User Location-Aware Video Delivery over Wireless Mesh Networks

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***Abstract*— Wireless Mesh Networks (WMN) have been widely deployed 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, resource sharing and live video delivery 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. Focusing on the quality of video delivery, this paper first presents 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. Then, a novel segment seeking algorithm is proposed to make use of the location-awareness of the associated peer-to-peer overlay to locate and retrieve requested video segments from the nearest peers in order to improve video quality. Simulation results show how the proposed peer-to-peer video delivery solution for WMN outperforms existing state-of-the-art solutions in terms of video quality.**

***Index Terms*— Video delivery, Video on Demand, 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 of the MRs have wired connections to the Internet or other networks. MCs are user devices connecting to the wireless backbone of WMN to gain access to the provided services. Lately, due to many pioneering deployments in community networks[1,2], WMNs have attracted many researchers trying to increase the achievable bandwidth, reduce interference [1]-[3] or enable sophisticated resource allocation techniques for supporting user or operator-specific applications such as VoIP, live video streaming, etc. [1], [4]-[6]. Being a common access network, WMN also needs to support increasing user demands for video exchange, especially Video-on-Demand (VoD). The introduction of this type of applications suggests that peer-to-peer (P2P) resource sharing will play a central role in future deployments of WMN. However, since the data rate between peers degrades sharply with the number of intermediate nodes between them [7], it is important that the constructed peer-to-peer overlay is not only aware of the status and availability, but also of the physical location of the peers. Hence, a hash-based ID assignment such as that of Chord [8], CAN [9], Pastry [10] and Viceroy [11], well suited in wired network, is not applicable to wireless scenarios where bandwidth is scarce and connectivity properties vary.

In [12] the authors proposed a network architecture to implement overlay networks over WMN and use a simple cross-layer approach of broadcasting-based lookups to all the network nodes to reduce lookup delay. While it is simple to implement, this flooding-based mechanism introduces excessive overhead and is not suitable for large-scale networks. Another approach to building overlays over wireless networks is to utilize geographic hash table-based on CAN in which IDs of data objects are hashed into geographic coordinates and subsequent data related to these IDs is stored at the peer in the vicinity of this location [13]-[15]. However, since data is stored at some geographic coordinates possibly far from the source peer, updating the data introduces a significant amount of overhead across the network, which makes this class of protocols not scalable. In [16], the authors proposed a geographic ID mapping scheme which exploits location information of stationary MRs on WMNs to build a location-aware Viceroy-based overlay. The authors also proposed the stretch factor as a metric of measuring how close the overlay is to the physical topology and proved that their geographic ID mapping can achieve the stretch factor of $O\left(\sqrt{N\log N}\right)$, i.e., an overlay lookup traverses $O\left(\sqrt{N\log N}\right)$ hops in the physical network. [17] - [18] extended the same ID mapping scheme to Chord and proposed a cross-layer mechanism to reduce the lookup time.

In a P2P video delivery system, users can interact with the system by seeking within a video or jumping to another video. In [19]-[20], the authors proposed improved mechanisms to speed up the lookup process of seeking the video segment by a grouping-based storage strategy [19] or by exploring overlay locality to build shortcuts over the Distributed Hash Table (DHT) network [20]. However, the P2P VoD system needs not only to provide fast lookup for the requested video segment but also to select from the peers that store the requested segment the one that can provide the best quality of service. As data rate reduces with the increase in number of hops, it is promising to choose the peer which is geographically closer to

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[1] MIT, ROOFNET project - http://pdos.csail.mit.edu/roofnet/doku.php

[2] Seatle Community Wireless Network - http://www.seattlewireless.net/

the requesting node to get the video segment from.

In order to improve the quality of video delivery, 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 assignment to the MRs on grid WMNs. An improved finger table is proposed to make use of geographical multi-level ID assignment to improve lookup efficiency. Then, **a WILCO-based novel geographical location-based video segment seeking algorithm** is proposed to make use of the location-awareness of the peer-to-peer overlay to locate and retrieve video segments from the closest peer in order to improve video delivery quality. Simulation results show how WILCO improves the quality of video retrieval in WMN in terms of average user perceived quality levels.

