A Study of MVNO Data Paths and Performance

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Abstract. Characterization of mobile data traffic performance is difficult given the inherent complexity and opacity of mobile networks, yet it is increasingly important as emerging wireless standards approach wireline-like latencies. Mobile virtual network operators (MVNOs) increase mobile network topology complexity due to additional infrastructure and network configurations. We collect and analyze traces on mobile carriers in the United States along with MVNO networks on each of the base carriers in order to discover differences in network performance and behavior. Ultimately, we find that traffic on MVNO networks takes more circuitous, less efficient paths to reach content servers compared to base operators. Factors such as location of the destination server as well as the provider network design are critical in better understanding behaviors and implications on performance for each of the mobile carriers.

1 Introduction

What factors cause one mobile Internet provider to be faster than another, even if they share some common core infrastructure? Traditional metrics chosen to represent speed may not perfectly correlate with end-user performance and are heavily influenced by the design and behavior of the underlying mobile data network. The challenge of mobile network characterization is further extended with the rise in popularity of mobile network virtual operators (MVNOs). In this paper, we shed light on observable traffic behaviors exhibited by mobile networks that affect performance metrics and user experience. We examine mobile data network behavior when connecting to popular content delivery networks used to serve media. We are particularly interested in performance comparisons between the four major mobile carriers in the United States and MVNOs that license use of the underlying base carrier infrastructure. Ultimately, we want to explore network topology factors that affect traffic in mobile data networks.

Increasingly popular due to relaxed contract terms, MVNOs have quickly grown their market share in recent years [1–3]. They operate by leasing access to base mobile network operator (MNO) infrastructure, thus avoiding the high cost of building their own networks or licensing spectrum. Performance of MVNO data networks is often assumed to be inferior, but ultimately at least somewhat attributable to the underlying base carrier network. Previous work [4] has shown that is indeed the case; application performance suffers when using MVNO networks compared to MNOs. We investigate MVNOs and MNOs, searching for potential causes of degraded performance such as server resolution location and inefficient (e.g. excess hop counts and geographically indirect) paths.

We focus on traffic to content delivery networks (CDNs), which improve performance for end users by replicating identical content across geographically diverse locations [5]. CDNs are important factors in the user experience as they are typically responsible for delivering large web objects. The exact CDN server chosen by the client when browsing is typically dependent on DNS resolution with the expectation that the client is 'near' the DNS resolver. Unfortunately for most users, mobile data networks are strongly hierarchical and it has been shown that accurately localizing mobile users is a difficult challenge [6]. The localization problem illuminates a critical issue for mobile networks: the closest or best server depends on the mobile network core topology as well as peering arrangements between the content providers and mobile carriers. We study geographic paths taken by traffic on all of the mobile networks in order to better understand the obtained performance and routing behavior of the networks. Specifically, we are interested in the following questions:

- *Can we identify reasons behind MVNOs performing worse than MNOs?* We characterize network performance for all four major U.S. carriers as well as a single MVNO for each, discovering that performance appears to be dramatically affected by destination server location.
- *Can we find potential areas for improvement in order to reduce performance gaps between mobile carriers?* We find that MVNOs have more intermediate hops, which are also geographically inefficient in the case of full MVNOs we study. From our study we believe there is room for improvement with regards to mobile network topology.
- *Do we observe marked difference between full and light MVNOs?* We observe that a light MVNO closely resembles the underlying MNO, while traffic on full MVNOs differs, often exceptionally, compared to respective MNOs.

2 Background

CDNs and DNS. The use of CDNs to deliver content from distributed replica servers is commonplace in order to improve performance as Internet content has become increasingly heavy and media-rich. Client DNS requests resolve to particular replica server IP addresses when the clients browse the Internet. Ideally, the resolved servers are 'near' (e.g. lowest round trip time) the client relative to other potential servers in order to maximize application performance [7, 8]. A challenge for mobile data networks is that the limited number of public-facing gateways in the cellular core network, as well as the location of cellular network DNS resolvers, make localizing clients from an outside perspective difficult. Peering arrangements, or lack thereof, between mobile providers and content providers also leads to inefficient traffic routes even with the presence of a nearby replica [9].

