Trust-free Service Measurement and Payments for Decentralized Cellular Networks

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ABSTRACT

Decentralized cellular networks have emerged to increase network accessibility by distributing infrastructure ownership over independent entities. Unlike the centralized setting, these architectures can allow users to connect to any untrusted base station without prior subscription. However, verification of the service is necessary in the absence of trust for commensurate payments by the user. Further, any method of verification must be non-intrusive and reliably agreed upon by the involved parties. To this end, we describe *two-sided measurements* where both the users and the providers independently assess the cellular service. We find that reconciling measurements from different layers of the cellular stack for a diverse set of matching observations is challenging but not impossible. Hence, new use cases such as a decentralized slicing marketplace, and contract-free roaming can be enabled by two-sided measurements. We envision applying two-sided measurements to real-time, on-demand network slicing and present an architecture that is capable of offering, as well as verifying, such slices in a scalable manner.

CCS CONCEPTS

• **Networks** → **Mobile networks**; **Network management**; Wireless access points, base stations and infrastructure;

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KEYWORDS

Cellular Architecture, Decentralization

1 INTRODUCTION

Decentralized cellular networks where users can be serviced by untrusted individuals and small businesses as opposed to monopolistic carriers herald a sea change in the telecommunications landscape. Originally conceived as community networks [6, 20, 23, 28, 47] to make Internet connectivity ubiquitous, these have now evolved to reimagine cellular access [14, 22, 30, 35, 46]. Driven by disaggregated and open source cellular stacks [10, 16, 18, 33, 39, 42, 44], access to lightly licensed spectrum [17, 55], and inexpensive commercial hardware, decentralized networks are uniquely poised to enable many remarkable new applications.

First, decentralized networks do not rely on pre-established legal agreements between users and providers for charging and billing [8]. This is pivotal for complex Service Level Agreements (SLAs) with Quality of Service (QoS) guarantees because establishing legal trust with central authorities is slow and limits SLA diversity. However, current proposals continue to use legal trust towards central authorities, i.e. brokers [35], network servers [22], exit nodes [46]. Instead, fast and independent verification of the service can enable opportunities for flexible, granular, and tailored services.

For instance, Mobile Network Operators (MNOs) could provide roaming without long-term agreements with other carriers. Setting up these agreements involves protracted and expensive negotiations for routing user data to the trusted home network for billing and charging. However, equipping

the user to independently quantify and pay for the service received from the visited network can undo this requirement.

Yet another exciting use case is customized network slicing. With 5G, even individuals and small enterprises can potentially obtain network slices with specific QoS parameters [31] to support various applications. However, a few key questions remain: How can a marketplace encourage competition between several providers and make adversarial behavior unprofitable? How can users and providers negotiate in real-time while ensuring spotless connectivity? More fundamentally, in the absence of trust, how does the user verify that they are indeed getting the service they paid for?

We observe that systematic verification of trust-free service is a recurring problem in the decentralized setting. We present the *two-sided measurements* framework as a solution to this. It allows the user and the provider to independently verify the service incrementally in small units without the intervention of a third party and continue transacting only if their measurements agree with each other. Indeed, they are both incentivized to continue transacting – the user needs connectivity and the provider is getting paid for its services.

The primary challenge with two-sided measurements is aligning the measurements, i.e. throughput, captured at various layers of the stack by different agents and at different times. We find that agreement depends on channel conditions, the transport protocol used, or where the measurement is made on the cellular stack. For instance, packet losses within the RAN are invisible to the measurements collected at the core of the provider. A provider may inadvertently assume the packet is served once it is observed at the core whereas the user does not receive it. Although low-level measurements at the base station (BS) can prevent this, it requires a precise mapping between the physical resource allocation and the actual amount of data transferred. In addition, most User Equipment (UE) is not provisioned to expose low-level telemetry about network usage, so convoluted high-level measurements are required to verify various SLAs.

We examine the challenges listed above in an over-the-air experiment, highlighting how the measurements diverge. In particular, usage measurements at the provider's core may deviate significantly from the user's measurements over weak channels. Instead, usage can be monitored closely with less than 1.5% error if the measurements are collected from the RLC layer of the RAN with enough precision.

Finally, we integrate two-sided measurements into the design of a competitive, trust-free marketplace for fine-grained, on-demand network slicing in decentralized networks. Custom network slices significantly improve the performance of many applications like IoT [26], edge computing [24], and virtual reality [41]. We attempt to further granularize this technology in the decentralized setting by replacing the central trusted authority with a distributed ledger where SLAs are negotiated on scalable smart contracts and incremental payments are made depending on the verified QoS.

In §2, we provide background on decentralized cellular environments and how two-sided measurements empower users to negotiate for the real-time SLAs of the slice they consume. Our architecture design is presented in §3 along with the details of our prototype and challenges we faced in §4. Further discussion for future work is provided in §5.

2 ENABLERS OF ON-DEMAND SLICING

Decentralizing the last mile of a cellular network stems from the idea of empowering communities as providers. Naturally, the next step is empowering individuals as users. In this section, we discuss three critical requirements to empower users and ensure rapid adoption while clarifying how our proposal is different from prior work compared to these.

