nodes in $H_K(u)$ (see Figure 1). In each iteration, the selection criterion is that the node with the largest number of uncovered neighbors is selected first. A tie is broken by choosing the node with a smaller ID. All selected nodes form u's forward node set $F(u)$. Algorithm 1 summarizes the forward node set selection process.

Algorithm 1 Forward Node Set Selection Process (FNSSP)

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1: $F(u) = \phi$
2: for $k$ = 0 to $K - 1$ do
3:     $F_k(u) = \phi$, $U(u) = H_{k+1}(u)$.
4:     while $U(u) \neq \phi$ do
5:         Find $f \in H_k(u)$ such that $|N(f) \cap U(u)|$ is maximized.
           Node ID is used to break a tie if needed.
6:         $F_k(u) = F_k(u) \cup \{f\}$, $U(u) = U(u) - N(f)$.
7:     end while
8: end for
9: $F(u) = \bigcup_{i=0}^{K-1} F_i(u)$.
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Theorem 1: The forward node set $F(u)$ is a CDS of u's K-hop zone $N_K(u)$.

Proof: Assume that node x is a randomly chosen node in $N_K(u)$ and $x \in H_k(u)$. Based on the forward node set selection process, x is covered by $F_{k-1}(u)$, which is a subset of H_{k-1}. H_{k-1} is covered by $F_{k-2}(u)$, which is a subset of H_{k-2}. .... H_1 is covered by $F_0(u)$, which is u itself. Since nodes in $\bigcup_{i=0}^{k-1} F_i(u)$ are all connected to u, and x can be any node in $N_K(u)$, $F(u) = \bigcup_{i=0}^{K-1} F_i(u)$ can cover $N_K(u)$. Thus, $F(u)$ is a CDS of $N_K(u)$. ■

Theorem 1 also suggests that the FNSSP generates a broadcast tree within its K-hop zone, starting from sender u as the root and each node in the tree choosing the node which first covers it as its parent (see Figure 1).

Theorem 2: The computation complexity of the FNSSP is $O(\Delta^{2K-2})$, where Δ is the maximum node degree.

Proof: Assume Δ is the maximum node degree, the nodes in $H_k(u)$ are $O(\Delta^k)$ for $0 \leq k < K$. For a given k, step 5 of the FNSSP needs at most $O(\Delta^{2k})$ times of comparison to find $F_k(u)$. The total comparison is $\sum_{k=0}^{K-1} O(\Delta^{2k}) = O(\Delta^{2K-2})$. ■

Theory 2 gives an upper bound of the computation complexity. The complexity depends on the storage information of the node coverage and the node status information that changes from uncovered to covered each time a new forward node is selected. The real complexity is much less than the upper bound.

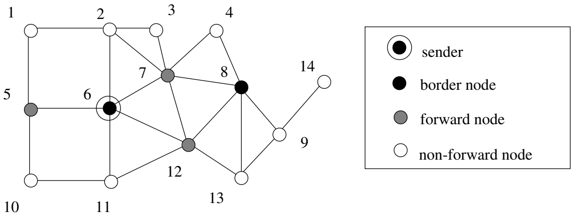

Fig. 2. A sample network with node 6's 3-hop zone.

A sample network is shown in Figure 2. Node 6 computes its forward node set. Table I gives node 6's k-hop node set $H_k(6)$ and neighbor set $N_k(6)$, where $k = 0, 1, 2,$ and 3. Node 6 covers $H_1(6)$. nodes 5,7 and 12 are selected from $H_1(6)$ to cover all nodes in $H_2(6)$. Node 8 is selected to cover nodes in $H_3(6)$. Therefore, $F(6)$=$\{5, 6, 7, 8, 12\}$.

C. *K-hop zone-based broadcast protocol*

Algorithm 2 is the K-hop zone-based broadcast protocol. There are two steps to disseminate a packet from a source to the entire network: First, the sender finds some forward nodes to cover all the nodes inside the sender's K-hop zone. Second, border nodes in the K-hop zone select their forward node set independently so that the broadcast packet can be propagated to the nodes outside the sender's K-hop zone. The forward nodes that are not border nodes just forward the broadcast packet. All other non-forward nodes in the sender's K-hop zone do not forward the packet when they receive the broadcast packet. These two steps continue until the broadcast packet traverses through the entire network (see Figure 3). Notice that the MPR [7] is a special case where K is 2.

Algorithm 2 K-hop Zone-Based Broadcast Protocol

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1. The sender $u$ uses the FNSSP algorithm to select its forward node
   set $F(u)$ to cover its $K$-hop zone $N_K(u)$. $u$ broadcasts the packet
   piggybacked with $F(u)$.
2. When a node $v$ first receives the broadcast packet,
     (1) If $v$ is a border node, it becomes a new sender and
         goes to step 1.
     (2) If $v$ is a forward node, but not a border node, it
         forwards the packet.
     (3) If $v$ is a non-forward node, it does nothing.
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Theorem 3: Given a connected network, the K-hop zone-based broadcast protocol correctly provides a broadcast operation.

