INVITED PAPER

Location Awareness—Improving Distributed Multimedia Communication

Transmission delay, the most significant parameter affecting multimedia quality, can be minimized when the geographical location of end users is known.

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ABSTRACT | Multimedia creation and consumption is highly intensive and makes up the majority of Internet traffic nowadays. End-users are able to share their digital content with each other and to build communities based on interests, which often differ drastically according to location. Distributing these media using a central server can be quite expensive for a content provider. Distributed (peer-to-peer like) systems share costs evenly among participants. Thus, distributed multimedia systems will be more important in the future. The global distribution of end-users aggravates high-quality delivery of multimedia content. In this paper, we argue that geographical location-awareness greatly helps distributed multimedia communication. It increases the quality of multimedia content delivery and at the same time satisfies the growing need for more personalized, location-based services. In this paper, as a proof of concept, we introduce an overlay structure for distributed multimedia systems (and similar systems), which is location-aware and uses the locations of its nodes to optimize node-to-node communication for performance and delay. At the same time, the system enables location-based services.

KEYWORDS | Delay; distributed multimedia systems; location-based search; overlay; quality of service

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I. INTRODUCTION

Nowadays everyone is able to create and publish digital content; thus we are witnessing new trends in multimedia consumption [1]. Podcasting [2] or using Web sites like YouTube[1] are just some of the ways to distribute multimedia content among end-users, who are building communities based on their interests (like in the music community Web site Last.fm[2]) or their location. For example, as the success of podcasting grows, broadcasting corporations, public and commercial radio stations, and television are increasingly starting to podcast parts of their programs. However, normal end-users also play a significant part in producing and distributing podcasting content; podcasting enables people to share their perspectives, experiences, and information about local areas—so-called citizen journalism [3]–[5].

Distributing these media using a central server can be quite expensive for a content provider [6]. Distributed (peer-to-peer like) systems share costs evenly among the participants. Thus, distributed multimedia systems will be more important in the future. Upcoming peer-to-peer based video-on-demand applications like Joost,[3] Babelgum,[4] or Zattoo[5] show this trend for future development of the Internet. Still, distributed multimedia applications face big challenges. First, the global distribution of end-users aggravates high-quality delivery of multimedia content, which composes the majority of Internet traffic. Secondly,

[1]http://www.youtube.com.
[2]http://www.last.fm/.
[3]http://www.joost.com/.
[4]http://www.babelgum.com/.
[5]http://zattoo.com/.

distributed multimedia applications have to satisfy a growing need for more personalized services often relating to specific geographical areas.

In this paper, we argue that geographical location-awareness can greatly help to meet both challenges: enabling highly personalized services (Section III) and increasing the quality of multimedia content delivery (Section II). In Section II, we justify that the transmission latency is a very important quality of service (QoS) parameter for multimedia content delivery and that traditional QoS methods can hardly influence it (contrary to queuing delay or loss, for example). As the geographical distance between two end-systems is strongly correlated with the transmission delay between those two nodes, knowledge of geographical positions can help to minimize the imposed delay in multimedia content delivery. As an example where location awareness helps to both enable location-based search and improve quality of service, we present Globase.KOM, a location-aware overlay. In Section - V, we analyze related work on meeting the two challenges mentioned above. This paper concludes in Section VI.

II. IMPROVING THE QUALITY OF SERVICE IN DISTRIBUTED MULTIMEDIA COMMUNICATIONS

Location-awareness can be used to improve the efficiency and quality of distributed multimedia content delivery. Most distributed multimedia applications require a specific kind of network quality of service. Network QoS is the well-defined and controllable behavior of a network with respect to certain quantitative parameters like loss, delay, and throughput [7], [8]. Let us briefly review the different alternatives for optimizing the QoS parameters on the network layer before analyzing where location-awareness can be employed to improve the quality of service in the medium- to long-term future.

Loss: The loss rate in today's Internet only very rarely exceeds critical levels, as most backbones are overprovisioned and most voice and video encodings work quite well with a low packet loss rate. Available quality of service architectures like Diffserv [9] can be used to further improve the loss rate for certain types of traffic.

Throughput: The throughput available for an application mainly depends on the available overall bandwidth. The available bandwidth in the Internet is roughly doubling every 10–14 months [10]. Therefore, bandwidth is growing even faster than the CPU power, which doubles every 18 months according to Moore's law [11].

Delay: The end-to-end delay d experienced by the packets of a distributed multimedia application consists of:

- the queuing delay d_o experienced in the queues of the network routers;
- the processing delay d_p incurred by the processing of the packet in the end-system and in each intermediate router
- the transmission delay d_t incurred by the speed of light in the fiber-optic cables (or electromagnetic waves in copper cables) over the total end-to-end distance.

It is possible to optimize the queuing delay for delay-sensitive applications with existing QoS architectures like Diffserv. Additionally, as shown by Kelly [12], with increasing bandwidths, the queuing delay becomes small compared to the other delay components. Therefore, in the medium to remote future, it will become more important to think about reducing the processing and transmission delay for multimedia applications.

