Location-Aware Chord-based Overlay for Wireless Mesh Networks

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***Abstract*— Wireless Mesh Networks (WMN) have been widely set up for last-mile network connectivity due to their flexibility, ease of use and low-cost deployment. When used in conjunction with peer-to-peer data transfer solutions, many innovative applications and services such as distributed storage, distributed resource sharing, and live TV broadcasting can be deployed without any centralized administration. However, in order to achieve good quality of service in wireless environments, it is important that the associated peer-to-peer overlay is not only aware of the availability, but also of the location, of its peers and services. This paper proposes a wireless location-aware Chord-based overlay mechanism for WMN (WILCO) based on a novel geographical multi-level ID mapping and an improved finger table. The proposed scheme exploits the location information of mesh routers to decrease the number of hops the overlay messages traverse in the physical topology. In comparison to the original Chord, WILCO has significant benefits: it reduces the number of lookup messages, has symmetric lookup on keys in both the forward and backward directions of a Chord ring and achieves a stretch factor of $O(1)$. Simulation results show how the proposed scheme outperforms the original Chord and the state-of-the-art MeshChord in terms of lookup efficiency and significantly reduces the overlay message overhead.**

***Index Terms*— Wireless mesh networks, Location-aware overlay, Chord.**

I. Introduction

Wireless Mesh Networks (WMN) are multi-hop wireless networks with two types of components: Mesh Routers (MR) and Mesh Clients (MC). MRs are assumed to be stationary, power-unlimited and connect to each other wirelessly to form a wireless backbone. Some MRs have wired connections to the Internet or access to other networks and services. MCs are user devices connecting to the wireless backbone of the WMN to gain access to the provided services. Unlike other types of multi-hop wireless networks, such as Mobile Ad-hoc Networks (MANET), the backbone of a WMN is mostly stationary, being very stable and capable of supporting high bitrate communications. Moreover, MRs can be modified in hardware with multi-channel, multi-radios or directional antennas which can further extend their coverage, increase bandwidth and reduce interferences [1]-[3]. MRs can also be customized in firmware to enable sophisticated resource allocation techniques for supporting user or operator-specific services such as VoIP or streaming video as well as future applications [1], [4], [5]. As they have many benefits, WMNs are regarded as the potential replacement of the traditional wired infrastructure to become the last-mile network for Internet access for both operators and self-managed community networks[1, 2].

Additional to being Internet access networks, WMNs can support many innovative services such as distributed storage services, distributed resource sharing, and live broadcast of local radio/TV channels [6]-[10]. The introduction of these applications suggests that peer-to-peer resource sharing will play a central role in future deployments of WMNs. However, this requires the construction of overlays which have to utilize efficient resource lookup, perform balanced content distribution and involve lightweight overhead so as not to greatly affect the normal operation of WMNs. Moreover, since the data rate between peers degrades sharply with the increase in the number of intermediate nodes between them [11], it is important that the constructed peer-to-peer overlays are not only aware of the status and availability, but also consider the physical location of peers.

Many vehicular applications would benefit from such location-aware overlays. In the context of vehicular networking, location-aware overlays could support smart traffic control systems in which real-time information about current road and/or traffic conditions is collected from the vehicles and disseminated to the drivers, reducing the probability of congestion and improving the overall driving experience. In addition, as the coverage of MRs is generally large, location-aware overlays could enable better data delivery by retrieving the content from the nearest service point, greatly enhancing user quality of service levels, even when user positions change in a highly dynamic fashion. In this context, Chord [12] is a very popular solution to building the overlay, mostly due to its simplicity and relatively high efficiency. In this paper, the focus is on further improving Chord lookup efficiency and reducing the overlay overhead when employed over WMN by using location information.

This paper proposes **a Wireless Location-aware Chord-based Overlay mechanism for WMN (WILCO)**. The location-awareness of the proposed mechanism is realized through a novel geographical multi-level Chord-ID

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[1] MIT, ROOFNET project - http://pdos.csail.mit.edu/~rtm/roofnet-b.pdf
[2] Seattle Community Wireless Network - http://www.seattlewireless.net/

assignment to the MRs on grid WMNs. An improved finger table is proposed to make use of the geographical multi-level ID assignment to minimize the underlay hop count of overlay messages. An analytical framework is developed to analyze the lookup efficiency of the proposed scheme. This study proves that in comparison with the original Chord, WILCO reduces the maximum number of lookup messages by half, and has symmetric lookup behavior in both forward and backward directions of the Chord ring. The analytical framework also shows that the proposed scheme has a stretch factor of $O(1)$, which implies that the constructed overlay closely matches the physical topology. Simulation results show that in comparison with Chord and MeshChord, WILCO significantly improves lookup efficiency in terms of the average number of lookup messages, number of hops a lookup travels on the physical network, lookup time and stretch factor. Additionally, the results indicate that the proposed scheme greatly reduces the message overhead and provides more overhead balance among the MRs, which indicates that WILCO scales to large WMNs.

The rest of this paper is organized as follows. In Section II, the related works and their contributions are presented. Section III describes the proposed multi-level ID assignment and the newly introduced finger table. In Section IV, simulation results are presented and commented on. Section V includes a discussion of the proposed scheme and Section VI concludes the paper.

II. RELATED WORKS

Unlike the client-server architecture, the peer-to-peer resource sharing-based approach relies on building up an overlay in which all members contribute their resources to the network in return for other resources from other members. This overlay has no centralized control, being fully distributed, self-organized, and supporting joining/leaving of members, self-healing following peer failure, etc. These benefits have made peer-to-peer a promising candidate for many applications such as distributed storage, resource sharing, distributed processing, and searching. Among the methods of building overlays, one of the most common approaches using Distributed Hash Table (DHT), is adopted by many proposed solutions such as Chord [12], CAN [13], Pastry [14] and Viceroy [15]. However, these solutions are proposed for wired networks where bandwidth and connection stability are not important issues.