The rest of this paper is organized as follows. Section II briefly summarizes the basic operation of Chord protocol. Section III describes the proposed multi-level ID assignment, the proposed modified finger table and the location-aware video segment seeking algorithm. Section IV describes the simulation and analyses the simulation results. Section V concludes the paper.

II. The Chord-based overlay

This section illustrates the overview operation of the Chord protocol that is used as the basic of WILCO. Chord [8] is a solution for connecting the peers on a peer-to-peer network to build up an overlay at application layer. The Chord overlay is composed of peers (MRs) and resources on the overlay, identified by the same m-bit ID space (to avoid ambiguousness, 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 its 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; and 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.

It is proved in [8] that this approach of lookup-through-finger table can resolve a lookup within $O(m)$ messages to other peers. However, since the finger table of Chord contains only IDs of 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 requesting peer in the forward direction travels through much less intermediate peers than that in backward direction of the Chord ring). Furthermore, 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 physical topology many times and tremendously increase the overlay overhead and response time. Besides, as the overlay is not location-aware, there is no way to determine a closer peer in geographical terms of number of hops for best content retrieval. 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, and a geographical segment seeking algorithm which will be detailed next.

III. WILCO Location-Aware overlay in WMN

This section shows WILCO network architecture which enables video sharing and overlay construction. Next, the proposed WILCO location-aware ID mapping and the improved finger table construction are described. Finally, the geographical location-aware video segment seeking algorithm is presented.

A. Network architecture

To accommodate resource sharing on WMN, a two layer architecture 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.

For P2P video distribution, when sharing by a server, each video will be assigned a unique key according to the HASH algorithm [8] and is managed by a MR according to the Chord protocol [8]. To support efficiently video delivery on peer-to-peer overlay, the server divides each video into equal size segments and assigns consecutive segment IDs to them in the order of playback. During the distribution process, many segments of the video become available in several places within the WMN. These segments are registered and periodically updated at the MR which manages the video and are stored in a database in the structure of $[ID_i, S_i, L_i]$ where ID_i is the ID of the MR under which the MC connects to; S_i is the start segment ID and L_i is the number of segments the node stores. In order to protect from single node failures, the successor of the MR which manages the key also stores and updates a copy of this database. When a peer requests segment S_j, the MR searches its database for the set of peers that has the segment $(S_j \in [S_i, S_i + L_i])$ and replies to the requesting peer with this set. Based on the ID of the requesting and destination peers, the geographical segment algorithm is performed and the requesting peer selects the destination peer with the closest distance in terms of hop count to retrieve the segment.

B. 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 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 [21].

We use a 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 1), 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 m-bit ID. For odd m, in the first step, a single bit is added to the ID, then the process continues similarly with the case of m is even.

We refer to the areas produced after step i as level i areas 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 2 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 areas at level i 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:

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

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. The last, but not the least important remark is that each area at level i contains a quarter of the number of MRs of an area at level $(i - 1)$, and hence, the maximum number of physical hops between two MRs from the same area at level i is half of that between two MRs reside in the same area at level $(i - 1)$. This fact plays a central role in our location-aware ID mapping in reducing the underlay hop count and hence, improving the lookup time.

It is noted that the location of each MR can be determined easily with a location-based solution such as using a GPS for example. Since MRs are assumed stationary, the mapping of IDs needs to be done only once at the planning stage and remains unchanged thereafter.

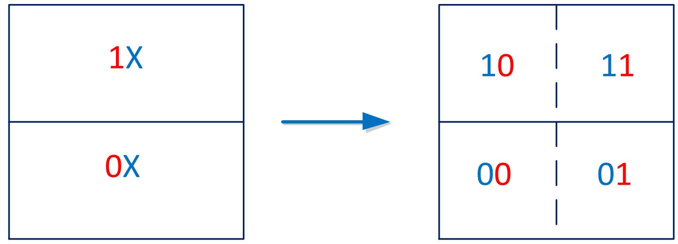


Figure 1: First step division.