The transmission delay d_t is given by the speed of the electromagnetic waves in the cable c and the total end-to-end distance l

$$d_t = c \cdot l.$$

As c is a constant, the transmission delay can only be improved by reducing the total distance l that a packet travels. For nonlive content, l is indirectly improved best by caching or placing the content as close as possible to the customers. This process is the basic idea of the business model of companies offering content delivery network (CDN)-solutions, e.g., Akamai.[6] For live content, however, this cannot be done. In this case, l is best optimized by choosing the shortest possible physical end-to-end path. At this point, knowledge about the geographical position of the involved edge systems and intermediate systems comes in handy, and as we argue next, the challenge is to create an efficient overlay for distributed multimedia systems with respect to QoS (mainly transmission delay).

Constructing the overlay requires knowledge about the delay incurring between pairs of nodes. In a distributed communication system, there is no global knowledge about the overlay structure available. Knowledge about the structure could be obtained by local measurements of the delay between two nodes, e.g., using ping or traceroute. This has obvious disadvantages.

- The traffic overhead caused by measuring the delay of all nodes.
- Only the aggregated total round-trip delay at the time of measurement is retrieved. If the load situation varies, measurements have to be repeated frequently.
- Firewalls, network address translation (NAT) gateways, and some providers block some kinds of measurement approaches like pings and traceroutes. This can become a particular problem if the distributed multimedia system is built from end-systems (e.g., a peer-to-peer system) because normal end-systems are typically inaccessible by pings and traceroutes.

[6]http://www.akamai.com.

Another alternative is to use either devices that determine geographical position (e.g., GPS receivers) or IP geolocation databases, which determine the country and the city for an IP address.[7] Shortening the physical distance that packets travel will clearly reduce the number of IP hops necessary to reach the destination and will therefore also decrease the other critical delay component d_p. However, the geographical distance between two systems is not necessarily exactly proportional to the transmission delay between those two systems for two reasons.

- If two IP hops are operated by different Internet service providers (ISPs), packets between the two nodes have to pass an interconnection point between the networks of the two ISPs. Since the number of interconnections between providers is limited, a packet sent between two geographically very close IP routers, e.g., in the same city, might have to travel over a much longer path through an interconnection point (for example in a different city) than is normally expected from the pure geographical distance. Providers can reduce such distortion by increasing the number of their interconnection points; a single provider can interconnect with up to 1000 other providers [13]. The average interconnection degree, i.e., the number of providers with which a certain provider has interconnection agreements, rose from 2.99 in September 1995 to 4.12 in December 1998. Therefore, this distortion can be expected to decrease over time. It is also obvious that the distortion mainly affects nodes in close proximity to one another and that decreases in distortion are proportional to the distance between the nodes.
- Cables are not necessarily laid in a direct line between the two routers they connect. However, because of the very high costs for laying and maintaining cables, empirical results show that the distance is strongly correlated to the incurred delay (respectively cable length).

The relationship between geographical distance and network delay was exploited in research on geographical mapping systems like IP2Geo [14]. In order to find that relationship, Padmanabhan and Subramanian used an empirical approach based on recorded relationships between delay and location. Among other things, they discovered that the ratio of linearized distance, sum of lengths of hops along the path, and geographic distance is close to one. This indicates that the number of network paths is minor. Zivani *et al.* [15] studied the correlation between network delay and geographical distance using two databases, one with poorly and one with richly connected networks. The results indicate that the richer the connection of the network is, the stronger the correlation becomes, and that hosts in neighboring areas have similar delays. The majority of users and hosts are located in richer connected areas, and therefore a strong correlation between distance and delay is valid. The final conclusion is that a decrease in the geographical distance between two end-systems improves the quality of distributed multimedia communications. In summary, after the investigation of different QoS parameters, we conclude that the transmission latency is a parameter that is very important for live multimedia applications and very hard to influence with traditional quality of service methods (contrary to queuing delay or loss, for example). In this context, location-awareness can be used to improve the overlay structure to minimize the incurred latencies. As the geographical distance between two end-systems is strongly correlated with the transmission delay between those two nodes, knowledge of the geographical positions can help to construct the overlay in a way that minimizes the imposed delay.

Another application that can benefit from using location information is *application layer multicasting* (ALM). ALM is used to distribute multimedia streams to a set of receivers. Knowledge of the geographical position helps to construct the multicast tree in a way that the overall network resource usage is minimized and that the incurred delay of the multicast tree from the source to all senders is minimized. In this paper, however, we focus on unicast overlays and do not explore the ALM aspect further.

It is important to note that we do not consider distributed multimedia communication via ad hoc or mesh networks, as they are not widely deployed. Further, we assume that the previous analysis holds for wireless networks, as they generally consist of single hop infrastructures. This final wireless hop does not have a significant effect on the delay of a global route, which has several hops more [16].

