Go This Way: Navigation for Better Access Quality in Mobile Networks *

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ABSTRACT

Despite the wide deployment of mobile network infrastructure, mobile users still experience varying network quality. We posit that it is caused by the combined effects of the imbalanced geographic coverage of mobile networks and users' lacking (and thus ignoring) such information when choosing their travel paths. In this paper, we propose a novel scheme, *network-oriented navigation (NetNavi)*, for mobile users to improve their network access on a trip. More specifically, we overlay the physical road map with mobile network performance maps to find paths satisfying user needs on both network quality and travel delay. Through evaluations of two major cellular networks on three maps of different scales and locations, we show that NetNavi can significantly improve network access quality at low cost for mobile users, increasing the average download throughput by 67.5% for 67.6% source-destination pairs with only 11.4% extra travel delay (and as significant as 193.8% with only 3% extra travel delay in some cases). Our results, although preliminary, demonstrate the great potentials of improving network access quality for mobile users, without even changing network infrastructure or mobile applications.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*distributed networks, network communications*

Keywords

Navigation; Access Quality; Mobile Networks;

1. INTRODUCTION

The wide deployment of mobile network infrastructure, *e.g.*, high-speed cellular networks and metro-scale WiFi, significantly facilitates the ubiquitous Internet access for mobile users. It is becoming a common practice for mobile users to use Internet services for browsing, audio/video streaming, and even video conferencing. However, these mobile applications have various requirements on the mobile networks (*e.g.*, high bandwidth, low loss rate), and current deployed mobile networks cannot satisfy these requirements everywhere due to many reasons, *e.g.*, imbalanced distribution of base stations (or access points for WiFi) and cell coverage in different regions. As a result, mobile users usually experience varying network quality during their movement (see, *e.g.*, [3, 7]).

To date, we have to rely on network carriers to improve network quality for mobile users. Mobile carriers can upgrade their infrastructure or improve their network coverage by deploying more base stations, in order to improve the quality of network access for their subscribers. Unfortunately, such solutions not only are costly and take time but also are limited by the progression of technology.

Recognizing these facts and challenges, we note that oftentimes mobile users are flexible on the travel paths, and that there typically exist many alternative paths for a pair of source and destination in metro areas. In other words, mobile users may be willing to tradeoff certain extra travel delay (or travel distance) to their destinations for better network access quality on a trip, especially when such a trip can be planned in advance. This suggests that it might be possible for mobile users to take a *proactive* approach to improving their network access quality, without involving mobile carriers to upgrade their infrastructure.

Such a proactive approach has many benefits. One example in the time-critical scenarios is that a business person has to take a taxi from the office to the airport while at the same time having an important video teleconference with his clients. The person prefers to keep the video teleconference session live (and of course with good network quality) while on the trip to the airport, even if the trip is a bit longer (*e.g.*, taking a detour to guarantee the quality of the video teleconference), rather than staying in the office to complete the teleconference (which may mean that the person has to cancel his flight due to the tight schedule). An example in the time-uncritical scenarios is that a group of friends driving from Los Angeles to San Francisco want good network access on the trip to kill their time in the car. If there are multiple routes to choose, they prefer to choose the one with better network access quality even if the route may be a bit longer than alternative routes. In both scenarios and examples, mobile users could proactively plan their trips (*e.g.*, taking alternative paths) in order to improve the network access quality on their trips. for

Motivated by the above observations, we believe that the challenges of network access quality for mobile users can potentially be mitigated even without any change to the deployed network infrastructure, *i.e.*, by navigating them to take paths with better network quality. This service will be beneficial to various traditional mobile applications (*e.g.*, web browsing and video streaming) and new mobile services such as computation offloading [5, 18, 19].

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In this paper, we propose a novel scheme, *network-oriented navigation* (*NetNavi* for short), to achieve the above goal by navigating mobile users to trade off travel delay for better network access quality, and thus avoiding the negative effects of the imbalanced geographical coverage of mobile networks. More specifically, we investigate the feasibility, potential methods and quantify the benefits of NetNavi in typical settings where mobile users move on a road map with a high-speed cellular network deployed.