MVNOs. Recently, MVNOs have increased in popularity worldwide. MVNOs are virtual in the sense that they offer telecommunications services without owning all of the mobile infrastructure used by clients. Instead, MVNOs pay MNOs for the right to service user traffic using the underlying base carrier network.

The rise in popularity of MVNOs is often attributed to relaxed contract terms such as pay-as-you-go and pre-paid plans compared to traditional base carriers in the U.S. which have traditionally operated using post-paid plans. MVNOs can be classified in one of two ways: **full** or **light**. Full MVNOs are carriers that license only the radio network of the base carrier. They implement their own core, including authentication and billing services (i.e. they distribute their own SIM cards). Light MVNOs, also called *resellers*, are re-branded versions of the base carrier, which means they can fully use the base carrier infrastructure. Mobile operators often create light MVNOs to target specific demographics or to lower consumer cost by cutting back on support services.

3 Data Collection

We collect data from eight mobile devices running on eight different carriers between March 6 and March 20, 2015. We conduct the experiment over two weeks to account for performance differences attributable to time-of-day patterns. All measurement phones are located in Santa Barbara, CA and left in a static location. All phones report ‘good’ or ‘great’ signal strength via the Android telephony API throughout the experiment. For simplicity, we focus on routes and performance associated with the popular social media sites Facebook and Instagram. These services are responsible for huge amounts of mobile Internet traffic, 19.43% and 4.27% respectively in North America [10], and are widely replicated across many well-known CDN data centers, which allows us to explore geographic differences between carriers. Measurements gathered across additional locations, carriers, and sites would be ideal; however, this study is an initial look at potential factors impacting MVNO network performance and we hope to motivate further, more in-depth research. The list of CDNs that we use as measurement points can be accessed on our project repository at `https://github.com/schmittpaul/mobileCDNs`. The list includes 108 servers: 72 associated with Facebook and 36 associated with Instagram. Some servers are location-specific, identified by location clues in the name. We include international servers in our study as through initial work we find that mobile traffic surprisingly resolves to such servers a significant portion of the time (>5%) for multiple carriers.

3.1 Carriers and phones

We collect data on all four of the major base carriers in the United States. We identify base carriers as A, B, C, and D. Carriers A and C are GSM networks while carriers B and D use CDMA technology. MVNO carriers are identified as A-1, B-1, C-1, and D-1, with their letters indicating the underlying base carrier. MVNO B-1 is a light MVNO, which means that it has full access to the infrastructure of carrier B. Carriers A-1, C-1, and D-1 are all branded as the same full MVNO with different SIM cards and contracts specifying the base carrier used. All phones run Android 4.4 and we leave them in a high-power state to avoid latency due to radios entering low-power states. All phones are attached to their carrier (i.e. not roaming). We choose to run all experiments while connected via 3G rather than 4G due to uneven 4G LTE coverage in our area between carriers. Recent work [9] has found that 3G and 4G mobile networks in the U.S. have few Internet ingress points, meaning 4G networks will exhibit similar behavior in terms of routes and CDN resolution as 3G networks.

3.2 Traceroute and location data

Each hour of the testing period, each device records a `traceroute` to each of the servers in the CDN server list, resulting in $14 \times 24 \times 8 \times 108 = 290,304$ records. We then use multiple techniques to estimate the location of each IP address in the traceroute records. We first employ the IP2Location DB5 database in order to map the traceroute IP addresses to latitude and longitude coordinates. Unfortunately, prior work has established that IP geolocation databases are often rather inaccurate [11]. We also verify through a manual sanity check of the IP-location mapping, where we find improbable location mappings. To fix inaccuracies we use two other sources to manually estimate location for 5,172 unique, routable IP addresses observed over the course of the experiment. We use `nslookup` to resolve the human-readable name of the IP address if it exists. We do this because routers and servers often include three or four character location clues in their names. Next, we use Internet looking glass servers, available through `traceroute.org` from multiple cities around the U.S., to traceroute to each IP address. Observing the paths taken and RTT values from geographically diverse vantage points enables us to further estimate location (e.g. RTT of a few milliseconds from a particular looking glass server and intermediate hops containing location identifying names). Overall, we find that out of the 5,172 unique IP addresses, we override 1,988 addresses (36.4%) from the IP2Location database with our manual location estimate.