III. LOCATION-BASED SEARCH

Location awareness can satisfy the growing need for more personalized services, which often relate to specific geographical areas. Existing patents [17]–[19] clearly show the huge commercial interest in location-based services. Emergency, informational, tracking, or entertainment services are just some examples of location-based services [20]. They can be either pull-based or push-based services, depending on whether the request for the transmission of information came from a publisher (push-based) or a consumer (pull). For example, a user can search for the closest cash dispensers, which is a pull-based request. If a user receives a message about impending bad weather on the hiking tour he/she is currently on, we are talking about push-based services. Most of the existing location-based services nowadays are pull-based. Location-based services are supported by the majority of GSM operators, which offer search facilities for

[7] See, e.g., IP2Location: http://www.ip2location.com/.

taxis, hotels, cash dispensers, pharmacies, restaurants, cinemas, entertainment, and local weather services. In addition, some operators (e.g., Vodafone) enable logistics that allow for vehicle tracking, transporting goods, and locating friends or children. iPling[8] provides a communication platform for the iPhone, where users are able to find and contact people nearby who share the same interests. Most car navigation systems, e.g., iDrive navigator,[9] allow the driver to find the nearest restaurant, gas station, shopping center, police station, or hospital; the driver's location is determined using a GPS receiver and all information about the object is stored in the navigation software (usually on CD). The development of location-based mobile applications is supported by Sun's Location API for J2ME.[10] Desktop location-based search is offered by many online maps like Google Maps,[11] which provides exact locations and driving directions. Everyone is able to add his business to the map and users are able to locate it as well as all related Web sites via geotagging or simply by text-based searching for the address. Other examples are Loki[12] and A2B[13] that offer user positioning via WiFi Positioning System (WPS)[14] or PlaceLab,[15] in addition to location mapping. In order to help customers find cheap offerings in local stores, GPShopper[16] and Slifter[17] provide location-aware searches for products. Physical objects are not the only subjects of location-based searches. According to [21], at least 50% of online news and communities are based on locality. Therefore, many news/blog applications cover locality, like Outside.in,[18] which specializes in location-based blogging that presents current events in the neighborhood [22]. Searched content can range from multimedia-related topics to specific geographical locations, e.g., videocasting or audiocasting of local news, announcement of events, sharing of experiences, and searches for live video/audiostreams from a given location [23].

In summary, location awareness offers many benefits for the user, particularly the numerous features location-based services hold. It also helps in placing and locating content[19] in large-scale distributed multimedia systems, as people have different interests in content according to their location. Furthermore, location information can be used to find sources that stream audio or video within a certain radius around a user. These sources will very likely connect well to the user, as discussed in the previous section.

IV. A LOCATION-AWARE OVERLAY NETWORK

Here we present Globase.KOM (Geographical Location Based Search), a location-aware overlay, as an example where location awareness helps to both enable location-based search and improve quality of service. It is a fully decentralized system for scalable, efficient, and fully retrievable location-based search.

- *Fully retrievable location-based search:* It is able to find *all* content or relevant services in a specified geographical area. The area can be circular or rectangular. The system will retrieve *all* results that fulfill the search criteria.
- *Efficient:* The system achieves an efficient mapping of the logical overlay to the physical underlay and therefore avoids unnecessary underlay traffic and reduces the total transmission delay.
- *Scalable:* The system and the search algorithm is scalable with respect to the number of nodes participating and the number of services offered.
- *Fully decentralized:* The content of the system and all operations are fully distributed over the participating nodes, thereby allowing users to store an unrestricted amount of information about the searched object (e.g., opening hours, prices, or menu) with frequent updates (e.g., number of free places in restaurant). In existing centrally managed solutions, this would overload the server. In a fully decentralized solution, each node is responsible for the information about the object it represents; therefore, updating and publishing information is done directly, bypassing the server and avoiding single point of failure. Thus, one can avoid the cases of passing by a gas station while our navigation system shows that the closest gasoline station is 5 km away, or navigating through a blocked road. Further, the system could be operated at low cost because of the natural scalability and administration-free character of decentralized systems, which makes them available for a wide community to join and publish their services.

We assume that each node is aware of its location. For the required calculations, we use the Plate Carée projection in order to represent the two-dimensional curved surface of the Earth on a plane. This projection plots directly latitude-longitude points on a regular X-Y graph, assuming the Earth is a sphere. The lines of longitude on the graph are spaced using the same scale as the latitude lines, forming a grid of equal rectangles. Fig. 1 shows a world map using a Plate Carée projection with 15° for the latitude and 30° for the longitude.

[8] http://www.ipling.com/What.htm.
[9] http://www.idrivenavigator.com.
[10] http://developers.sun.com/mobility/apis/articles/location/.
[11] http://maps.google.com/maps.
[12] http://www.loki.com/.
[13] http://www.a2b.cc/.
[14] http://www.skyhookwireless.com/.
[15] http://www.placelab.org/.
[16] http://www.gpshopper.com/.
[17] http://www.slifter.com.
[18] http://www.outsidein.com.
[19] Geographical location information, for example, can be used to preselect a number of sources from all possible sources that are close to the receiver and then stream from the source with the best ping time or smallest current load (or a combination of these).