Proof: Assume that a node x is k hops away from source u. If x is in $N_K(u)$, that is, $k \leq K$, Theorem 1 proves that x can receive the broadcast packet from u. If x is not in $N_K(u)$, that is, $k > K$, there exists a shortest path $P = (u, p_2, ..., p_K, ..., p_{k-1}, x)$ from u to x. Theorem 1 proves that $N_K(u)$ is covered by $F(u)$. Therefore, there exists a border node v in $F_{K-1}(u)$ that covers node p_K. From v to x, the path $P' = (v, p_K, ..., p_{k-1}, x)$ is shorter than P. Since v becomes a new sender and determines its own $F(v)$ to cover $N_K(v)$, x will eventually receive the broadcast packet from u. ■

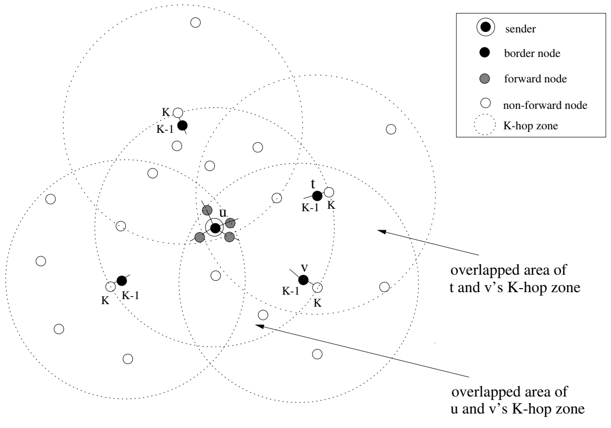

Fig. 3. Illustration of the K-hop zone-based broadcast protocol.

Figure 3 illustrates the K-hop zone-based broadcast protocol. The source u selects forward nodes to cover its K-hop zone. The black nodes are the border nodes that have their own K-hop zones. The gray nodes are forward nodes that just relay the broadcast packet. The white nodes are the non-forward nodes that only receive the packet.

D. Reduce redundant coverage for each forward node

In Algorithm 2, each border node becomes a sender after receiving the broadcast packet. Figure 3 shows the case when border node v receives a packet from sender u; there is a large overlapped area between u's K-hop zone and v's K-hop zone. As u is within v's K-hop zone, v can exclude the overlapped area from its K-hop zone $N_K(v)$. Two border nodes of u (e.g., nodes t and v in Figure 3) may also have overlapped area if these two border nodes are within K hops from each other. The K-hop zone of a border node with a smaller ID, say t, can also be excluded from the K-hop zone of a border node with larger ID, say v. That is, nodes in the overlapped area of two border nodes, v and t, are designated to be covered by the border node with a smaller ID (node t). In Figure 3, suppose that u selects its border node set $B(u)$ and $v \in B(u)$, v updates its uncovered K-hop zone $N_K(v) = N_K(v) - (N_K(u) \cup (\bigcup_{f \in B(u) \wedge id(f) < id(v)} N_K(f))) \cap N_K(v)$. If the updated $N_K(v)$ is not empty, the border node v becomes a new sender to execute Algorithm 2, otherwise, it stops.

When the overlapped areas are extracted from the sender, the broadcast operation in Figure 2 works as follows: Node 6 selects its forward node set $F(6)=\{5, 6, 7, 8, 12\}$, and node 8 is a border node and then becomes a new sender. Among nodes in node 8's 3-hop zone, all nodes are within 2 hops of source 6, except nodes 9 and 14. Node 9 will be selected by node 8 to cover node 14.

IV. PERFORMANCE EVALUATION

In this section, we measure the ratio of the average number of the forward nodes in the network for relaying a broadcast packet in a randomly generated network under different zone sizes as well as the delivery ratio when the node's mobility is in consideration. The simulation runs under the following simulation environment: Nodes are randomly placed within a confined area of 1000×1000. With a predefined fixed transmission range r, two nodes have a bi-directional link if their distance is less than r. If the network is not connected, it is discarded. No transmission errors (such as contention and collision) are considered here. We simulate different scenarios that the size of the network n is from a sparse network (n=200 and r=100) to a dense network (n=1000 and r=250). For each scenario, a sufficient number of simulation results are averaged to provide 90% confidence interval within ± 5%.

Figure 4 shows the ratio of the number of the forward nodes in the network versus the hop count of the K-hop zone under the scenarios that n=200 or 1000, and r=100 or 250. In Figure 4 (a) where r is 100, the ratio does not drop much when the radius of the zone increases for the 200-node network; in contrast, the ratio for the 1000-node network remains almost flat when the radius increases from 2 to 6. Dramatically, the ratio drops to 0.2 when the radius keeps increasing from 6 to 10. Figure 4 (b) shows that when r is 250, the ratio drops remarkably as the radius increases from 2 to 5 for both the 200-node network and the 1000-node network. The curve of the 1000-node network drops more than that of the 200-node network. After the radius of the zone passes a certain threshold (K = 5), increasing the radius does not affect the ratio. This indicates that increasing the radius of the zone does not reduce the ratio of the number of forward nodes unless the radius is comparable to the diameter of the network. The density of the network also affects the ratio since more forward nodes need to be selected as the network density increases.