Firstly, the feasibility of NetNavi depends on the predictability and geographic diversity of the network quality on all roads. We measure and analyze the performance of two major cellular networks on three road maps of different sizes and locations. The results verify our intuition that the network performance is stable for the same location but quite diverse for different locations, supporting the prediction based method.

Secondly, the key technical challenge of NetNavi is how to capture user needs and efficiently find the desirable path. We formulate it as an optimization problem and propose an algorithm for it. Basicly, NetNavi constructs and records the network footprints for every cellular network on every road measured by itself or reported by its users. Upon receiving users' navigation requests, NetNavi finds and replies with a satisfactory path based on those network footprints and other road information. Our preliminary evaluation on the data traces demonstrates the great potentials of NetNavi.

We summarize our key contributions as follows:

- We conduct a measurement study on the access quality of the cellular networks in various areas. We identify the geographic variation of the access quality of cellular networks.
- We propose an algorithm that efficiently searches the travel paths according to the requirement on both network access qualities and travel properties, and demonstrate its effectiveness via extensive evaluations based on real-world traces.

The rest of the paper is organized as follows. Section 2 studies the geographic coverage of cellular networks. Section 3 proposes and presents an overview of the network oriented navigation. The problem of network oriented navigation is formally formulated and solved in Section 4, while a preliminary evaluation is conducted in Section 5. Various issues related to NetNavi are discussed in Section 6. Section 7 provides an overview of the related work. We conclude the paper and discuss the future work in Section 8.

2. CELLULAR NETWORK COVERAGE

We first present a measurement study on the diversity of the cellular network coverage in various areas and the access quality. We are specially interested in the geographic distribution of network access quality and their impacts on the design of NetNavi.

2.1 Data Collection

We measure the network performance of two major cellular networks when moving on three maps of different scales, locations and properties. The networks and measuring devices are summarized in Table 1.

Table 1: The measurement environments

Carrier	Network	Device	OS
Carrier1	EVDO	Samsung Galaxy Tab	Android 2.2
Carrier2	HSPA	Motorola ATRIX 4G	Android 2.2

The three maps include a suburb map for a suburb area in Santa Clara, CA, a downtown map for San Jose downtown, CA, and a highway map for south bay area highways, CA. The total lengths of all unique roads in the three maps are 21.0 km, 14.5 km and 205.2 km, respectively. The biking/driving speed during measurement is relatively stable for each map, *i.e.*, approximately 5 m/s, 10 m/s and 26 m/s for the suburb, downtown and highway map, respectively. For each network on each road, we repeated the measurement twice in the same direction at different times. Note that hereafter we refer to a "road" as the road segment between two neighboring crossroad points along a path and a "path" as a route (or equivalently, the sequentially connected roads) between a pair of source and destination.

2.2 Data Delivery Properties

Our empirical measurement study intends to shed some lights on the diversity of the network access quality in different geographic areas and its temporal stability for the same area at different times. We compute the average throughput for every road.

We summarize in Figure 1 the distributions of roads' average upload and download throughput on the three maps. We observe that for every network on every map, different roads have quite different average download throughput. However, the diversity varies across different carriers and maps. The average upload throughput exhibits less diversity than the download throughput.

We also summarize in Figure 2 the comparisons of the temporal stability of the network access quality for the same roads using the aforementioned two traces. Note that the network access quality are measured twice at different times for every map, and the roads are sorted for each carrier according to the download throughput in the first data trace. In the suburb map, both carriers demonstrate good temporal stability, *i.e.*, the two traces for every carrier are similar to each other. Carrier1's performance is also stable in the downtown map, while the variation is larger for Carrier2. Our traces show variable average throughput for both carriers on the highway map. Two possible factors cause this phenomenon. First, every road is long and has variable download throughput along the road. Second, our measurement is sparse and leads to the inaccurate estimation.

From these results, we observe that mobile networks may exhibit significant *diversity* of access quality both in different geographical areas and at different times. The geographical diversity suggests that it is possible to trade off geographical costs (*e.g.*, travel distance) for better access quality by taking alternative routes, and the temporal diversity suggests that dynamics of access quality should be taken into account when making the trade-off.