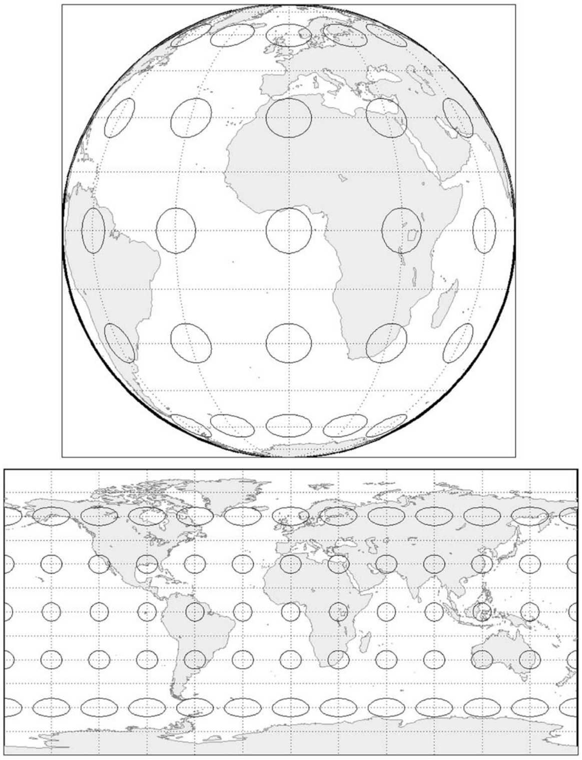


Fig. 1. *Plate Carée projection (source: http://www.mathworks.com).*

All map projections introduce some kind of distortion because an ellipsoid cannot be mapped to a plane without stretching, tearing, or shrinking. The distortion introduced by the Plate Carée increases with the latitude. For zones lying on the equator, there is little distortion, but zones far away from it are strongly distorted. This distortion has to be taken into account when performing geographical calculations. If we want to search for zones lying within a specified radius of a point on the surface of the Earth, this circle is transformed into an ellipse on the overlay's flat projection. To visualize this, the mapping of the same circle on different locations is shown in Fig. 1.

Next, we describe how the overlay is built, starting from a hierarchical tree of supernodes, forming the zones, and building interconnections, describing the overlay operations.

A. Overlay Structure

Globase.KOM is a superpeer-based overlay forming a tree enhanced with interconnections. The hierarchical approach allows us to exploit and support the heterogeneity of the participating nodes. Nodes have different capabilities. Some of them might be mobile end-devices with little storage capacity and processing power and with poor network connection, while others might be powerful desktop machines or even server-like machines with large random-access memory and good network connectivity. Furthermore, nodes differ in their online behavior. Some might be online for very long durations, while others are not. To learn about the online behavior, a mechanism like the burn-in optimization of [24] can be used.

We use the more powerful nodes with good network connectivity, which tend to stay online for a long time as supernodes in Globase.KOM. Supernodes are responsible for indexing all nodes/services in one clearly defined geographical area. The "normal" (nonsuper) nodes in the network simply offer and consume services without having additional responsibilities.

The world projection is divided into disjoint, nonoverlapping zones. Each zone is assigned to a supernode located inside the zone that keeps overlay/underlay contact addresses for all nodes in that zone. Supernodes form a tree where node A is called the parent of node B when B's zone is inside A's zone (see Fig. 2).

Each supernode maintains the contact addresses of:

- nodes inside its zone, excluding the inner zones;
- supernodes responsible for inner zones, children in a tree;
- the parent in a tree;
- the root supernode;
- interconnected supernodes (see Section IV-A3).

Each node maintains the following contact addresses:

- the parent superpeer;
- the root superpeer;
- an interconnection list;
- a cache list of already contacted peers.

Therefore, a location-based search starts with contacting one supernode, which then forwards the query message to its parent or children.

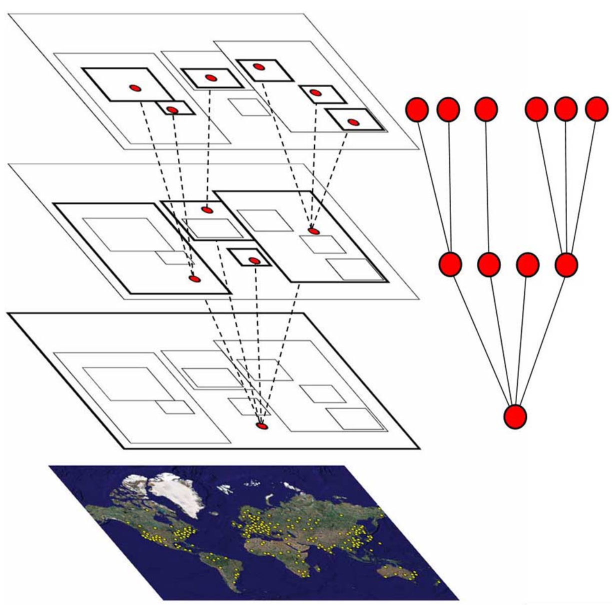


Fig. 2. *Network of supernodes with their zones of responsibility.*

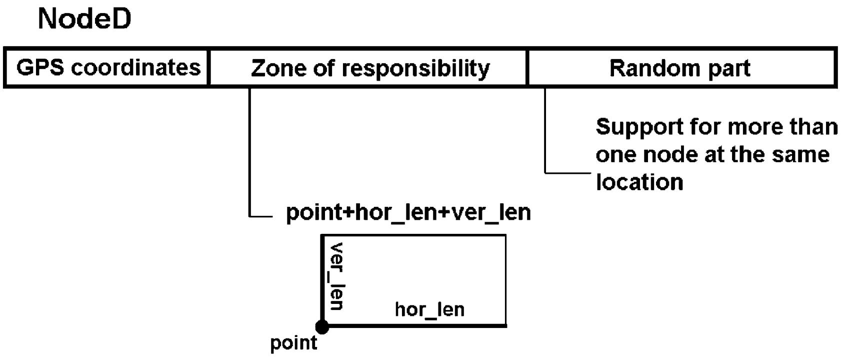


Fig. 3. ***Structure of node ID.***

1) Node ID: Resolving search and lookup queries is alleviated by the specific structure of the Node ID (Fig. 3). The ID of a node contains the following information:

- the GPS coordinate of the node;
- the zone it is responsible for, if it is a supernode;
- a random part in order to support the existence of more than one peer at the same location.