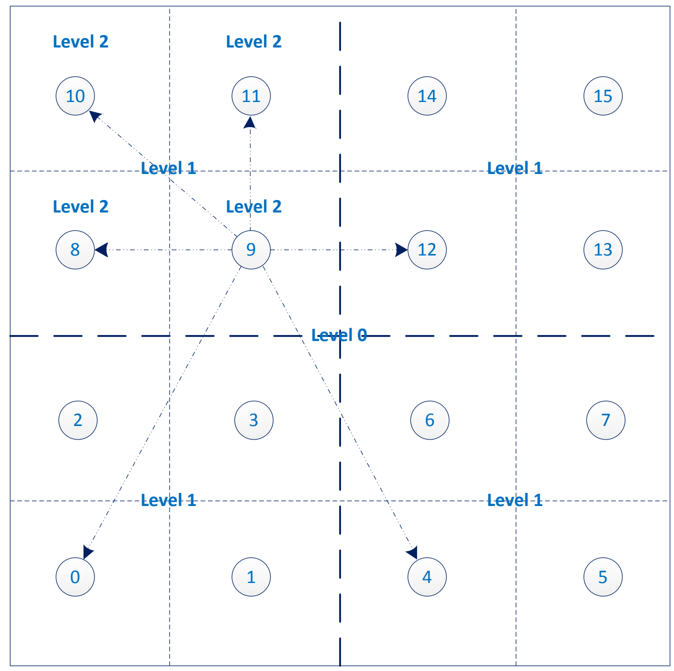


Figure 2: WILCO location-aware ID mapping for *m*=4.

C. WILCO finger table

In order to speed up the lookup process and make use of the proposed multi-level location-aware ID mapping, WILCO 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 2 (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 $(0 \le i < m/2)$ can be 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:

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

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

Similar to a Chord finger table, WILCO finger table provides higher resolution information at lower level areas (large i) in its vicinity than at the higher level. Another important remark is that since the three level 0 fingers in WILCO finger table of any MRs points to three MRs with lowest IDs in the three level 1 areas except the level 1 area where it resides, for a 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 ($i < \log_4 N$), the proposed finger table of p provides at least one finger f that shares the same area at level $(i+1)$ with k. Moreover, it can be demonstrated that the following characteristics hold for the combined location-aware ID mapping and Chord modified finger table:

- If MRs p and k share the same area at lowest level i (i.e., the lowest level area that both p and k reside), a lookup for key k from p requires $(\log_4 N - i)$ lookup messages to resolve. This is because p has one finger which shares the same area at level $(i+1)$ with k. This finger in turn has one finger in its finger table that shares the same area at level $(i+2)$ with k. There are $(\log_4 N + 1)$ levels in total, hence p needs $(\log_4 N - i)$ lookup messages to resolve k.
- Lookup is symmetric on both directions of the Chord ring: MR p can resolve lookups for key k ($p < k$) and k' ($p > k'$) with the same number of lookup messages provided that p shares the same lowest area at level i with both k and k'.

D. WILCO geographical location-aware video segment seeking algorithm

In P2P VoD, there may be many people watching the same video at the same time, but at different points in the video stream. Hence, the same segment of the video may be simultaneously available at several places in the network. In this context, a novel geographical location-aware video segment seeking algorithm is proposed for a peer to get the requested segment from the geographically closest peer for improved video quality retrieval.

Let r be the ID of the requesting peer and $\{d_j, j = 1, \dots, k\}$ be the set of destination peers that store the requested video segment, where d_j is the ID of the destination peer j. WILCO segment seeking algorithm is based on its location-aware ID assignment and includes three steps:

In the first step, the requesting peer constructs a coarse destination set by checking all of the destination peers and selecting only the ones with which it shares the lowest level area i_{max} by using equation (1). Algorithm 1 explains the coarse selection step.