We run `whois` on each observed IP address to determine the associated Autonomous System (AS) number. With this information, we create a data set corresponding to each attempted traceroute that includes: the number of hops, the IP address associated with each hop, the geographic coordinates associated with each hop, the autonomous system number for each hop, and the observed RTTs associated with three traceroute probes.

4 Network Analysis

We measure traffic on the four major mobile network operator networks in the United States as well as MVNO carriers operating on each of them. We first look at network performance using standard metrics such as round trip times, hop counts, and autonomous system paths. We then combine geographic information and traceroute records to explore traffic route path characteristics.

4.1 Round trip times (RTT)

We begin by investigating RTTs for packets traversing the mobile networks to the 73 **non-location specific** servers specified in our CDN server list. RTT is

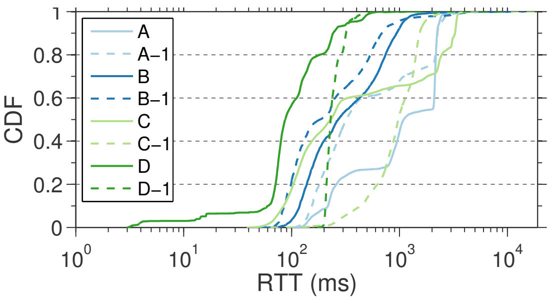


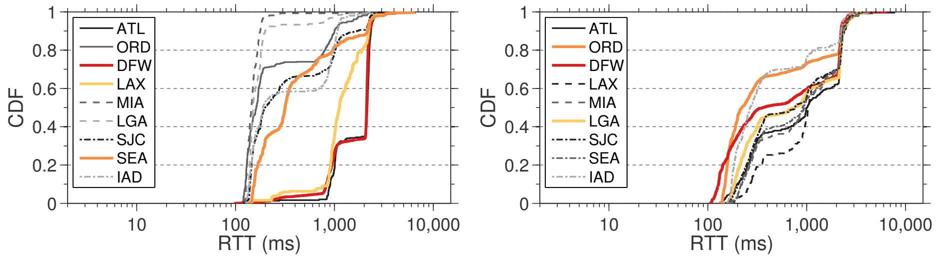
Fig. 1. RTT measurements for mobile carriers to non-location specific servers.

a critical metric in network performance as the majority of TCP variants rely on RTT to determine throughput [12]. Figure 1 shows a cumulative distribution function (CDF) plot of measured RTT values for all carriers in our study. We see considerable performance variance between the networks despite all measurements originating from the same location.

We also observe significant performance differences between base carriers and MVNO carriers operating on the corresponding base carrier infrastructure. For instance, in Figure 1 we see a 772.03 ms difference between the median RTT values for carrier A and the MVNO carrier A-1. However, the most surprising results are that MVNO carriers A-1 and B-1 outperform their respective base carriers in terms of achieved RTTs, with the aforementioned 772 ms lower median value for A-1 and a 87.24 ms median difference between B and B-1. These results contradict the expectation that MVNOs universally offer inferior performance. Previous work has established the widespread use of transparent middleboxes on mobile networks [13], which could help explain why networks with better RTT performance do not necessarily outperform others as such middleboxes likely ignore our measurement traffic. In order to understand round trip performance more fully we must also consider the *locations* of servers to which client traffic is resolved, explored in the next section.