3. AN ARCHITECTURE FOR NETNAVI

We next present an overview and an architecture for NetNavi.

3.1 Rationale

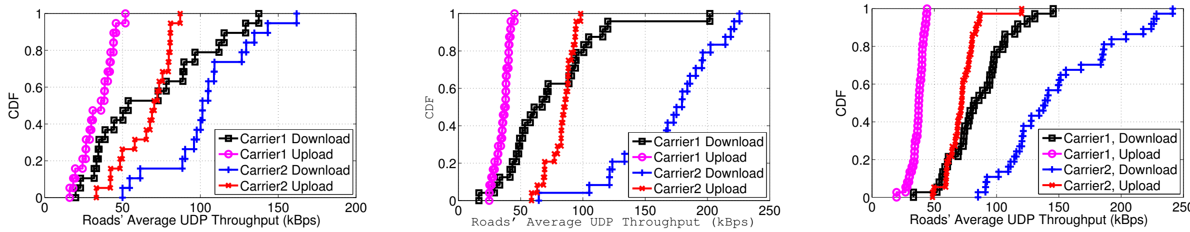
NetNavi aims to provide a novel navigation framework that helps mobile users to proactively improve their access quality of the subscribed mobile network, by trading off travel costs (*e.g.*, travel distances) for network access quality.

In order to make the appropriate trade-offs, NetNavi allows mobile users to specify their requirements on the travel properties (*e.g.*, the distance is within 110% of the shortest path) and the network access quality (*e.g.*, the download throughput is higher than 400 Kbps) so that they can customize their mobility behaviors to best fit the mobile applications' requirement on network access quality.

3.2 Key Components

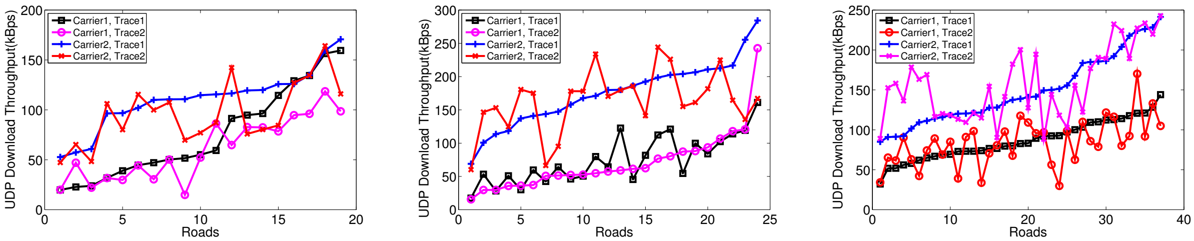
The NetNavi architecture consists of three key components: (1) a road map (such as the open street map [1]), (2) an overlay of network access quality on top of the road map, and (3) a service layer that allows users to specify their requirements and finds the paths satisfying all the requirements, as illustrated in Figure 3.

The fundamental difference of NetNavi from existing navigation systems lies on the network quality layer and the service layer. The



(a) Suburb Map (b) Downtown Map (c) Highway Map

Figure 1: Geographical diversity: the distribution of roads' average throughput for two carriers in three different areas.



(a) Suburb Map (b) Downtown Map (c) Highway Map

Figure 2: Temporal diversity: the distribution of average download throughput at different times for the same roads.

network quality layer integrates the information of access quality with the street map. Meanwhile the service layer uses the information of the street map and the network quality layer to provide the NetNavi services to mobile users.

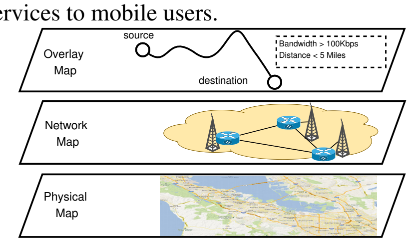


Figure 3: An architecture for NetNavi.