Different from wired networks, wireless multi-hop networks are bandwidth limited, error prone and time varying. These critical characteristics of wireless multi-hop networks make scalability a big issue when applying existing overlay protocols "as is" as a high maintenance traffic will eventually overwhelm the network capability. Moreover, in wireless multi-hop networks, it is well known that data delivery quality degrades significantly in terms of bandwidth and delay with an increase in number of hops between the two peers [11]. As a result, it is beneficial for the constructed overlay to be somehow aware of the physical topology.

In [16], the authors have proposed OverMesh, a novel network architecture to implement an overlay network over WMNs. To reduce search complexity and decrease the response time, a cross-layer search method was proposed based on the Gnutella flooding-based search. It can be seen that although this simple approach reduces the lookup delay in comparison with, for example, routing lookup messaging through finger tables in a Chord-based protocol, the flooding-based mechanism introduces excessive overhead and is not suitable for large-scale networks.

Another approach to building overlays over wireless network is to utilize geographic hash tables based on CAN. In these solutions, the IDs of data objects are hashed into geographic coordinates and all subsequent data referring to these IDs is stored at peers in the vicinity of these geographical locations [17]-[19]. In [17], the authors proposed TSAR, a two-level storage architecture for wireless sensor networks in which the sensor level gathers sensing data and the proxy level forms an overlay with a distributed index structure to enable range and summary queries which greatly reduces the overlay overhead. In [18], a data dissemination method for sensor networks using geographic hash tables is studied in which for each event, its related information is stored at a sensor node chosen based on the event name. Subsequent queries are directed to the sensor node that stores the event instead of flooding queries to all sensor nodes, minimizing the communications cost. In [19], the authors studied the usage of geographical hash tables to enable resource sharing in a continuously changing physical topology such as vehicular traffic in a city. However, since data is stored at some geographic locations, possibly far from the source peer, updating the data introduces a significant amount of overhead across the network, which makes this class of solutions not scalable.

In WMNs, where MRs are mostly stable and stationary, it is natural to see that a location-aware overlay of MRs (i.e., MRs which are close together in the physical topology should stay close in the overlay) will bring many advantages. First, when the constructed overlay is location-aware, a lookup message will go through less wireless hops and hence results in faster overlay communications. Besides, when the overlay peers are close together physically, the control messages for maintaining the overlay need to travel a minimal number of wireless hops only; therefore, network overhead decreases significantly and the overlay response to network failure is shorter. Moreover, if multiple copies of popular resource items are spread across the network, the content retrieval is improved by knowing the physical location of the content in the network and enabling distribution from geographically closest peers. In [20], the authors proposed a geographic ID mapping scheme which exploits location information of MRs to build a location-aware Viceroy-based overlay. The authors also proposed the *stretch factor*, a metric for measuring how close the overlay is to the physical topology and proved that their geographic ID mapping can achieve a stretch factor of $O\left(\sqrt{N \log N}\right)$ (i.e., an overlay lookup traverses $O\left(\sqrt{N \log N}\right)$

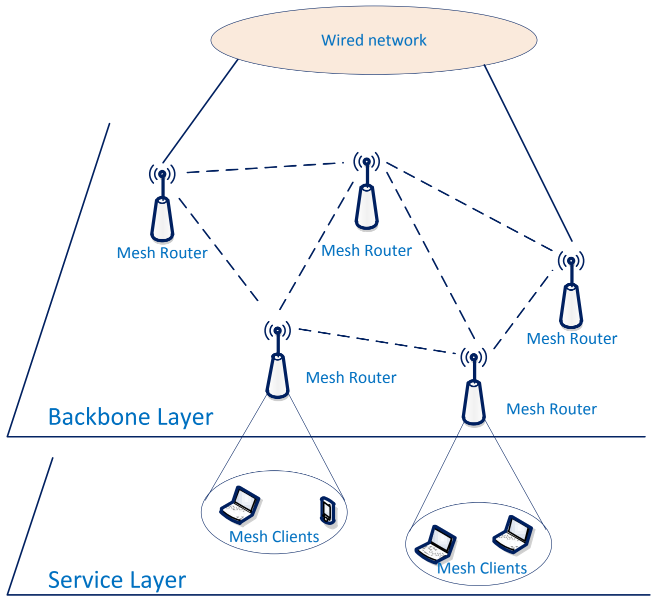


Figure 1: Network architecture.

hops in the physical network). Other works [21]-[22] extended the same ID mapping scheme to Chord and proposed a cross-layer mechanism to reduce the lookup time.

In this paper, we focus on WMNs, and following the idea of location-aware overlay, we choose Chord to construct the overlay. We first propose a multilayer physical location - ID mapping mechanism to provide location awareness. We then propose a modified Chord finger table to make use of this location-aware ID mapping which also provides symmetric lookup on both directions of the Chord ring. The proposed scheme is analyzed to show its superior lookup efficiency in comparison to the original Chord. By using the stretch factor as defined in [20], we prove that the proposed scheme achieves a stretch factor of $O(1)$. Simulation results show how WILCO, the proposed scheme, significantly improves the lookup time, reduces the number of lookup messages and the number of hops the lookup travels on physical topology and decreases the network overhead in comparison with Chord and MeshChord.

III. Location –aware Chord-based overlay

First, this section describes the network architecture which enables resource sharing and overlay construction. Then, it presents an overview of the operation of the Chord protocol. Finally, the proposed location-aware ID mapping and the improved finger table construction are described.

A. *Network architecture*

To accommodate resource sharing in WMNs, the two-layer architecture shown in Figure 1 is employed. The service layer includes MCs, which share services and resources as well as use those shared by other MCs. The backbone layer includes stationary, power-unlimited MRs with some of the MRs having wired Internet connectivity. These MRs run a Chord-based DHT to build up an overlay for locating resources and services within the WMN to serve the MCs.