A rectangular zone is simply described as a concatenation of its vector representation—left bottom point of the zone and its side lengths.

2) Forming the Zones: When bootstrapping the system,[20] the whole world is one zone for the first supernode. When the network grows, highly loaded areas are clustered into rectangular zones by a clustering algorithm and assigned to one node (preferably one in that area), which then becomes a supernode by taking over the zone. Fig. 2 presents this process and the matching tree of supernodes. For each node, a level of allowed load is defined. We used the number of connected nodes as a load metric, as this directly influences the number of messages a supernode receives on average. There are three load levels—*normal* (below a threshold L_1), *overloaded* (between thresholds L_1 and L_2), and *critically overloaded* (above L_2). Once a supernode's load exceeds the threshold L_2, it runs a single linkage clustering algorithm in order to create a new zone inside its own zone. The new zone is then assigned to one of the nodes in the formed zone that is marked as a potential superpeer.

3) Interconnections: As mentioned above, each supernode is connected with supernodes other than its parent and children. Also, each node caches contact information about other supernodes besides the one it is connected to. The main purpose of these so-called interconnections is to provide robustness and fault-tolerance. Additionally, bypassing the root supernode makes query responses more efficient, especially in the case of a degenerated tree. Reiter *et al.* [25] presented an algorithm for constructing a fault-tolerant communication structure out of a core tree structure, where each node initially knows only its parent and children. Their focus is the construction of an expander graph from a tree, using a random walk for collecting new edges, such that the nodes in the graph have node degrees close to some constant. The tree reconstruction after failures is done using new edges and relies heavily on the root of the tree. We do not rely on the root supernode in tree reconstruction but on our interconnections, which can direct us to new parents/children. While a random walk introduces additional protocol overhead and traffic, our approach instead learns about new contacts through received messages (a similar approach is used successfully in the Kademlia overlay network [26]). When a node joins the system or does not receive any messages for some time, it receives a random interconnection from the bootstrapping supernode. Each query message includes the address of the query initiator and the address of the

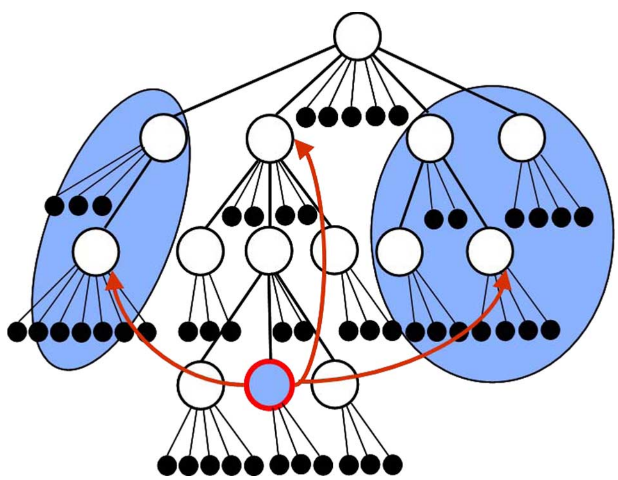


Fig. 4. ***Example of interconnected supernodes.***

[20]More sophisticated bootstrapping mechanisms are envisioned for the system, but for the purpose of understanding the basic idea of the overlay, this simple bootstrapping mechanism is sufficient.

responsible supernode. Upon receiving a message, each supernode/node checks if the initiator is its parent or child and if it is part of its subtree. Checking is done with simple calculation of the described zone in the sending node's ID. If the sender is not a parent or a child, then the recipient adds an appropriate contact to its interconnection list. The size of an interconnection list allows at least one contact per subtree, as shown in Fig. 4. Interconnections provide for each node a rough view of the tree structure in order to optimize tree recovery actions and searches. They are most valuable when the root supernode fails because they can recover its nodes and reconstruct the rest of the tree. Failure recovery in Globase.KOM is discussed in [27]. Simulation results also show that interconnections have a significant role in eliminating the effect of an unbalanced tree.

B. Operations

Globase.KOM enables a node to perform lookup and area search, to find the geographically closest node, and to join and leave the overlay network. In this paper, we will describe lookup and area search. Description of other operations can be found in [27].

1) Lookup: In our case, the lookup operation is used to determine the underlay address (IP address and port) of a node from its geographical location. Each supernode knows the IDs/locations of all nodes it is responsible for. A lookup operation basically routs the lookup message to the supernode responsible for the node with the given location. A node that performs the lookup will first contact its supernode, sending it a LOOKUP message with a sequence number, the reply address, and the address of the responsible supernode. The supernode then checks whether the given location is inside its zone. If so, then it checks whether it is responsible for this location or its children. If it is not inside its zone, it forwards the LOOKUP message further to its parent, which repeats the same actions. Finally, the supernode that is responsible for the queried point sends a LOOKUP_RESULT including the overlay/underlay address of the node, if it exists, and null if it does not exist.