In the network quality layer, NetNavi records all relevant information of network access quality for each road segment, for instance, upload / download throughput, network delay, packet loss rate, *etc*. We take a road segment as the basic unit to record the network access quality because the finer granularity will demand more storage space for the data and increase the computational cost of path search in NetNavi. As network access quality may vary within a single road segment, NetNavi records both the average values and their variations to better characterize the access quality. A challenging problem to NetNavi is how to collect the data of network access quality, especially when NetNavi provides service in a large area. A possible solution to this problem is to let mobile users of NetNavi to voluntarily report their active and/or passive measurement results. However, this is out of the scope of this paper and we will leave it as part of our future work.

In the service layer, NetNavi takes user requirements on the travel property and the network access quality to find an appropriate travel path for them. The key problem is how to simultaneously satisfy these two different requirements in searching travel paths. In addition, as different mobile applications have different requirements on the network access quality, NetNavi should allow the flexibility of mobile users specifying their requirements.

4. NETWORK ORIENTED NAVIGATION

We now formally formulate the problem of proactively navigating mobile users for better network access and propose an algorithmic solution in this section.

4.1 Network Model

Consider a roadmap $G(N, E)$, where $u \in N$ is a vertex, and $(u, v) \in E$ is the directed road from vertex u to v. Assume users move at the speed limit of every road, $S_{(u,v)}$, and there is no traffic lights to stop, the same assumptions used by most GPS navigators. Let $D_{(u,v)}$ denote the length of the road (u, v). Let w_i be the i-th network metric such as download throughput and loss rate. $w_{i,(u,v)}(d)$ represents the i-th network metric of the spot on the road (u, v) whose travel distance from vertex u is d, where $d \in [0, D_{(u,v)}]$. Let $T_{(u,v)} = \frac{D_{(u,v)}}{S_{(u,v)}}$ be the travel delay of the road (u, v) when moving at the speed limit.

Let $p_{(u_1,u_k)} = \{(u_1, u_2), (u_2, u_3), \ldots, (u_{k-1}, u_k)\}$ be an acyclic path from vertex u_1 to u_k. (u_i, u_{i+1}) is a road along the path $p_{(u_1,u_k)}$ where $1 \le i \le k - 1$. We denote by $P_{(u_1,u_k)} = \{p_{(u_1,u_k)}\}$ the set of all acyclic paths from u_1 to u_k. The travel delay of path $p_{(u_1,u_k)}$ is:

$$T_{p_{(u_1,u_k)}} = \sum_{(u,v)\in p_{(u_1,u_k)}} T_{(u,v)} \tag{1}$$

We denote the shortest delay path by $p^*_{(u_1,u_k)} \in P_{(u_1,u_k)}$, *i.e.*, $T_{p^*_{(u_1,u_k)}} \le T_{p_{(u_1,u_k)}}$. The travel distance of moving from u_1 along $p_{(u_1,u_k)}$ after time t can be calculated as follows:

$$\begin{aligned} f_{p_{(u_1,u_k)}}(t) = {} & \textstyle\sum_{m=1}^{n-1} D_{(u_m,u_{m+1})} \\ & + S_{(u_n,u_{n+1})} \times (t - \textstyle\sum_{m=1}^{n-1} T_{(u_m,u_{m+1})}), \\ \text{if} \quad & t \in [\textstyle\sum_{m=1}^{n-1} T_{(u_m,u_{m+1})}, \textstyle\sum_{m=1}^{n} T_{(u_m,u_{m+1})}) \end{aligned} \tag{2}$$

where $t \in [0, \sum_{m=1}^{k} T_{(u_m,u_{m+1})}]$.

The spot where travel distance from vertex u_1 along the path $p_{(u_1,u_k)}$ is d belongs to the n^{th} road along the path, *i.e.*, $(u_n, u_{n+1}) \in p^j_{(u_1,u_k)}$.Thus, its i^{th} weight can be expressed as:

$$\begin{aligned} & w_{i,p_{(u_1,u_k)}}(d) = w_{i,(u_n,u_{n+1})}(d - \textstyle\sum_{m=1}^{n-1} D_{(u_m,u_{m+1})}), \\ & \text{if} \quad d \in [\textstyle\sum_{m=1}^{n-1} D_{(u_m,u_{m+1})}, \textstyle\sum_{m=1}^{n} D_{(u_m,u_{m+1})}) \end{aligned} \tag{3}$$

where $d \in [0, \sum_{m=1}^{k} D_{(u_m,u_{m+1})}]$.