If there is only one destination peer in d_{coarse}, r chooses this peer to retrieve the video segment, otherwise the algorithm continues. In the second step, the requesting peer associates costs to all the destination peers from the coarse destination set based on the distance between the requesting peer area at level $(i_{max}+1)$ and the destination peer. This step contains $(m/2 - i_{max} - 2)$ sub-steps. In each sub-step, the area at level t, $t \in [i_{max}+1, m/2-1]$, in which destination d_j resides is divided into two halves, notated as near and far halves with respect to the area at level i_{max} in which r resides as illustrated in Figure 3b. If d_j is in the far region, its cost increases by $2^{\frac{m}{2}-t}$. Based on these costs, r

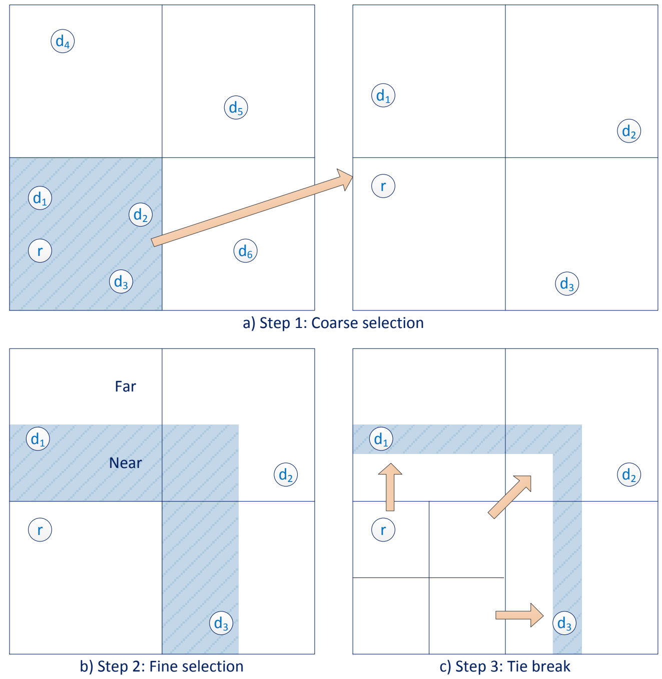


Figure 3: Geographical segment seeking algorithm example.

Algorithm 1: Coarse selection step

Compute $i_{max} = \max\left\{i: \left\lfloor \frac{d_j}{N_i} \right\rfloor = \left\lfloor \frac{r}{N_i} \right\rfloor, j = 1, \dots, k\right\}$

Find $d_{coarse} = \left\{d_j: \left\lfloor \frac{d_j}{N_{i_{max}}} \right\rfloor = \left\lfloor \frac{r}{N_{i_{max}}} \right\rfloor, j = 1, \dots, k\right\}$

Algorithm 2: Fine selection step

for each $d_j \in d_{coarse}$
  for $t = i_{max} + 1$ to $m/2 - 1$
    divide level t area containing d_j into near and far halves with respect to level i_{max} containing r
    if $d_j \in$ far half
      $cost_{d_j} = cost_{d_j} + 2^{\frac{m}{2}-t}$
    end if
  end for
end for
Compute $cost_{min} = \min\left\{cost_{d_j}, d_j \in d_{coarse}\right\}$
Find $d_{fine} = \{d_j \in d_{coarse}: cost_{d_j} = cost_{min}\}$

Algorithm 3: Tie break step

if $\left(\left\lfloor \frac{r}{N_{i_{max+1}}} \right\rfloor \bmod 4\right) \neq \left(\left\lfloor \frac{r}{N_{i_{max+2}}} \right\rfloor \bmod 4\right)$
  $d_{tb} = \left\{d_j \in d_{fine}: \left(\left\lfloor \frac{d_j}{N_{i_{max+1}}} \right\rfloor \bmod 4\right) = \left(\left\lfloor \frac{r}{N_{i_{max+2}}} \right\rfloor \bmod 4\right)\right\}$
else
  $d_{tb} = d_{fine}$
end if
if $size(d_{tb}) > 1$
  $destination\ peer = \{d_j \in d_{tb}: |r - d_j| = \min_j\{|r - d_j|\}\}$
else
  $destination\ peer = d_{tb}$
end if