2) Area Search: Area search is performed using the SEARCH message, which includes a description of the geographical area (center and radius) plus metadata describing the object/service that is being searched. When a supernode receives a SEARCH query from one of its nodes, it calculates the searched ellipse onto the map projection. Next, it checks if that ellipse intersects the zone it is responsible for. All further actions are the same as in LOOKUP, with the exception that all supernodes responsible for the nodes inside of the searched area send a SEARCH_RESULT with a list of matching nodes. The search is considered finished after a specific timeout. Simulation studies showed that the optimal value for this timeout is 2 s. For each received message, interconnections are updated as described in Section IV-A3.

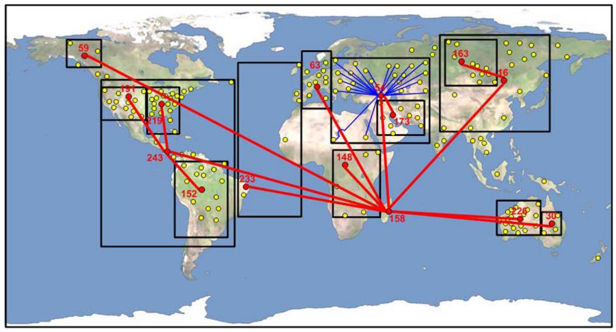


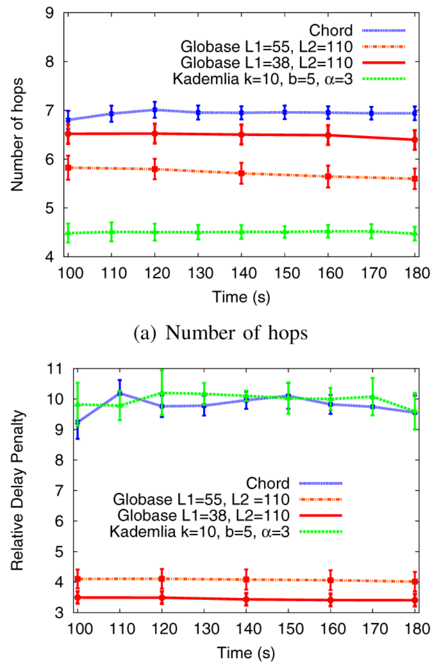
Fig. 5. ***Zones, nodes, responsible supernodes, and their connections. Red lines are connections to supernodes and blue lines are connections to normal nodes.***

C. Evaluation

In this section, we evaluate how location awareness has helped Globase.KOM to enable location-based search and improve the quality of service. In order to evaluate the improvement of quality of service, we have measured the relative delay penalty (RDP) and operation of a lookup operation. The RDP describes how well the overlay structure matches the underlying network topology. It is defined as the ratio RDP $= d_{\text{overlay}}(A,B)/d_{\text{underlay}}(A,B)$ of the measured latency introduced by sending a message from point A to B through the overlay structure and the corresponding latency when sending it directly through the underlay [28]. Location-based search is evaluation by measuring the duration and retrievability of an area search operation. For our evaluation, we used a simulation with PeerfactSim [29], as it models geographical-location based node distribution and churn. The underlying network model abstracts geographical distance between nodes, the processing delay of intermediate systems, signal propagation, congestion, retransmission, and packet loss. In order to get a realistic model of the node distribution over the world, a grayscale colored bitmap of the world is used. Sparser areas are lighter and darker areas correspond to the more densely populated areas. Therefore, the darker a point in the bitmap is, the higher is the probability that a node will be mapped to this location. The bitmap is created using the world map of Internet users.[21]

In the simulation scenario, we distribute the system nodes randomly over the world. The distribution of the nodes follows the population density of the Internet users in the world. Fig. 5 shows the zones and the distribution of nodes and supernodes for one overlay with 200 nodes. Red lines represent edges of the tree, i.e., connections to supernodes. Blue lines represent connections to normal nodes.

[21] http://upload.wikimedia.org/wikipedia/commons/.



(a) Number of hops

(b) Relative delay penalty

Fig. 6. ***Lookup performance of Globase.KOM, Chord, and Kademlia with 10 000 nodes. (a) Number of hops and (b) relative delay penalty.***

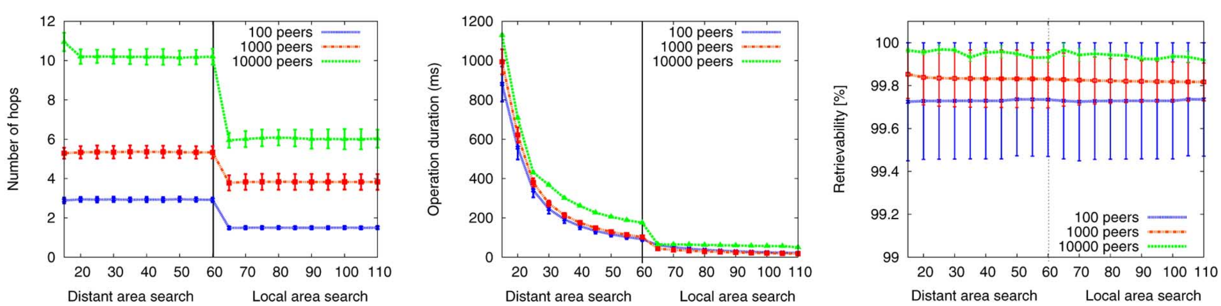
In the following experiments, all the peers join and, after the stabilization phase, do appropriate overlay operations. Churn rate is mixed log-normal. Experiments were done with 20 simulation runs each. The results are presented using 95% confidence intervals.