4.2 Problem Formulation

Let $u_w(p)$ denote a utility function of path p on weight w. The goal of NetNavi can be stated as finding a path to optimize the utility function under the constraint that the travel delay is within $1+\alpha$ of the shortest delay path, where $\alpha \geq 0$ is a parameter chosen by the user. The formulation is shown in Figure 4.

$$\begin{aligned} \max \quad & u_{w_i}(p_{(u_1,u_k)}) & (4) \\ \text{s.t.} \quad & T_{p_{(u_1,u_k)}} \leq (1+\alpha) \times T_{p^*_{(u_1,u_k)}} & (5) \\ & p_{(u_1,u_k)} \in P_{(u_1,u_k)} & (6) \end{aligned}$$

Figure 4: A problem formulation for NetNavi.

Note that the travel delay constraint can easily be replaced by constraints on travel distance. Note also that it is straightforward to extend (5–6) to incorporate multiple constraints on network quality. Note also that the objective function (4) is abstract as we try to make it as general as possible. In practice, however, it can be any function that captures user needs on network access quality.

To make it more concrete, we use two examples to illustrate such user needs. The first example is to maximize the average download throughput on a trip; therefore,

$$u_{w_i}(p_{(u_1,u_k)}) = \frac{\int_0^{T_{p_{(u_1,u_k)}}} w_{i,p_{(u_1,u_k)}}(f_{p_{(u_1,u_k)}}(t))dt}{T_{p_{(u_1,u_k)}}}.$$

The selected path will be desirable for downloading large files. The second example is for applications that require continuous high throughput along the path, *e.g.*, video conferencing; the utility function can be set as the x-percentile value, *i.e.*,

$$u_{w_i}(p_{(u_1,u_k)}) = \max_x\left\{\frac{\int_0^{T_{p_{(u_1,u_k)}}} I(v - w_{i,p_{(u_1,u_k)}}(f_{p_{(u_1,u_k)}}(t)))dt}{T_{p_{(u_1,u_k)}}} \leq x\right\},$$

where v is the desired throughput. $I(y)$ is an indicator variable (*i.e.*, 1 if $y > 0$ and 0 otherwise). It means that along a large portion (*i.e.*, $1-x$) of the path, user has high throughput which is larger than v.

4.3 A NetNavi Algorithm

To find the desirable travel path for a given pair of source and destination, A naive solution is to explore all candidate paths that satisfy the constraints (*e.g.*, use the breadth-first search on all acyclic paths) and then find the optimal path. However, the number of paths grows exponentially with the network size, it may not be practical for maps with a large number of vertices. We notice that in the breadth-first search process a candidate path consists of a path from the source to current node that has been explored (referred to as a *prefix*), and one of those from current node to the destination (referred to as a *suffix*). All paths starting with a *prefix* are not shorter than that with the same *prefix* and the shortest *suffix*. Thus, if it doesn't satisfy the constraint, we can safely stop exploring paths starting with *prefix*.

We present in Algorithm 1 the pseudo code based on the above intuition. More specifically, we first construct a shortest path tree to the destination with function *DstDijkstra()*. It is very similar to Dijkstra's algorithm, except that the outgoing edges are replaced by incoming edges. We then use breadth-first search of all candidate acyclic paths until the distance constraint is violated. The function *Utility* can be any utility function of interest as discussed in the preceding subsection.

5. EVALUATIONS

We next evaluate the proposed NetNavi framework and quantify its performance.