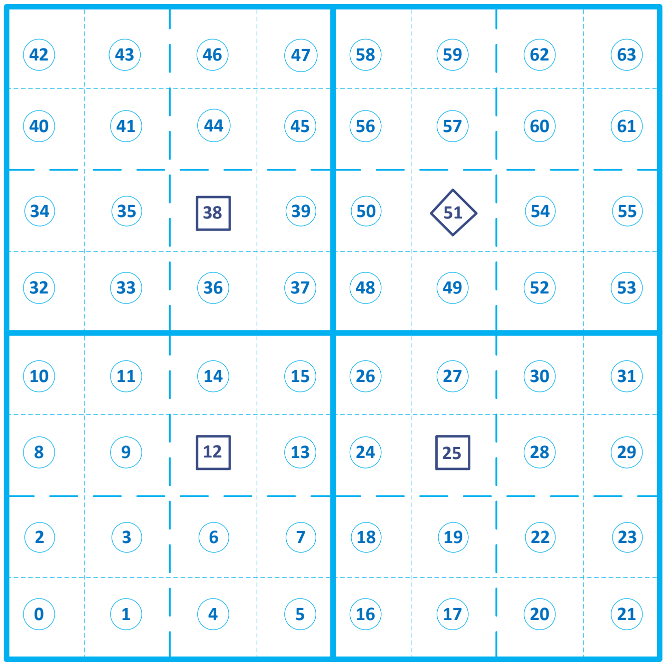


Figure 4: Simulation scenario.

retains only the destination peers with the minimum cost in the fine destination set d_{fine}. This set of destinations form a collar around the level $(i_{max}+1)$ area containing r as in Figure 3c. Algorithm 2 illustrates the fine selection step.

If there are more than one destination peer in d_{fine}, the algorithm continues with the tie break step. In this step, the level $(i_{max}+1)$ area containing r is divided into 4 equal level $(i_{max}+2)$ areas and depending on which area r resides in, the destination peers are selected accordingly, as illustrated by the arrows in Figure 3c. If there are more than one d_j satisfying this condition, r chooses d_j with the closest ID to its own ID. Algorithm 3 shows the tie break step.

IV. Simulation-Based Testing

The performance of WILCO, the proposed location-aware scheme is evaluated through detailed, packet-level simulations using Network Simulator NS-3. The simulated topology follows the descriptions from Section III.B, and consists of $N = 64$ MRs arranged in a grid, with the distance between two adjacent MRs set to 100m. In the simulations, all MRs are equipped with IEEE 802.11b radios and OLSR is chosen as the routing protocol. The simulation scenario is depicted in Figure 4.

In our simulations, three 10-second video segments $(S = \{S_1, S_2, S_3\})$ will be retrieved by each of the overlay peers. The video server is located at MR 51 (diamond node in Figure 4) and contains all the three video segments. Video segments are also partly available at MR 12 $(\{S_1, S_2\})$, 25 $(\{S_2, S_3\})$, 38 $(\{S_3, S_1\})$ (square nodes in Figure 4). Video quality retrieval performance is then analyses to show the benefit of the proposed geographical location-aware video segment seeking in terms of Peak Signal-to-Noise Ratio (PSNR), Mean Opinion Score (MOS) and packet loss in comparison with downloading the video from the video server only and with choosing the peer to download the video in a round-robin basis, without considering its location [19]. PSNR of received videos is calculated according to equation (3) [22], which translates the effect of bit rate and packet loss to user perceived quality.

Table 1: PSNR and packet loss comparisons of WILCO and the two compared schemes.

		WILCO	Round Robin	Single Server
PNSR	Average PSNR	39.22	25.64	22.70
	PSNR Variance	13.15	17.31	16.66
Average Packet Loss (%)		2.38	8.38	11.81

Table 2: PSNR to MOS mapping [23].