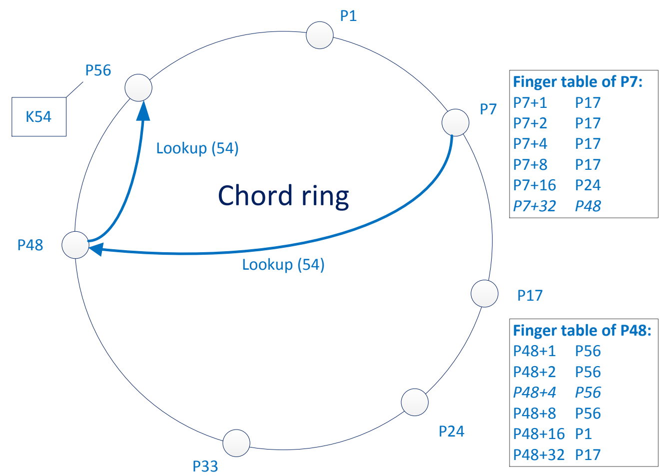


Figure 2: Overview of Chord operations for *m*=6.

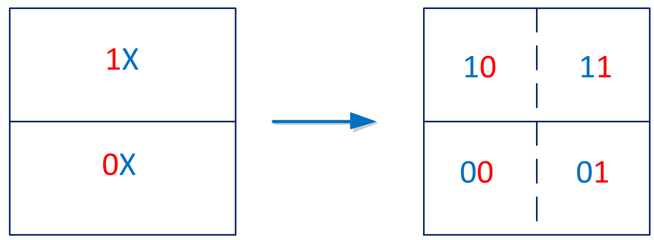


Figure 3: First step division.

B. *Overview of Chord*

In this paper, the DHT-based protocol of interest is Chord [12]. To identify peers (MRs) and resources on the overlay, the same m-bit ID space is used (to avoid ambiguity, the term *key* is used for resource IDs while *ID* implies peer ID). The IDs are ordered in an ID circle of modulo 2^m positions (the Chord ring). Each key is managed by a peer with the smallest ID greater or equal to that key. To efficiently locate a key, a peer with ID i builds and maintains a finger table which stores IP addresses of m other peers at ID $(i + 2^k) mod\ 2^m$ $(1 \leq k \leq m)$. To locate a key, the peer sends a lookup message to the MR in the finger table with greatest ID less than or equal to the key. Upon receiving the lookup message, the receiving peer checks if it manages the key; if so, it sends back the reply, otherwise it forwards the lookup message to its finger peer with the greatest ID less than or equal to the key. The process continues until the lookup message reaches the peer that manages the key. An example of this lookup process in which peer 7 searches for key 54 is illustrated in Figure 2.

This approach of lookup-through-finger table can resolve a lookup within $O(m)$ messages to other peers, as proven in [12]. However, since the finger table of Chord contains only IDs on half of the Chord ring entries in the forward direction (the increasing IDs direction of the Chord ring), Chord lookup is not symmetric (i.e., a lookup for a key close to the requested peer in the forward direction travels through much less intermediate peers than that in backward direction of the Chord ring). Another remark is that the Chord overlay IDs and the finger tables are independent of the physical topology (Chord IDs are generated by some hash function) and hence Chord is not location-aware. Consequently, lookup and overlay maintenance messages may travel across the entire

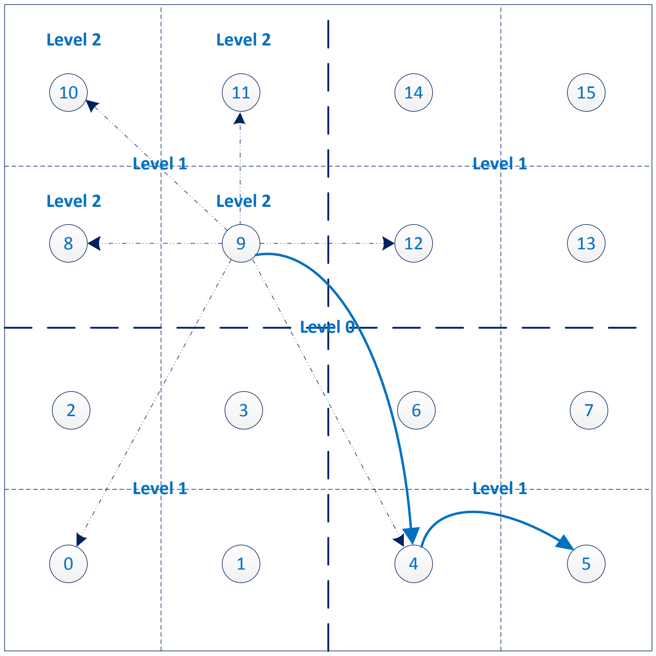


Figure 4: WILCO location-aware ID mapping for *m*=4.

physical topology many times and tremendously increase the overlay overhead and response time. To overcome these shortcomings of Chord on WMNs, in this study, we propose a location-aware ID mapping along with a new Chord finger table, which will be detailed next.

C. *WILCO location-aware ID mapping*

This paper considers a planned WMN deployment over an approximately square area with $N = 2^m$ stationary MRs laid out in a grid manner: i.e., MRs are almost equally distanced between each other. This grid-like WMN is used since it is shown in [23] that a random topology is unsuitable for large-scale mesh deployment and the grid topology provides the best balance between MR density, backbone connectivity and network capacity.

We use an m-bit binary addressing scheme where the location of the MR is encoded as follows. We first assume that m is even (the topology represents a square grid). The deployment area is divided into 2^m equal areas each containing a single MR in $\log_4 N$ steps. Each step subdivides the deployment area into 4 subareas, dividing along the vertical axis (y axis) and the horizontal axis (x axis). We assign two bits of the ID space to the MRs according to this division as follows and recursively use the subdivisions to assign a unique m-bit address to each MR. In the first step (Figure 3), the division on the y axis separates the deployment area into two halves and all the MRs residing on the upper half have the most significant bit set to 1. Likewise, all of the MRs residing on the lower half have the most significant bit set to 0. Next, the division on the x axis partitions each of these two halves into two areas; MRs on the left side get their second significant bit set to 0 and the MRs on the right side have their second significant bit set to 1. In the subsequent steps, each of the four areas from the previous step will be partitioned further into four smaller areas following the same mechanism as in the first step. After $\log_4 2^m$ steps, the deployment network is divided into 2^m areas, each containing one MR with a unique ID.