Figure 5 shows the delivery ratio when the mobility of the node is considered (v = 1 and 10). Figure 5 (a) shows the result when r is 100 whereas Figure 5 (b) is the result when r is 250. As we can see, as the the speed of the node increases, the delivery ratio decreases. The radius of the K-hop zone also effects the ratio. The larger the radius is, the more remarkable is the ratio drop. This is because a larger radius of the K-hop zone leads to a smaller selected number of forward nodes. As the node mobility is high, more forward nodes are likely moving outside the range of the K-hop zone, and thus, the resulting decrease of the delivery ratio. The network density can improve the delivery ratio. Comparing the curves of the 200-node network and the 1000-node network, we can see that the delivery ratio in a sparse network (200-node network) is more sensitive to the speed of the node mobility.

From the primitive simulation, we say that the K-hop zone-based broadcast protocol is effective only when the radius of the K-hop zone is comparable to the diameter of the network, depending on the density of the network. Although increasing the radius of the zone reduces each node's forward node set which also results in reduced broadcast redundancy, it also forces each node to keep a large neighbor set. Also, the delivery ratio is affected by reducing the number of the forward nodes when the node's mobility is considered. Therefore, a sensitive trade-off is needed.

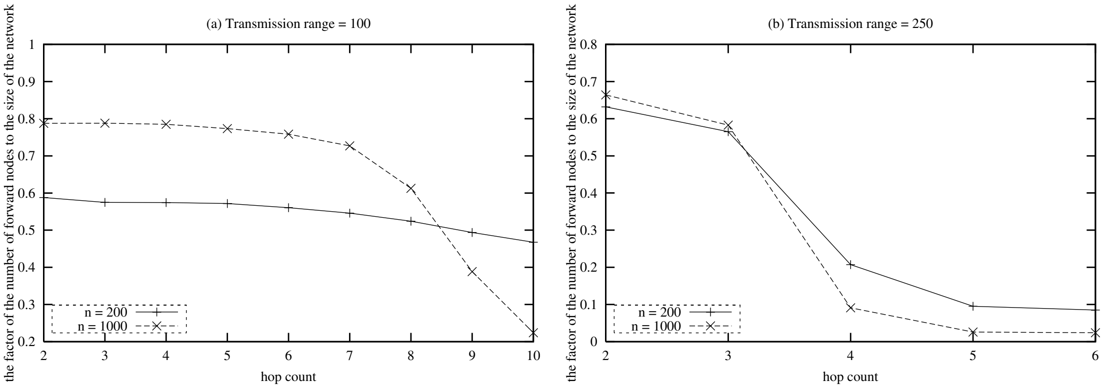

Fig. 4. The ratio of the number of forward nodes in the network under different node's transmission ranges: (a) range = 100, and (b) range = 250.

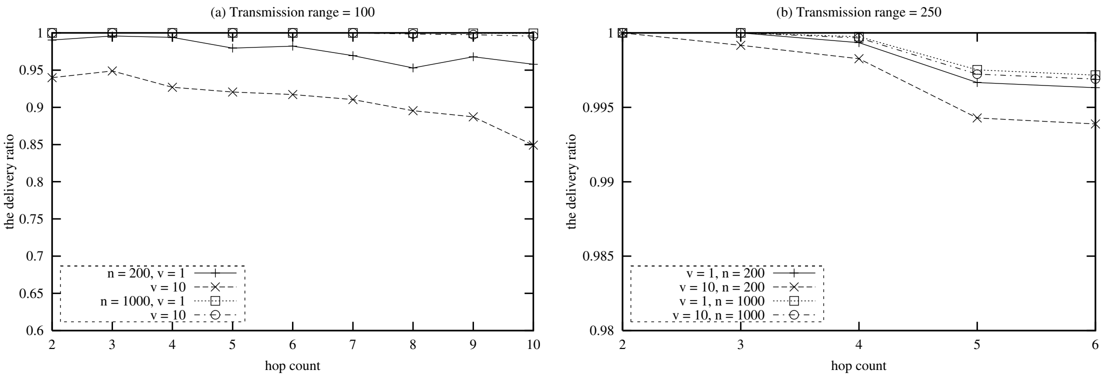

Fig. 5. The delivery ratio vs. the radius of the zone under different node speeds and transmission ranges: (a) range = 100, and (b) range = 250.

V. CONCLUSIONS

In this paper, we discuss the generic K-hop zone problem and propose a K-hop zone-based broadcast framework that utilizes the node's K-hop zone to reduce the size of the forward node set. Simulation shows that the radius of the K-hop zone effects the number of the forward nodes and delivery ratio as the node mobility is considered. Therefore, to improve the broadcast performance, there is a trade-off between maintaining a smaller K-hop zone and selecting less forward nodes to relay a broadcast.

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