1) Improving Quality of Service: In spite of the fact that Chord [30] and Kademlia [26] were designed for lookup rather than for retrievable search, the performance of their lookup operation will be used here as reference for a comparison (see Fig. 6). The experiments are run with 10 000 nodes; load-level parameters in Globase.KOM are $L_2 = 110$, $L_2 = 110$ and $L_1 = 38$, $L_2 = 110$, ten successors in Chord with stabilization interval of 650 ms; $k = 10$, $b = 5$, and $\alpha = 3$ for Kademlia. In Fig. 6(a), we can see that the number of hops in Globase.KOM is 18% better in the case of parameters $L_1 = 55$ and $L_2 = 110$. Chord needs on average 22.8% more hops per lookup operation then Globase.KOM with $L_1 = 55$ and $L_2 = 110$, while Kademlia performs 21% better due to parallel lookup queries and big contact lists. However, Fig. 6(b) shows that location awareness in Globase.KOM significantly reduces RDP, bringing better underlay awareness of the overlay.

2) Location-Based Search: Here Globase.KOM is observed with $L_1 = 10, 25, 55$; $L_2 = 20, 50, 110$, respectively, for experiments with 100, 1000, and 10 000 nodes. We have considered two cases of area search based on the distance from the searched area to the node that initiated the area search—local (from 60 to 110 s in simulation scenario) and distant area search (from 0 to 60 s). Local area search performs better, as the node often needs to contact just its own supernode in order to get all results Fig. 7(a) and (b). The steep decrease of the operation time during the simulation of distant area search proves the significance of interconnections, which are built by learning from received messages and therefore do not exist at the beginning of the simulation, resulting in longer durations for search operations. Fig. 7(c) shows that for a distant area search with 100 nodes, in the worst case, only 0.3% of the results are not delivered. This percentage decreases to 0.1% for 1000 nodes and 0.05% for 10 000 nodes. The main reason for not delivering all results in these experiments is the timeout, which is set to 2 s. As we can see, there is no difference in retrievability between local and distant area search.

V. RELATED WORK

Since the focus of this paper is the improvement of QoS and the enabling of location-based search through location



(a) Number of hops

(b) Operation duration

(c) Retrievability

Fig. 7. ***Performance of a local and distant area search operation in Globase.KOM. (a) Number of hops, (b) operation duration, and (c) retrievability.***

awareness, we now discuss a variety of related works in the field of topology-aware overlay networks and overlays for location-based search (using space-filling curves and distributed space partitioning tree).

A. Topology-Aware Overlay Networks

Achieving overlay efficiency through appropriate mapping to underlay network and thus eliminating unnecessary underlay traffic gained attention recently. Liu *et al.* in [31] proposed a location-aware topology matching (LTM) technique, where the overlay neighborhood is chosen from physically closer nodes. Low productive connections are disconnected and closer nodes are added as direct neighbors. This does not require global knowledge of the overall overlay network, but each node builds its own neighborhood. A similar approach is described in [32], in which the distance between peers in a global P2P domain is determined by measuring the latency between each peer to appropriate Internet servers called landmarks. Clustering physically close peers by using proximity awareness was presented in [33]–[35]. Banerjee *et al.* developed a protocol for efficient application layer multicast, which arranges the set of end hosts into a hierarchy. All close members are mapped to the same part of the hierarchy. In the hierarchy, they are partitioned into a set of clusters. End-to-end latency is used as a distance metric between hosts. The same metric is used in [34], where nodes close to one another in terms of network latency are partitioned into clusters (so-called bins). Tang and McKinley [36] additionally considered link sharing (an underlay network link is shared by multiple overlay edges) as a metric for overlay performance in the sense of underlay mapping. Nakao *et al.* [37] added a new layer (the "routing underlay") between the overlay and underlay network layers. When making application-specific routing decisions, the overlay queries the underlay, which extracts and aggregates topology information like disjoint paths. Han *et al.* [38] measured the diversity between different ISPs and between nodes inside one ISP. Based on these measurements, they were able to place nodes in a topology-aware manner. In conclusion, the related work is mainly concerned with overlay–underlay mapping. Location-based search is not offered by these overlays. Additionally, Globase.KOM avoids additional overhead, as we use the absolute geographical location for the mapping.

B. Space Filling Curves

So far, location-based search in P2P networks has mainly been approached by reusing existing structured overlays that are used to provide efficient one dimensional lookups. The linearization of two-dimensional map projections is achieved using different space-filling curves, the suitability of which is discussed in [39]. The focus of [40] in developing prefix hash trees was to meet the needs of PlaceLab's [41] end-user positioning system without modifying the underlying DHT. It is able to perform