We refer to the areas produced after step i as level i area with the area at level 0 being the whole WMN deployment area containing all the MRs and the areas at level $\log_4 N$ each containing a single MR. Figure 4 illustrates WILCO location-aware ID mapping for 16 MRs ($m = 4$) and the resulting areas at level 0, 1 and 2. We denote the number of MRs at a level i area by N_i. An intuitive interpretation of the address produced is that when considerd at level i, the high $\log_2 N_i$ bits represent a unique identification of the area within the level and the low $(m - \log_2 N_i)$ bits represent a unique identification of a MR within a given area. Note that in each step, each of the areas considered in the previous step is divided into 4 equal-sized areas, and hence, the number of MRs in an area at level i is $N_i = 4^{\frac{m}{2}-i}$. Furthermore, two MRs with IDs p and k share the same area at level i if:

$$\left\lfloor \frac{p}{N_i} \right\rfloor = \left\lfloor \frac{k}{N_i} \right\rfloor \quad (1)$$

It is remarked that after the $(\log_4 2^m - 1)$-th step, there are only 4 MRs in each area and all but the last two ID bits are determined. Since the last 2 bits are decided in the next step, those MRs have consecutive IDs. This ensures that MRs that are close together in physical topology stay also close to each other in the overlay. Assuming that the communication range of each MR covers the distance from itself to the nearest MR in diagonal direction (i.e., in Figure 4, MR 0 can connect MR 3 directly), then all four MRs with consecutive IDs can directly communicate with each other. The last, but not least important remark is that each area at level i contains a quarter of the number of MRs as an area at level $(i - 1)$, and hence, the maximum number of physical hops between two MRs residing in the same area at level i is half of that between two MRs reside in the same area at level $(i - 1)$. This remark plays a central role in our location-aware ID mapping in terms of reducing the underlay hop count and in the proof related to the stretch factor to be presented.

Coming back to the assumption that m is even, it is easy to see that the proposed location-aware ID mapping also holds when m is odd. In this case, in the first step only one division is performed and the most significant bit is allocated only; all subsequent bit allocation steps remain unchanged, as already described. It is also noted that the location of each MR can be determined easily with a location-based solution such as using a GPS for example; and that since the MRs are assumed stationary, the mapping of IDs needs to be done only once at the planning stage and stay unchanged thereafter.

It is noted that for the deployment of real WMNs, the MRs do not need to be strictly equally separated for the location-awareness of WILCO to be feasible. From Figure 4, it can be seen that WILCO location-aware ID mapping only requires each MR to reside in its lowest level area (level 2 in this case) so that each MR has a unique ID. For a real network deployment, assuming the separation between the MRs is designed to be 100m, the size of each lowest level area is 10,000m^2. Finding a suitable place to install a MR in such a large area is not a very big issue, especially since MRs nowadays are so versatile that they can be easily mounted on streetlights[3].

D. WILCO finger table

In order to speed up the lookup process and make use of the proposed multi-level location-aware ID mapping, a new Chord finger table of $3 \times \log_4 N$ entries is proposed. Starting from the highest level $(\log_4 N - 1)$, at every level i, each MR maintains three entries (fingers) pointing to MRs with the lowest ID in each of the other area at level i with which it shares the same level $(i-1)$ area. For example, the finger table of MR 9 in Figure 4 (shown as dash-dot arrows) is as follows:

- Level 1 fingers: ID 8, 10, 11.
- Level 0 fingers: ID 0, 4, 12.

In general, the finger table of MR with ID p at level i $(0 \le i < m/2)$ is expressed as described next:

$$\text{Let } ID = N_{i-1}k + \left\lfloor \frac{p}{N_{i-1}} \right\rfloor N_{i-1}, \qquad k = 1,2,3$$

Then:

$$Finger_{i,k} = \begin{cases} ID & , if \left\lfloor \frac{ID}{N_i} \right\rfloor = \left\lfloor \frac{p}{N_i} \right\rfloor \\ \left\{\left\lfloor \frac{p}{N_i} \right\rfloor + 1\right\} N_i - ID + \left\{\left\lfloor \frac{p}{N_{i-1}} \right\rfloor - 1\right\} N_{i-1}, & if \left\lfloor \frac{ID}{N_i} \right\rfloor \ne \left\lfloor \frac{p}{N_i} \right\rfloor \end{cases} \quad (2)$$

where $N_i = 4^{\frac{m}{2}-i}$ is the number of MRs in an area at level i.

The operations and usage of the updated finger table is the same as in the original Chord. For instance, for MR 9 to locate key 5, MR 9 searches its finger table for a finger with the greatest ID less than or equal to 5 (MR 4) and sends a lookup message to this peer. When MR 4 receives the lookup message, it searches its finger table and finds MR 5 as its level 1 finger entry. It then forwards the lookup message to MR 5 to complete the lookup process. As depicted in Figure 4 (curved lines), this example further illustrates that the proposed ID indexing and finger table is location-aware. The lookup message is systematically forwarded from the geographically larger areas starting at the lowest level where the areas are not shared to smaller areas on higher levels. In our example, the lookup goes from MR 9 → MR 4 on level 1 and then from MR 4 → MR 5 on level 2. Hence, the search is geographically limited on a step by step basis.

Similar to a Chord finger table, WILCO finger table provides higher resolution information at lower level areas (large i) giving more location information about MRs in the immediate vicinity than at higher level areas. Another important remark is that since three level 0 fingers of any MRs point to the three MRs with the lowest IDs in three areas at level 1 (except the level 1 area where the MR resides), for lookup for key k at MR p, the proposed finger table provides at least one finger f that shares the same area at level 1 with k. In other words, if p and k share the same area at level $(i < \log_4 N)$, the proposed finger table of p provides at least one finger f that shares the same area at level $(i+1)$ with k.