5.1 Evaluation Methodology

We collect data traces on the three maps and use them in evaluations. More specifically, for each of the two carriers, we collected

Algorithm 1 Network Oriented Navigation

```
procedure NetNavi(src,dst,α)
    DstDijkstra(dst);   ▷ construct the shortest path tree from all nodes to dst.
    threshold = α × src.delay2dst;
    result = GetShortestPathToDst(src);
    maxUtl = Utility(result);
    p = new Path(src);                    ▷ p.dst = src; p.delay = 0.
    queue.push(p);
    while not queue.empty() do
        p = queue.pop();
        for each oe in p.dst.outgoingEdges do
            if (not p.contain(oe.dst)) && (p.delay + oe.delay + oe.dst.delay2dst ≤ threshold) then
                newPath = p.copy().append(oe);
                newPath.delay + = oe.delay;
                if oe.dst == dst && Utility(newPath) ≥ maxUtl then
                    maxUtl = Utility(newPath);
                    result = newPath;
                else
                    queue.add(newPath);
    return result;
```

measurement data twice for every map. For each carrier and each map, we use one of the two traces to construct the network footprints, and use the other for testing, vice versa. We evaluate the performance of every pair of crossroads as the source and destination. Only those having at least two paths and satisfying the travel delay constraint are reported. The shortest path is used as the baseline for comparison. The average results are reported.

We use two metrics to quantify the performance of NetNavi: (1) the percentage of improvement on throughput over the baseline, and (2) the percentage of extra travel delay over the baseline. We also report the performance of NetNavi with a network oracle to show the largest possible gain of the NetNavi scheme.

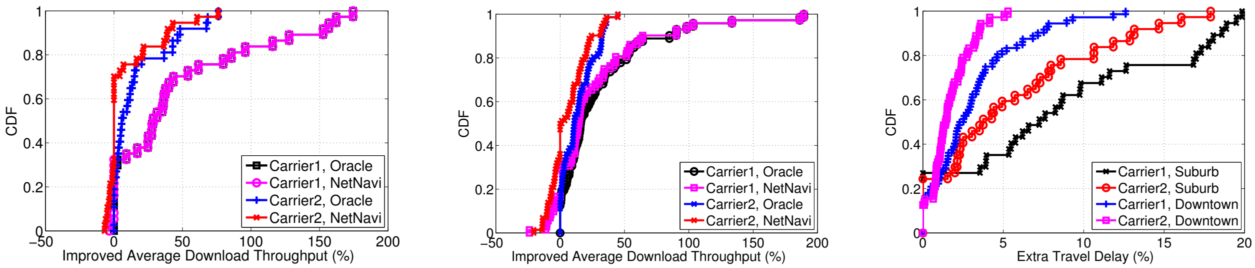
Note that in our evaluations, we assume that the network access quality on both sides of a road is the same. We also assume that user speed is constant for the same map; as a result, the travel delay is proportional to the travel distance.

5.2 Average Download Throughput

We first quantify the performance improvement on average download throughput under the constraint that the extra travel delay ratio, α, is less than 20%. We plot in Figure 5 the performance for both carriers on the suburb and downtown map. The results on highway do not show significant improvement and are omitted.

We observe that in both maps, NetNavi significantly improves the performance of Carrier1. Specifically, among all source-destination pairs with multiple paths satisfying travel delay constraints, NetNavi finds paths with 67.5% and 42.8% improvement on average for 67.6% and 69.4% pairs in the suburb and downtown map, respectively, at costs of increasing the delay by 11.4% and 4.1% on average. The most significant improvements on the two maps are 174.5% and 193.8% at the cost of 18.9% and 3.0% extra delay.

We also compare the prediction-based NetNavi (*pNetNavi* for short) against the oracle-based NetNavi (*oNetNavi* for short). For Carrier1, oNetNavi achieves the similar performance as oNetNavi. Specifically, only for 5.4% and 16.7% pairs on suburb and downtown maps, pNetNavi reduces the throughput by 2.9% and 8.4% on average. For Carrier1, which has high download throughput on the two maps, pNetNavi still can significantly improve the performance for some source-destination pairs. The gap between pNetNavi and oNetNavi for Carrier2 is larger than that of Carrier1, indicating the room to further improve NetNavi.



(a) Suburb Map (b) Downtown Map (c) The Extra Travel Delay

Figure 5: The performance of NetNavi to improve the average download throughput on the Suburb and Downtown Map.