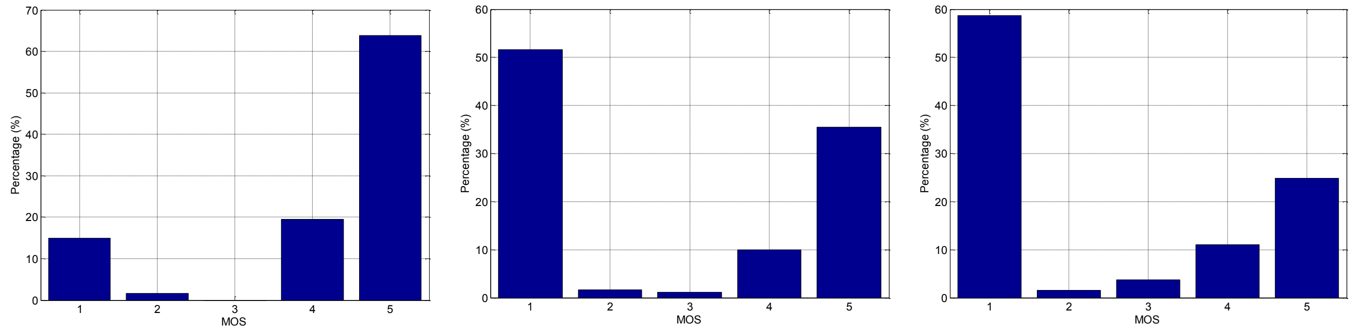
PSNR	MOS (Mean Opinion Score)	Value
>37	5 (excellent)	Imperceptible
31-37	4 (good)	Perceptible but not annoying
25-31	3 (fair)	Slightly annoying
20-25	2 (poor)	Annoying
<20	1 (bad)	Very Annoying

$$PSNR = 20\log_{10}\left(\frac{Bitrate}{\sqrt{(EXP\_Thr - CRT\_Thr)}}\right) \quad (3)$$

Where $Bitrate$ is the average bit rate of the data stream transmitted, EXP_Thr is the average throughput expected to be obtained and CRT_Thr is the actual average measured throughput.

Table 1 shows the average PSNR and packet loss results when WILCO and the other two compared schemes are employed in turn. It is observed that WILCO outperforms both schemes significantly by a huge margin of more than 13dB in average PSNR. Moreover, the PSNR variance of WILCO is also the lowest among the three compared schemes with roughly 4dB difference. These results illustrate that the video quality delivered by WILCO is not only the highest but also the most consistent across the peers. Using t-test it can be said that there is a statistical difference in favor of WILCO in PSNR with confidence level of 99% when applying pair-wise comparison between WILCO set of results and those of the two other schemes. This improvement is achieved due to WILCO's ability of intelligently choosing the nearest peer to get the video segment from, greatly improving the available bandwidth. Table 1 also shows that WILCO reduces more than three times the packet loss bringing it to less than 3% in comparison with more than 8% of the two compared schemes. As packet loss is one of the key factors that decide the received video quality level, this result confirms the PSNR-based evaluation and gives another view on the effectiveness of WILCO. Comparing the non-location-aware round robin and the single server approach, the results in Table 1 show that the PSNR and packet loss performance can also be improved by making use of the existing video segments distributed in the network rather than blindly getting all the video segments from the single server.

The MOS distribution of the video streams of the three schemes is investigated to show the distribution of perceived video quality across different users. Perceived video quality levels are mapped from the PSNR results according to Table 2 which is recommended in [23]. Figure 5 illustrates that user perceived video quality level is the best when WILCO is employed. This figure shows that WILCO enables "excellent"



a. MOS distribution of WILCO. b. MOS distribution of round robin approach c. MOS distribution of single server. approach.

Figure 5: MOS distributions of WILCO and the two compared schemes.

quality videos in 63% of the video streaming sessions, greatly outperforms the two compared schemes by roughly 20%, significantly improves perceived video quality. In addition, while in the case of WILCO there are only 15% of users suffer from "bad" videos, this figure is more than 50% for the compared schemes, clearly reveals the inconsistence in video quality retrieval of the compared schemes.

V. CONCLUSION

This paper proposes WILCO – a novel location-aware ID mapping scheme and modified finger table for building a Chord-based video delivery overlay on grid-like WMN. The proposed scheme exploits the location information of MRs to build up an overlay in which neighboring MRs in the physical topology are also closely located in the overlay. A novel geographical segment seeking algorithm is also proposed based on the location-aware ID assignment. Our simulation results show that in comparison with two other schemes WILCO significantly improves video delivery quality in both average and in terms of distribution across different users by choosing the geographically closer located peers to retrieve the video segments from.

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