[3] Cisco Wireless Mesh Networking – http://www.cisco.com/en/US/docs/solutions/Enterprise/Mobility/emob41dg/ch8_MESH.html

Compared to the finger table of Chord, with $\log_2 N$ entries, WILCO finger table has an overhead of $3 \times \frac{\log_4 N}{\log_2 N} = 1.5$ times more entries. This overhead of the new WILCO finger table is just a scale factor from that of Chord [12], i.e., $O(\log N)$; hence, with the increase in network size WILCO finger table is as scalable as Chord.

E. Lookup efficiency analysis of WILCO

Lemma 1: Suppose MR p wishes to resolve a query for key k. If, p and k share the same area at level $i, (0 \le i < \log_4 N)$ then $(\log_4 N - i)$ lookup messages are required for p to resolve the lookup.

Proof: We use induction to prove the lemma.

We first show that the Lemma holds when p and k share the two lowest levels ($i = \log_4 N - 1$ and $i = \log_4 N - 2$):

- For $i = \log_4 N - 1$: Since the area at level i includes only 4 directly connected MRs and, according to the definition of the improved finger table, level i finger table of p has already included all these fingers, including k. Hence, p reaches MR k with only one lookup message.
- For $i = \log_4 N - 2$: Since the finger table of p at level i includes all the other three fingers, each at one area at level $(i+1)$ with which it shares the same area at level i, p sends lookup request to finger f with greatest ID less than k. Since f is the MR with the lowest ID in this area, f and k share the same area at level $(i+1)$. When f receives the lookup request, it forwards this request to k as in the case of $i = \log_4 N - 1$. Hence, $\log_4 N - i = 2$ lookup messages are required for p to reach MR k.

Suppose this lemma holds until level i $(i > 0)$, we now prove that it also holds for level $(i-1)$:

- Since p and k share the same area at level $(i-1)$ and p holds a level i finger f that shares the same area at level i with k (according to the definition of our improved finger table); p needs one lookup message to reach f. Since f and k share the same area at level i, additional $(\log_4 N - i)$ lookup messages are needed to get to k. Consequently, there are needed a total of $\left(\log_4 N - (i-1)\right)$ lookup messages. This concludes the proof.■

Theorem 1: With the proposed finger table, a lookup for any key k from any MR p requires at most $\log_4 N$ lookup messages.

Proof: Suppose MR p wishes to lookup for key k, we analyze the number of lookup messages to reach MR k.

Let i be the lowest level for which p and k share an area. According to Lemma 1, $(\log_4 N - i)$ lookup messages are required to find k. Since $i \ge 0$ the maximum lookup messages required is $\log_4 N$.■

Lemma 2: The proposed finger table gives symmetric lookup on both directions of the Chord ring.

Proof: Suppose MR p wants to resolve look-ups for key k and k'. Assume that level i is the lowest level where k and k' share the same area. Further assume that $p < k$ and $p > k'$. We show that using the proposed finger table, p can find k and k' with the same number of lookup messages.

According to Lemma 1, since p, k and k' share the same area at level i, it requires $(\log_4 N - i)$ lookup messages to resolve for k as well as $(\log_4 N - i)$ lookup messages to resolve for k' ■.

To evaluate the location-awareness of the proposed scheme, we adopt the definition of stretch factor in [20]-[22].

Definition: Stretch factor of network A is defined as

$$stretch(A) = \max_k \left\{ \frac{l(P(k))}{l(k)} \right\} \quad (3)$$

where:

$P(k)$ is the shortest path traversed by the lookup for key k in the overlay network.

$l(P(k))$ is the shortest hop length of $P(k)$ in the physical network.

$l(k)$ is the hop length in the physical network between the MR at which the lookup is invoked and the MR that manages the key range to which k belongs.

Theorem 2: The stretch factor of the proposed location-aware ID mapping and modified finger table is $O(1)$.

Proof: From the proposed location-aware ID mapping, each area at level i contains a quarter the number of MRs as at level $(i-1)$; hence, the maximum number of physical hops between two MRs residing in the same level i area is only half of that between two MRs residing in the same area at level $(i-1)$.

From Lemma 1, every time a MR forwards a lookup message on the overlay, it forwards the message to its finger which shares the same area with the key, but at one level lower than itself. As the result, for each finger lookup on the overlay, the searching area shrinks by a quarter and the maximum number of physical hops from the next finger shrinks by half. It is noted that the maximum number of hops a lookup message needs to travel in physical topology at level 0 area is $\sqrt{N}$. From Theorem 1, the proposed scheme requires the maximum of $\log_4 N$ lookups; hence, the maximum number of hops a lookup traverse in the physical topology is:

$$\max_k\{l(P(k))\} = \sqrt{N} + \frac{\sqrt{N}}{2} + \cdots + \frac{\sqrt{N}}{2^{\log_4 N}} = \sqrt{N} \sum_{j=0}^{\log_4 N} \frac{1}{2^i} \quad (4)$$

Since $\lim_{m\to\infty} \sum_{i=0}^{m} \frac{1}{2^i} = 2$, for large topologies $(m \to \infty)$, we have $l(P(k)) = 2\sqrt{N}$.

For the considered grid topology, the hop distance in physical network between two MRs is $l(k) = O(\sqrt{N})$. Hence, the stretch factor can be calculated as follows:

$$stretch(A) = \max_k \left\{ \frac{l(P(k))}{l} \right\} = O\left(\frac{2\sqrt{N}}{\sqrt{N}}\right) = O(1) \ ■ \quad (5)$$

IV. Simulation Results

The performance of the proposed location-aware scheme is evaluated through detailed, packet-level simulations using Network Simulator NS-3 [25]. The simulated topology

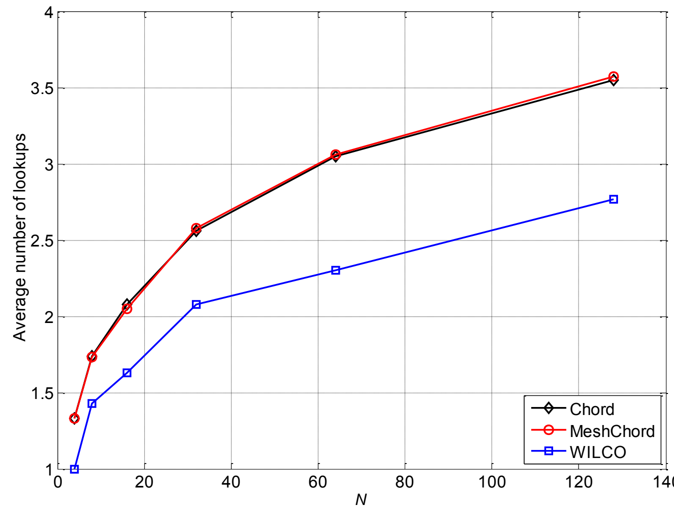


Figure 5: Average number of lookup messages vs. *N*.