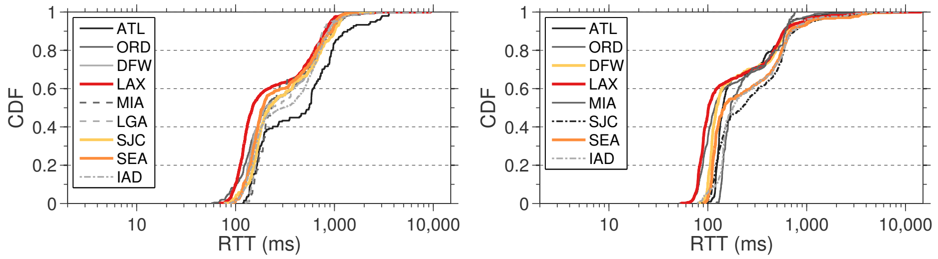
4.2 Location-specific RTTs

We study performance by examining the data center locations to which carriers are most likely to resolve. We record the geographic location for the destination server in all of the traceroutes corresponding to non-location specific requests in the previous experiment and find that the vast majority of requests resolve to data centers in nine US cities and most carriers heavily favor relatively few server locations. We then measure RTT performance to all locations using our list of location-specific servers, which are identified using 3-character airport codes in server names (e.g. `scontent-a-lax.cdninstagram.com` corresponds to an Instagram server in Los Angeles). Figure 2 shows RTT CDFs for each of the data center locations and highlights each carrier's top three 'preferred' locations. We find location preference by calculating the percent of 'hits' at each location for all non-location specific requests.



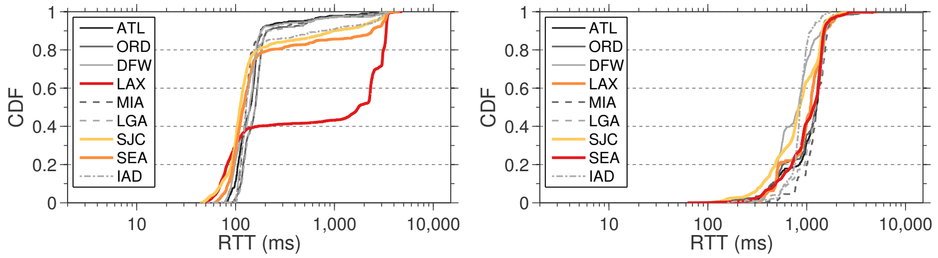
(a) Carrier A:
DFW: 95.4%, SEA: 0.2%, LAX: 0.2%

(b) Carrier A-1:
DFW: 34.2%, ORD: 29.7%, LGA: 21.1%



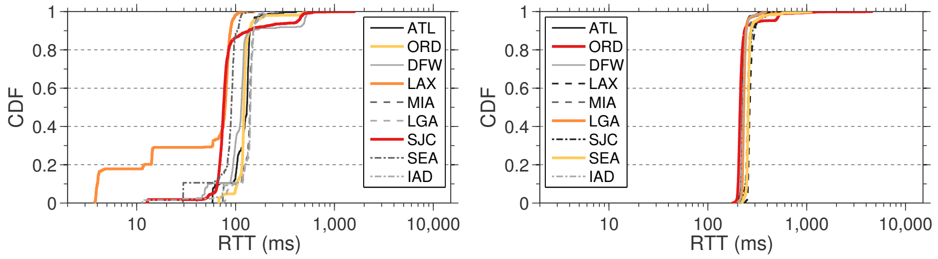
(c) Carrier B:
LAX: 51.1%, SEA: 17.5%, SJC: 15.1%

(d) Carrier B-1:
LAX: 66.2%, SEA: 17.0%, DFW: 5.9%



(e) Carrier C:
LAX: 26.7%, SEA: 24.2%, SJC: 23.8%

(f) Carrier C-1:
SEA: 52.5%, LAX: 19.4%, SJC: 15.9%



(g) Carrier D:
SJC: 56.6%, LAX: 14.0%, ORD: 9.4%

(h) Carrier D-1:
ORD: 53.1%, LGA: 24.5%, SEA: 5.9%

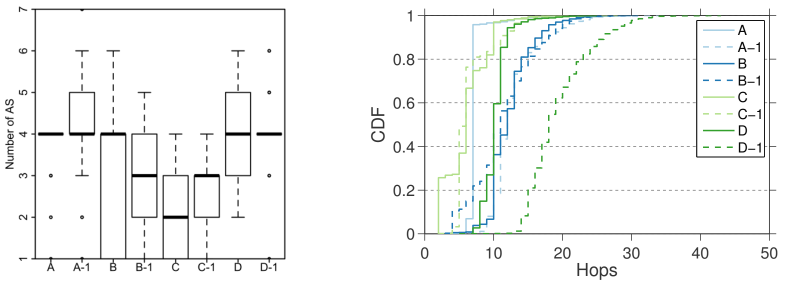
Fig. 2. RTT comparison for specific CDN locations identified by airport codes: Atlanta (ATL), Chicago (ORD), Dallas (DFW), Los Angeles (LAX), Miami (MIA), New York (LGA), San Jose (SJC), Seattle (SEA), Washington DC (IAD). Each carrier's top three preferred locations are indicated.