5.3 Percentile of Download Throughput

We next evaluate the improvement on the t percentile of download throughput along the travel path, as we discussed in Section 4.2. It is important to those mobile applications that requires consistently good network-access quality over time. We plot in Figure 6 the results for Carrier1 with $t = 30\%$.

We observe that in all experiments, NetNavi significantly improve the performance for most navigation requests. We make the following observations. First, NetNavi significantly improves the value by as large as 452.6% (from 19.0 kBps to 105.0 kBps) on the suburb map. It helps more than 60% navigation requests to improve their performance. Second, NetNavi achieves very similar performance as Oracle in this scenario. Third, even on the highway map, NetNavi improves the performance by 48.5% for 53.5% source-destination pairs on average, although it causes some false positives and slightly reduces the corresponding network access quality.

5.4 Average Upload Throughput

We next evaluate the improvement on the upload throughput, which is another important property of cellular networks impacting many mobile applications such as VoIP and file sharing.

We plot the results on the Suburb Map in Figure 7. We make the following observations. First, NetNavi still greatly improves the performance by helping more than 60% requests to achieve as significant as 60% improvement. Second, compared with the download throughput, the improvement on the upload throughput is relatively small. This is because the variation of upload bandwidth is relatively small over different roads. Third, Carrier2 sees higher improvement than Carrier1, because the former's average upload throughput is more varying as shown in Figure 1(a). Finally, NetNavi achieves very similar performance as Oracle, indicating the accuracy of the performance prediction.

5.5 Trade-offs

We next study tradeoff between the travel delay and the average download throughput by varying α from 10% to 50%, by taking into account the fact that different mobile users are likely to have different requirements on the travel delays and the network access quality in various scenarios. We plot in Figure 8 the results of Carrier1 on the suburb map. We observe that when $\alpha \geq 0.2$, relaxing the delay constraints does not help further improve the average download throughput. This is determined by the path diversity in the map. For example, the downtown map has multiple paths with similar travel delays for many source destination pair, its extra travel delays are very low as shown in Figure 5(c).

6. DISCUSSIONS

There are many challenges in the measurement, design and implementation of NetNavi. We next discuss several important issues and potential solutions.

User speed: We assume that users always move at the speed limit of every road, as a simple approximation of the reality. In practice, human mobility models (*e.g.*, [12]) and vehicle mobility models (*e.g.*, [17]) should be taken into account for two typical navigation scenarios, walking and driving, respectively. Additionally, the live traffic information from online maps such as Google Maps can be used to estimate the extra travel delay incurred by traffic. We can easily change Equation 2 in Section 4.2 to incorporate these information into NetNavi. Besides choosing alternative paths, users may also improve their overall network access by intentionally slowing down the speed on the shortest path when the network access quality is good. This method extends NetNavi by replacing the constant speed with a variable speed on every road. We will study the performance of these variants in our future work.

Network Footprints: We directly use the measured data to derive the network footprints. However, this could lead to inaccurate predictions due to the varying network performance and limited amount of data. To construct better network footprints for more accurate prediction, NetNavi should collect more data by, *e.g.*, asking users to report their network performance. By considering the distribution of network access quality on every road, NetNavi can identify travel paths with consistently high network quality. Additionally, we can construct different footprints for different time to further improve the prediction accuracy.

In addition, our current approach constructs a network footprint for every network metric on every road. It is likely that some network metrics correlate with each other (*e.g.*, throughput and loss rate). We will investigate such correlation and construct compact network footprints for multiple metrics. Such footprints are useful for applications having requirements on multiple network metrics.

Herd Effect: The access quality of mobile networks is also affected by the number of mobile users accessing the same base station. As the traffic on the roads show diurnal variation, constructing network footprints for different periods of time could be an effective solution.

More interestingly, NetNavi itself is likely to change the distribution of mobile users on the roads, by navigating users to roads with better network access quality. Consequently the network access quality on these roads may be worsen. To alleviate the problem, NetNavi could randomly choose and reply with one of the top K travel paths, instead of the optimal ones. If NetNavi is implemented as online service accessible to all mobile users, it can predict the distribution of user requests based on historical information and conduct the global optimization for all navigation requests within a period of time.