TABLE 1: Simulation parameters for 802.11b.

Radio Technology	802.11b (Ad-hoc)
Peak Data Rate	11Mbps
Rate control algorithm	AARF-CD
Channels Sharing	CSMA/CA
Slot time	9µs
SIFS	16 µs
CTS Timeout	75 µs
ACK Timeout	75 µs
Antenna Type	Omni Antenna
Wireless transmission range	150m

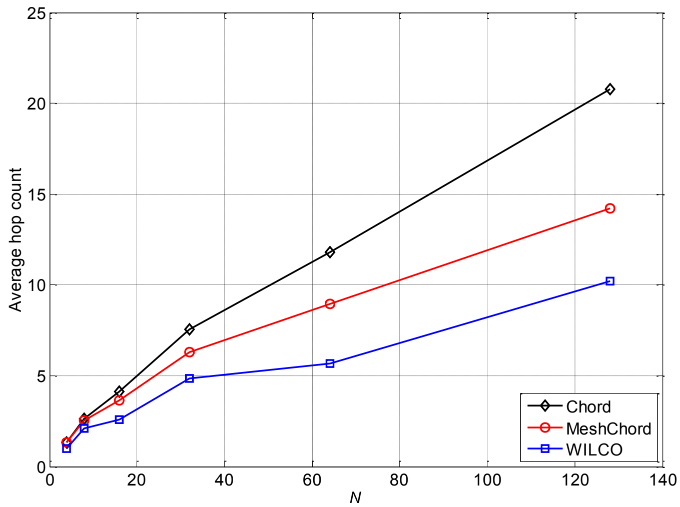
follows the descriptions from Section III.C, consisting of N MRs arranged in a grid, with the distance between two adjacent MRs set to 100m (a common network scenario for WMN simulations, i.e., [20]-[24]). In the simulations, all MRs are equipped with IEEE 802.11b radios (details as in Table 1) and OLSR is chosen as the underlay routing protocol. For the purpose of comparison, the original Chord with IDs of MRs randomly assigned from the ID space with no overlap and a finger table as in [12] and MeshChord [22] with geographical ID mapping, but not the MAC cross-layer support, are also considered on the same topology. In each case, 5000 lookups are generated; each from a MR to a key following a uniform distribution and the results are averaged.

The performance of WILCO is compared with the original Chord and MeshChord in both lookup efficiency and message overhead efficiency. In particular, the lookup time, number of lookup messages and message overhead are monitored. These are important parameters for evaluating the overlay performance and are commonly used in the literature ([7],[10]-[20]). In addition, the underlay hop count and stretch factor ([20]-[22]) are also investigated to demonstrate the location-awareness of the proposed scheme. The descriptions of the performance measurement parameters are as follows.

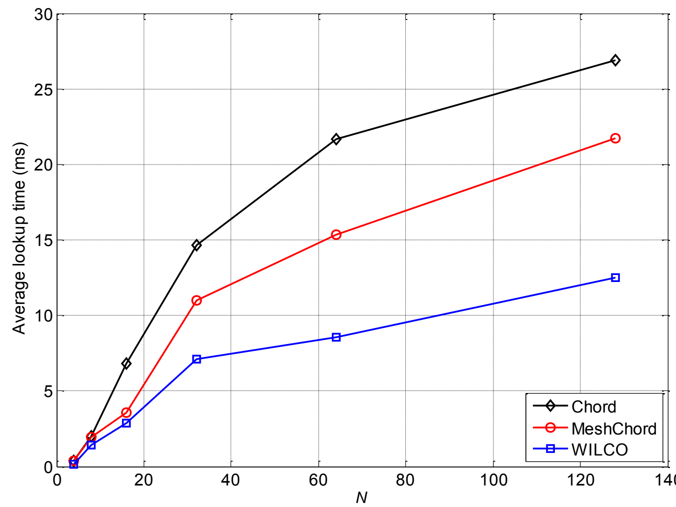
- *Underlay hop count*: average number of hops a lookup process traverses in the physical topology.
- *Lookup time*: average period of time for a lookup request to be resolved.
- *Number of lookup messages for each lookup*: average number of fingers a lookup traverses to reach its destination.

TABLE 2: NUMERICAL COMPARISON OF CHORD, MESHCHORD AND WILCO FOR *N*=128.

	Lookup efficiency								Message overhead			
	Number of lookup messages	WILCO Benefit	Hop count	WILCO Benefit	Lookup time (ms)	WILCO Benefit	Stretch factor	WILCO Benefit	Average Overhead (pk/s)	WILCO Benefit	90-percentile overhead (pk/s)	WILCO Benefit
WILCO	2.77	-	10.19	-	12.50	-	1.96	-	30.01	-	51.16	-
MeshChord	3.57	22.31%	14.23	28.40%	21.76	42.57%	3.52	44.42%	35.98	16.58%	52.56	2.66%
Chord	3.55	21.90%	20.80	51.01%	26.89	53.51%	5.21	62.41%	63.52	52.74%	94.87	46.07%



a. Average hop count versus *N*.



b. Average lookup time versus *N*.

Figure 6: Average hop count and lookup time comparisons.