The figure illustrates large performance differences and unique behaviors between carriers. Some MVNOs appear to mimic the underlying base carrier, while others behave in drastically different ways. Perhaps the most interesting performance is seen on carriers A and A-1. Carrier A experiences vastly different round trip times between different CDN locations. Additionally, carrier A favors CDN sites (Dallas, Seattle, Los Angeles) that have the slowest median RTT compared to the other locations. The latency to Los Angeles servers is the second longest, despite Los Angeles being the data center nearest our measurement location of Santa Barbara. Carrier A-1 (Figure 2(b)) displays the broadest range of RTT values across all CDN sites, and also favors servers located in Dallas, TX. However, carrier A-1's second and third most popular locations are Chicago and New York, respectively. We believe these results are due to A-1 being a full MVNO; thus, they employ their own core infrastructure and have service and peering arrangements independent from the base carrier A.

Carriers B and B-1 (Figures 2(c) and 2(d)), on the other hand, perform more similarly in both latency measurements and preferred destinations. In fact, MVNO B-1 slightly outperforms the base MNO in terms of RTT in our experiments. Both carriers tend to route traffic toward Los Angeles. Los Angeles also tends to correspond to the lowest RTT values for both carriers. The striking similarity can be explained as carrier B-1 is a 'light MVNO,' thus B and B-1 use the same infrastructure to handle client traffic. In this regard, it stands to argue that customers considering carriers B and B-1 are essentially choosing between the same service when it comes to connecting to our specified CDN sites.

Carriers C and C-1 are quite different from one another in terms of performance even though they favor the same three data center locations. Interestingly, carrier C (Figure 2(e)) routes the highest percentage of its traffic to servers in Los Angeles, which achieve highly variable RTT values (seemingly bimodal). We speculate that this result is due to the carrier load-balancing flows across dissimilar paths. Latency values on carrier C-1 (Figure 2(f)) are rather consistent to all CDN locations, with higher RTTs overall compared with carrier C. Carrier D (Figure 2(g)) experiences the lowest network latencies overall. This carrier tends to favor CDN servers located in San Jose, CA, which also has the lowest median RTT value for carrier D. MVNO carrier D-1 (Figure 2(h)) shows the most consistent latency across all data center locations, but interestingly favors CDN servers in Chicago, 2,961 km away from San Jose. Similar to A-1, we believe this is likely due to D-1 being a full MVNO, with traffic traversing a different core network than the base MNO.

Overall, we observe that some MVNOs exhibit drastically different RTT performance from their MNO counterparts, while others are similar. While it seems that the light MVNO can be characterized as simply a re-branded version of the base MNO, our experiments using full MVNOs show unique latencies and resolutions between them and their MNOs. Thus, these carriers do not appear to simply reflect the performance of the MNO network on which they reside. Such behaviors will clearly impact network latency and throughput and may help to explain why MVNOs networks generally perform worse than MNOs.



(a) Number of unique AS numbers observed per carrier.

(b) Number of hops observed per carrier.

Fig. 3. Path metrics for mobile networks. MNOs and MVNOs exhibit similar AS path lengths but differ in the number of hops taken to reach the destination.

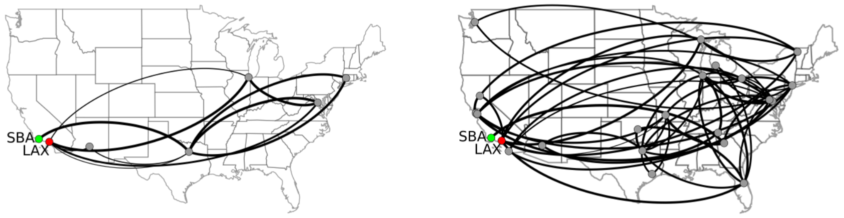
4.3 Autonomous system paths and hop counts

We next investigate traffic routes with respect to autonomous system (AS) paths in the traceroutes for each carrier to non-location specific servers. We use `whois` queries to map all IP addresses seen in carrier traceroutes to AS numbers. Figure 3(a) shows the number of unique AS numbers observed across the carriers, with the dark line indicating the mean. As shown, it appears as though MVNO behavior overall is similar to MNO networks. This result illustrates that MVNO networks are bound to some degree to the MNO network configuration. We study the actual AS numbers traversed by traffic between MNOs and MVNOs and find that they generally match, and as such omit this analysis for brevity. Interestingly, although carriers A-1, C-1, and D-1 all fall under the 'same' MVNO brand, traffic for each client behaves differently based on the underlying carrier. It appears that in terms of AS paths, MVNOs closely reflect the underlying MNO. These results lead us to investigate hop counts to help explain performance differences between MVNOs and MNOs.