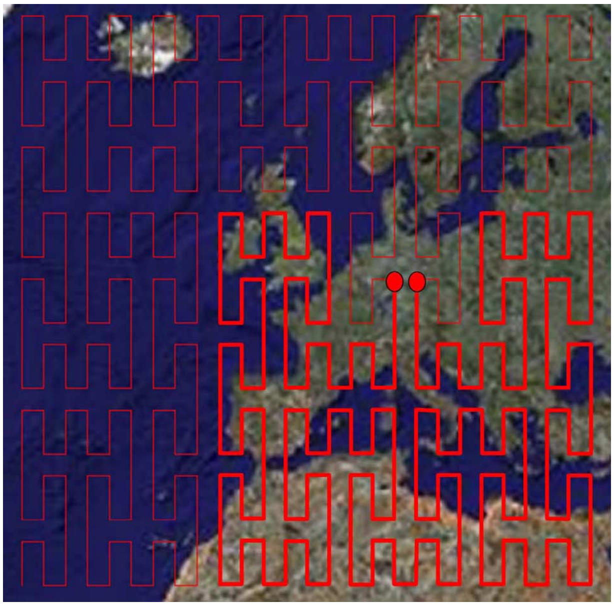


Fig. 8. ***Example of an inefficient lookup operations in a system based on a Hilbert space-filling curve. Though two points may be very close geographically, they can be very distant in the overlay key space, in which case implementing a location-based area search will require that many different parts of the DHT be reached.***

two-dimensional geographical range queries applying a z-curve linearization of the 2-D space. In [42] and [43], location-based node IDs are used and mapped into the 2-D space using space-filling curves as well. Other works that are based on similar transformations of the 2-D space onto a one-dimensional space are [44]–[46]. All approaches with space-filling curves suffer from not matching the geographical distance with the distance in the overlay ID space. One worst case example is shown in Fig. 8, in which two points are very close geographically but have an inappropriate distance in the overlay. This results in inefficient query replies, which introduce additional delay into the communication. Another important point is that most approaches with space-filling curves use DHTs, which do not provide a guarantee for full retrievability of all results matching a search request.

C. Distributed Space Partitioning Tree

Search for spatial content was the focus of [47]–[49]. Harwood and Tanin recursively divided a 2-D space into smaller zones and used a distributed quadtree index for assigning responsibilities for regions of space to peers. For each zone, a control point is assigned and hashed into the node ID on the Chord ring. Copies of the objects associated with a region are stored on the node that was assigned the control point. As a result, the 2-D space is transformed into a tree structure. Zimmermann *et al.* discuss in [50] and [51] that such an approach can lead to load-balancing problems; therefore they introduced a mapping of the physical space into the [52] overlay instead of [53]. Identification of spatial data is created with a concatenation of the respective location, a random part, and the identification of the content of the object. Similar work is presented in [54] based on K-D trees [55]. The search space is repeatedly hierarchically partitioned into smaller zones, and each internal node splits its zone into two subzones. The data points are stored in leaf nodes. This solution creates a performance bottleneck at the higher level nodes since a query has to be propagated to the nodes close to root of the tree. LL-Net [56] uses the same zone division and assigns an R-Peer to each area as the root of the tree topology formed by the N-Peers contained in that area. Besides the zone division and routing, this work differs from our approach by using a central instance, the S-Peer, which manages contacts of all R-Peers, bringing all drawbacks of central management. A binary tree as a distributed space partitioning tree is used in RectNet [57]. It dynamically adapts to the geographical distribution of the workload caused by the storage of (location, object)-pairs and the processing of queries. This tree has a binary structure that simplifies the recovery of the structure in the instance of node failures but significantly reduces the search performance. GeoPeer is a location-aware peer-to-peer system [58] that uses Delaunay triangulation to build a connected lattice of nodes and it implements a DHT for geographical routing, similar to GHT [59]. The focus of both systems is to look up and to route. Neither provides support for complete retrievable search.

In summary, to the best of our knowledge, a solution has not yet been developed that meets our requirements for distributed multimedia systems: first, an efficient mapping of the overlay to the underlay, and secondly, a fully retrievable location-based search.

VI. CONCLUSION

The new trend towards multimedia consumption imposes higher demands that centralized solutions cannot fully meet. The amount of services and multimedia content that users consume will continue its steep growth, as will the amount user-generated content, which is already becoming increasingly more available. Thus, distributed multimedia applications will obviously be even more significant in the future. At the same time, media consumption often varies by region in content such as local news, announcement of events, sharing of experiences, etc. New requirements will arise for distributed multimedia systems, which are addressed by this paper, including adapting the storage and retrieval of content to the regionally varied media consumption, optimizing communication and content delivery for traffic overhead, and quality of service. We have shown that location awareness can greatly improve distributed multimedia communication in both ways. GPS receivers are becoming increasingly affordable and are being integrated into many everyday items such as cars, personal digital assistants, and mobile phones. Additionally, IP geolocation databases give sufficient estimation of a user's location for globally distributed systems. We have analyzed and shown that decreasing geographical distance between communicating parties decreases transmission delay, which is the most significant QoS parameter for multimedia communication. As a proof of concept, we presented a novel overlay structure for distributed multimedia systems (and similar systems) that is location aware and uses the locations of its nodes to optimize node-to-node communication for performance and delay. At the same time, the system also enables location-based search. The evaluation indicated that location-aware building of an overlay significantly decreases response time and so-called relative delay penalty in comparison with non-location-aware overlays.

In summary, location awareness brings many benefits to the user via location-aware services. At the same time, it helps in storing and locating content in large-scale distributed multimedia systems. This is already used in modern centralized content distribution networks, like Akamai, where multimedia content is first transmitted to regional distribution servers before sending it to the end nodes. All network applications would greatly benefit from location information. Future Internet protocols will have to provide information about users' locations in a decentralized way in order to deliver highly personalized multimedia services in high-definition quality, thereby building the location-aware Internet. ■

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