7. RELATED WORK

Improving the network access for mobile users is a long-standing important topic. A major class of solutions are based on the prediction of user mobility (see, *e.g.*, [2, 8, 12, 16]) and network condi-

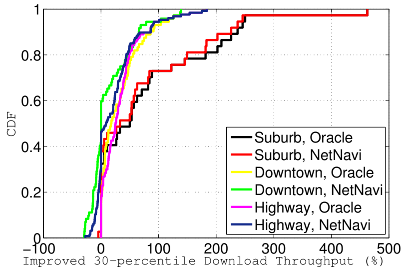


Figure 6: Improvement on the 30-percentile download throughput.

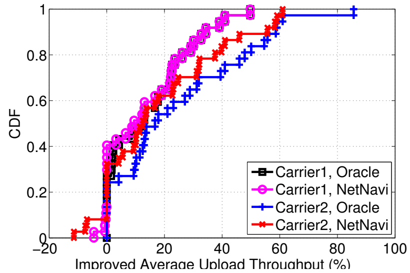


Figure 7: Improvement on the upload throughput (Suburb Map).

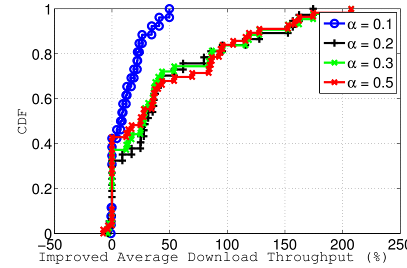


Figure 8: Tradeoffs.

tions (see, *e.g.*, [9]) to schedule the data transmission. Specifically, predictive methods are not only used to predict a single user's mobility and network access opportunities based on the historical information (*e.g.*, Breadcrumbs [16]), but also used to improve the WiFi access from vehicles (*e.g.*, [8]). All of them treat user mobility as a constraint, while our approach is to pro-actively navigate users to improve their network access.

Another class of solutions intend to fully use the available communication channels. In [3] Balasubramanian *et al.* proposed to argument 3G network with WiFi. ViFi [4] opportunistically uses the multiple APs within the device's communication range for data transmission. These techniques require fundamental changes on the networks and applications, which is unnecessary for NetNavi.

Our work is also related to proactive routing in MANET. Li and Rus [14] proposed a proactive scheme that changes node trajectories to transmit messages through intermediate nodes. Message ferrying [21] uses dedicated ferrying nodes to collect and deliver data among nodes in sparse MANET. Different from them, our work focuses on infrastructure-based mobile networks.

Multi-constrained path problem (MCP) [13] intends to find routing paths satisfying multiple quality-of-service constraints. MCP and its variants are known to be NP-complete [13]. Many algorithms are proposed to efficiently solve this problem (*e.g.*, [6, 11]). We formulate the navigation problem as a generalized MCP problem and allow flexible weights and utility functions.

Lastly, our work also is related to the measurement study of cellular networks and mobile devices. Huang *et al.* [10] studied the performance of 3G and WiFi from smart phones. Xu *et al.* [20] analyzed the infrastructure characteristics of cellular networks. Deshpande *et al.* [7] compared the performance of 3G and Metro-Scale WiFi. The TCP performance in 3G networks are also studied (*e.g.*, [15]). Our focus is the geographic coverage of cellular networks and, thus, different from them.

8. CONCLUSION AND FUTURE WORK

In this paper we proposed a network-oriented navigation scheme, NetNavi, to improve access quality of mobile networks for mobile users via proactively navigating their movement. By overlaying the physical road maps with footprints of corresponding mobile network performance, NetNavi is able to find the travel path satisfying user needs on both network quality and travel delay. Our evaluations demonstrated the great potential of NetNavi to improve mobile network access without any change to mobile network infrastructure. There are multiple avenues to the future work. We plan to investigate how to further improve its performance by considering user movement behaviors (*e.g.*, speed and directions), collecting users' measurement results in a scalable and cost efficient manner, creating compact network footprints of multiple quality metrics, and analyzing the trade-offs as well as the herd effect.

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