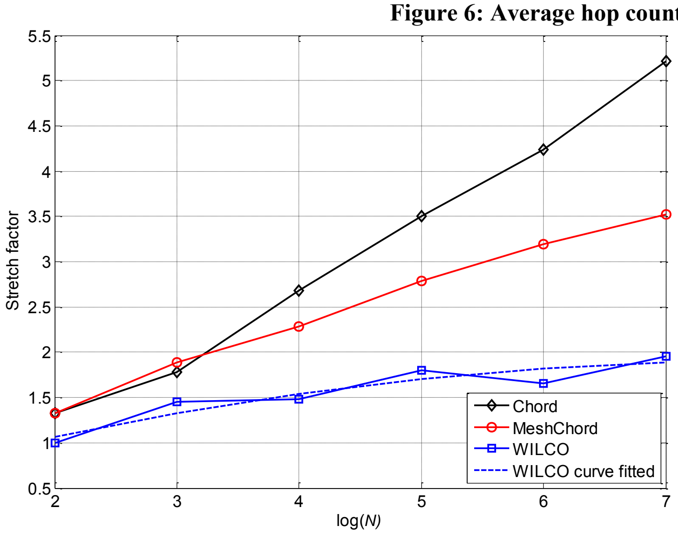


Figure 7: Stretch factor versus log(*N*).

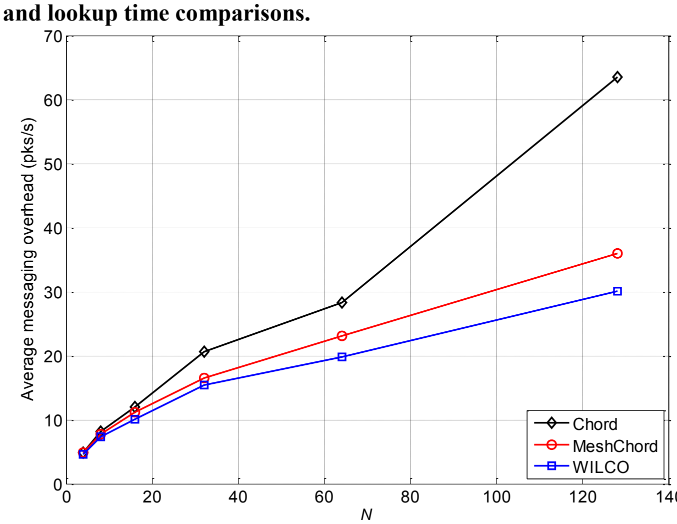


Figure 8: Message overhead with increasing number of nodes *N*.

- *Stretch factor*: the ratio between the hop count the lookup traverses on the overlay (through intermediate fingers) and the actual physical hop count between the MR source and destination. This metric evaluates the location-awareness of the proposed scheme and is adopted from [20]-[22].
- *Message overhead*: is the packet rate received at each MR to maintain the overlay and to resolve the lookups.

A. Lookup efficiency

We first examine the lookup efficiency of WILCO. Figure 5 shows the average number of lookup messages for each lookup with increasing number of MRs, when WILCO and the two compared schemes are employed respectively. It is observed that both Chord and MeshChord require the same number of lookup messages on average to resolve a lookup. This is due to the fact that both schemes use Chord finger table. Figure 5 also illustrates that WILCO, with the improved finger table, requires the least number of lookups among the three and although this number increases logarithmically for all compared schemes, the rate of increase is the slowest with WILCO. This is because the maximum number of lookup messages to resolve a lookup by WILCO with its modified finger table is $\log_4(N)$; hence, the average number of lookup messages should increase with $\log_4(N)$. In contrast, the number of lookup messages exchange by Chord should increase with $\log_2(N)$ following the same argument. The numerical result in Figure 5 also shows that the proposed scheme consistently saves up to 22% of the number of lookup messages in comparison with Chord and MeshChord.

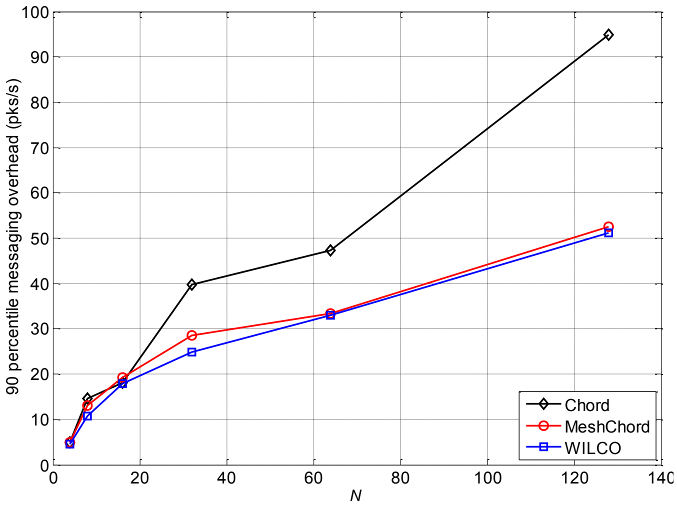


Figure 9: 90-percentile overhead versus *N*.

Figure 6a compares the average undelay hop count of Chord, MeshChord and WILCO. It is observed that for all network size, both the average hop count and its rate of increase of Chord is the highest, MeshChord comes second and WILCO is the most efficient scheme in this category. In particular, whenever N is doubled, the underlay hop count of Chord increases approximately 2 times, while that of MeshChord increases approximately 1.5 times. The underlay hop count for WILCO only doubles every time N increases by 4. Since both MeshChord and WILCO are location-aware, this figure implies that geographical ID assignment plays a central role in reducing the number of underlay hops and hence, improving the lookup efficiency. However, since WILCO requires a lower number of hops to resolve a lookup, this result implies that its multi-level location-aware ID mapping is better than the geographical ID mapping of MeshChord, especially for large WMNs. Figure 6a illustrates that WILCO can reduce by 50% the number of underlay hops as compared to Chord and roughly by 30% as compared to MeshChord. This result is confirmed by Figure 6b where WILCO outperforms Chord by approximately 50% and MeshChord by approximately 40% respectively in terms of lookup time.