We consider the total number of hops in traceroute records for traffic on each mobile network to non-location specific servers. We only consider records that reach the destination server. Figure 3(b) shows the results. As with other metrics, we observe considerable variability between carriers. Carriers A and D both use dramatically fewer hops to reach the server compared to their respective MVNOs, while carriers B and C closely resemble their respective MVNOs. The path length inflation seen on carriers A-1 and D-1 could help explain poorer RTT performance compared to the base carrier. We also observe that MVNOs A-1, C-1, and D-1, which are all marketed as the same carrier, experience very different length paths to reach the destination servers. We believe the variance may be attributable to the different preferred locations observed in Figure 2.

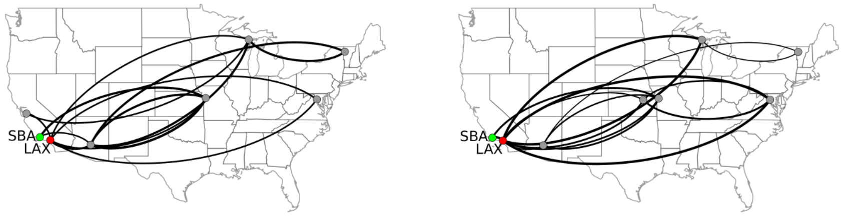
4.4 Geographic path analysis

Lastly, we study the geographic paths taken by traffic on each mobile provider going to specific CDN locations. This analysis provides us visual insight into



(a) Base Carrier A

(b) MVNO Carrier A-1



(c) Base Carrier B

(d) MVNO Carrier B-1

Fig. 4. Paths taken for each carrier to reach servers located in Los Angeles (LAX) from clients in Santa Barbara (SBA). Arc weight indicates the number of times a particular hop was taken. Clockwise arcs indicate direction of traffic between adjacent hops.

the carrier network behavior and performance. Figure 4 illustrates hops taken by traceroutes over our two-week experiment where the destination servers are located in Los Angeles, CA (140 km away from our location in Santa Barbara, CA). Due to space limitations, we only include plots for Los Angeles and four carriers, as it is representative for all locations observed and illustrates the contrast between full and light MVNOs. The figures indicate the differences in behavior between MVNOs and their base carriers. For instance, carrier A (Figure 4(a)) clearly operates over different, more stable routes compared with its corresponding MVNO (Figure 4(b)). This helps explain why there is such a marked difference in performance between the two when connecting to various data centers. Carriers B and B-1 (Figures 4(c) and 4(d)), on the other hand, are quite similar to one another. This result depicts the difference between light and full MVNOs, where the light MVNO (B-1) routes traffic in the same way as the base MNO, while full MVNOs that implement their own core are influenced by outside factors and differ from their respective base carriers.

A curious finding is that many of the carriers, particularly the MVNOs, contain paths that pass through Los Angeles only to continue with subsequent hops in distant locations before finally returning to Los Angeles. This seems to indicate the lack of peering between the network that the earlier Los Angeles hop is within and the content provider located in Los Angeles. This behavior is interesting given that [9] found three of the four major US MNOs have peering arrangements with Google servers in Los Angeles. The propagation delay introduced by such scenarios can be considerable, without accounting for additional potential for congestion or queuing delays. Bottlenecks such as these must be removed in order for mobile data to shrink the performance gap between mobile and traditional wired connectivity.

Overall, path visualization gives us an increased understanding of how carriers differ. The full MVNOs that we measure share many locations with their underlying MNO, but their routes are more frenetic. This could be due to different peering arrangements versus the base carrier or simply due to different overall Internet connectivity. We also see that the light MVNO in our study closely resembles its base carrier. Given all that we have observed it seems clear that light MVNOs are, at their foundation, re-branded base carriers.

5 Related Work

There has been significant effort towards measuring, characterizing, and improving the performance of cellular network infrastructure with respect to the user experience [14, 15, 9]. Sommers et al. [14] compare the performance of cellular and WiFi networks using a crowdsourced approach for measuring network throughput. Nikrashev et al. [15] measure longitudinal performance from end-devices to uncover the prevalence of middleboxes in mobile networks. Zarifis et al. [9] use end-devices to identify latency caused by inflated routes and the relationships between user performance, Internet ingress points, and peering agreements. Similar to previous work, we use measurements from the end-user perspective to understand the impacts of network infrastructure on user experience.

Zarinni et al. [4] compare application performance over two major carriers and three MVNOs per carrier. Our work focuses on performance with respect to underlying network layers (e.g. latency and route paths) and considers all four major U.S. carriers and MVNOs operating on top of each.

As cellular networks become the primary mode of Internet connectivity, research efforts have focused on the analysis of the impact of content placement and network configuration on end-user experience [9, 6]. Zarifis et al. [9] find that route inflation leads to increased RTT experienced by end users connecting from locations with limited infrastructure. Rula et al. [6] explores the relationship between cellular DNS infrastructure and the location of selected content replicas, finding that instability of cellular DNS resolvers significantly degrades the experience of mobile users. We find that locations of resolved content servers are not universally attributable to one single factor.

6 Discussion and Conclusion

Given the results of our measurement study, what are the overriding lessons?

Round trip times. We observe that round trip times vary significantly between MNOs as well as MVNOs. Additionally, we see that location of destination servers drastically affects RTTs, and resolved server locations do not appear to be logical in that they are often physically distant from the client location. Such behavior could be the result of mobile carrier peering arrangements, DNS infrastructure, and Internet ingress points. Future work should focus on making more efficient network topologies in order to close the performance gap between mobile carriers.

Route paths. We find that MVNOs typically traverse the same autonomous systems as their MNO counterparts in their paths to reach servers. However, we often observe a higher number of hops on the MVNOs. The root cause of such path inflation needs more thorough investigation, as it could be attributable to multiple factors such as: Internet ingress points or middleboxes used for accounting or traffic shaping in the mobile core network. Given our geographic analysis, we believe that full MVNOs, which operate their own core networks, route traffic through seemingly inefficient paths. Perhaps increasing the number of ingress / egress points as well as replicating middlebox functionality across more geographic locations could improve the directness of mobile traffic on such networks.

MNOs vs MVNOs. With the exception of carrier B-1, we observe marked performance differences on MVNO networks compared with their underlying MNO networks. As carrier B-1 is a light MVNO, while the others are all full MVNOs, we can argue that consumers should expect a different user experience when connecting via full MVNOs compared with base carriers. The observed light MVNO leads us to conclude that its use is in essence the same as the base carrier. It remains to be seen whether the same is true for all light MVNOs. We find that full MVNOs tend to share some infrastructure with the MNO, but that they are less predictable in terms of routing paths. Latency differences are also considerable between MNOs and full MVNOs and some variability can be attributed to destination server location. It seems likely that MVNOs may have fewer peering agreements with content providers, evidenced by considerably longer, more circuitous paths taken.

We do not believe that MVNOs, by their nature, are bound to offer inferior performance compared to MNO carriers. There appears to be multiple avenues available to explore for MVNO carriers in order to maximize traffic efficiency. For researchers, this subject deserves more in-depth, longitudinal studies from many locations to fully understand performance of these networks. For consumers considering which MVNO or plan is the best option, there is currently no clear answer. Additionally, the ‘best’ carrier will likely vary based on what content the user intends to consume on the Internet. The inherent tradeoffs between carriers are worthy of future exploration using real-world user traffic.

Limitations. Our measurement study provides only a limited glimpse into the performance of mobile data networks given a single measurement location and targeting a small set of servers. A longitudinal, in-depth measurement campaign is required to fully understand the tradeoffs between mobile carriers and content delivery networks. Measurements also rely on the efficacy of the tools we use, such as `traceroute`, and the equal treatment of measurement traffic by the carrier core networks. A larger study must include more real world traffic.

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