Figure 7 compares the stretch factor of the three schemes with the increase in N. The graph has $\log(N)$ on the x axis. This figure illustrates that the stretch factor of Chord increases linearly with $\log(N)$, showing that the number of hops a lookup traverses on the underlay increases with the network size. Hence, on a large WMN, communication over the overlay is very inefficient and introduces a significant overhead. The stretch factor for MeshChord also increases linearly with $\log(N)$, confirming the result of the proof presented in [22] with the stretch factor of $O\left(\sqrt{N \log N}\right)$. However, the increase rate of the stretch factor of MeshChord is noticeably lower than that of Chord, which confirms the analysis presented previously that location ID assignment can improve overlay communication.

Following MeshChord geographical ID assignment which zigzags across the network row by row, it is easy to see that lookup messages also zigzag the network towards theirs destinations making the stretch factor increase with the size of the network and hence not being very efficient. Table 2 shows

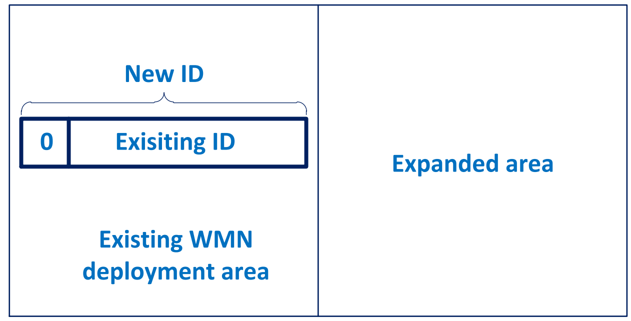


Figure 10: WILCO deployment area expanding.

that the stretch factor of WILCO is significantly lower than the two schemes it is compared against with only 1.96 for a network size of 128 MRs (roughly 60% lower than Chord and 40% lower than MeshChord). Moreover, the curve fitted representation in this figure illustrates the saturated trend of the WILCO stretch factor. This result confirms the $O(1)$ stretch factor which is proved earlier in Theorem 2. This efficient stretch factor of WILCO comes from the proposed multi-level ID assignment and the used of the modified finger table which narrows down the search to a quarter of the network for each intermediate lookup. These results illustrate that the proposed location-aware ID assignment and modified finger table reflect the physical topology accurately, i.e., communications on the overlay should be as efficient as the communication between the same MRs on the physical topology.

B. Overhead efficiency

The overall overhead efficiency of the three schemes considered is studied first by measuring the average message overhead, illustrated in Figure 8. It is observed that WILCO introduces the lowest message overhead, significantly lower than Chord and noticeably lower than MeshChord. This result shows that the random ID assignment of Chord is not efficient since overlay maintenance and lookup messages have to travel across the entire network to reach its successor, predecessor or finger peers. This results in a massive message exchange and the situation gets substantially worse with the increase in network size. On the other hand, a systematic planned ID assignment such as that of MeshChord and WILCO restricts overlay messaging geographically and hence, significantly reduces the network overhead. For a considerably large WMN of 128 MRs, as shown in Table 2, the message overhead of WILCO is approximately 50% and 20% lower than those of Chord and MeshChord, respectively. Consequently, among the three schemes, WILCO is the most scalable for WMN.

The 90-percentile message overhead is examined next, in order to evaluate the load balance of the three schemes. The Chord value is almost two times higher than those of WILCO and MeshChord. This result illustrates that in the worst-case scenario, 90% of the MRs in Chord must withstand twice the message overhead in comparison with MeshChord and WILCO, and hence, Chord provides not only the highest overhead, but also the poorest load balance. A highly unbalanced network overhead results in more chance of collisions and congestions which make the network unstable. Compared to MeshChord, the 90-percentile of WILCO is always lower, but not by a large margin. For a WMN of 128

MRs as shown in Table 2, the improvement is roughly 3%. Perhaps MeshChord already provides good load balancing and the multi-level ID assignment of WILCO can further improve this by only a small amount.

V. DISCUSSION

This paper shows how a location-aware ID assignment improves the overlay lookup efficiency in terms of average hop count on the underlay and lookup time. Depending on the location-aware indexing scheme, the overlay routing (finger table) has to be tweaked accordingly and an appropriate enhancement of the finger table could greatly improve the overlay communication. For example, in the case of WILCO, a stretch factor of $O(1)$ can be obtained. Furthermore, an appropriate location-aware overlay is also the key to a lightweight peer-to-peer protocol on WMN that can support many services without greatly affecting the overall network performance.

We observe that the hierarchical addressing scheme used in WILCO presents advantages over MeshChord in terms of scalability. MeshChord's geographical ID assignment is based on a predetermined fixed size of the deployment area and therefore it is not flexible. In such a case, the whole network has to be re-planned and all MRs have to be reassigned new IDs. The larger the network is, the more complicated and less feasible is this task. On the other hand, the proposed multi-level ID assignment of WILCO is modular as the IDs allocated to the two areas at the same level differ from each other in their prefixes only. Figure 10 shows an illustrative example when the network size is doubled. In this case, the existing MRs only need to add a prefix bit to their current IDs, without the need to redo the whole ID mapping procedure. This demonstrates how the proposed multi-level location-aware ID assignment is scalable and is suitable for real WMN deployment.

VI. CONCLUSION

This paper proposes WILCO - a location-aware overlay mechanism for WMN which includes a new ID mapping scheme and an improved finger table for improving the overlay's performance. The proposed scheme exploits the location information of MRs to build the overlay in which neighboring MRs in the physical topology are also closely located in the overlay. The simulation results show how WILCO significantly improves with up to 50% the lookup time, number of lookup messages and stretch factor in comparison with Chord and MeshChord. It also noticeably reduces the overlay overhead with up to 50% and 20% in comparison with Chord and MeshChord, respectively. Future work will focus on proposing algorithms to efficiently deploy peer-to-peer services, content replication and update and make use of the location-awareness to improve service quality.

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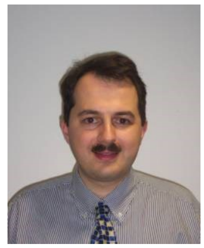

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