2.1 Trust-free

Ensuring continued and honest service is a key challenge in decentralized networks. CellBricks [35] centralizes trust with users handing over the management of their service to a broker. Ironically, brokers (carriers in general) have limited visibility into the instantaneous service needs of users which can change depending on the application used. On the other hand, there is a rich literature on how application performance can be improved when UEs are given visibility and control over the cellular service received [7, 32, 50–52].

In a truly decentralized cellular network, the trust should be established via verification directly between the base station and the UE instead of a third party, i.e. broker. When only two parties are involved, both are guaranteed to detect the other's adversarial behaviour as long they are confident in their own measurement of QoS.

Two-sided measurements refer to both entities taking their own measurements as the ground truth. If the two disagree, the UE (or the provider) immediately stops paying for (or supplying) connectivity. Note that frequent measurements can detect any mismatch quickly. This keeps the UE from paying despite inadequate service or the provider from supplying service without payment. Nonetheless, the trade-off between the overhead of measurements and the granularity of service verification deserves consideration. We call this approach *micro-payments for incremental SLAs*.

2.2 Permissionless

Trust-free networks allow infrastructure ownership disaggregation while also being robust. This lowers the barrier to deploying competitive networks. For instance, in CellBricks [35], RAN belongs to bTelcos and user management is offloaded to brokers. Users subscribe to brokers which authenticate them to bTelcos when connecting.

Even with disaggregated ownership, permissioned systems require a central authority for vetting equipment which impedes rapid scaling. For example, the Helium 5G network [22] requires a BS gateway manufactured only by FreedomFi which has a months-long waiting list. Instead, *permissionless* systems where anyone can deploy software on off-the-shelf hardware without central registration motivate innovation similar to how OpenFlow [38] did with programmability in switching. In turn, providers will offer services tailored to users' needs, drawing them to markets where they have the most control and the best application performance [7, 32, 50–52].

2.3 Backward Compatible

Although designing a clean slate architecture for a trust-free, and permissionless slicing marketplace is simpler, ease of adoption is as vital to reduce the per-user costs [29]. Hence, any new decentralized architecture should be backward compatible. For instance, the Personal Router Project [11] relied on a new piece of hardware that negotiated with the base stations and created its own wireless connections with UEs. Rolling out millions of these devices and having them create their own wireless channels without interference were two major challenges for the project.

We propose a user-space application running over the standard OS without modifying the UE networking stack. It negotiates with the base stations, makes passive measurements, and sends payments for the service. Similarly, the data plane of the base stations is left as specified in the standards [2] while using open interfaces for service measurements [40]. A separate virtual network function runs in the core network to authorize UEs and verify their payments. Overall, this approach enables all the existing equipment to start using the decentralized marketplace as soon as users and providers install the applications and the functions respectively.

3 DECENTRALIZED MARKETPLACE FOR ON-DEMAND NETWORK SLICING

We present a decentralized cellular network where UEs connect to any base station, negotiate for SLAs and monitor the service. In the absence of pre-established subscriptions, we use blockchain primitives for authorizing and billing UEs. Figure 1 presents an overview of the architecture.

miniTelcos are the independent providers with an arbitrary number of–even just one–base stations. Their core network can be co-located with the base stations as in dLTE [30], deployed in a central office or in the cloud [18]. They declare available cellular resources and slices in supplier smart contracts (❶ in Figure 1) and can service any UE as a roamer.

Bridges are the intermediaries that manage payment channels for UEs and miniTelcos. Each bridge interacts with
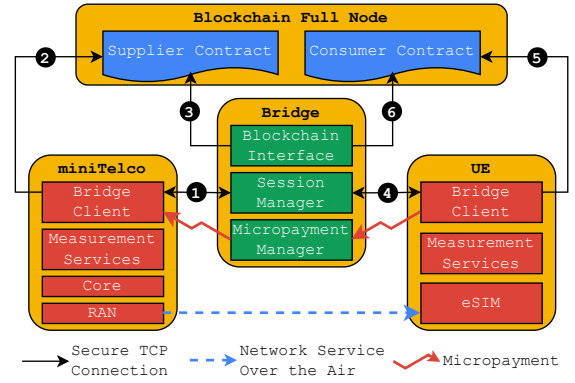

Figure 1: A decentralized cellular network design. Orange blocks can be owned individually without trust in others.

many miniTelcos and UEs in the region. Further, a miniTelco (or a UE) can also have supplier (consumer) smart contracts with multiple bridges. Note that neither UEs nor miniTelcos need to trust bridges because all the transactions are cryptographically authenticated and protected by the contracts to prevent adversarial behavior. Moreover, it is in the interest of bridges to mediate cellular connections only for credible UEs and feasible SLAs. Otherwise, the connection between the UE and the miniTelco would not last and the bridge would end up collecting a smaller commission. More details on how bridges work while preserving security are provided in §3.3.

In the discovery phase, the UE sends standards compliant attach requests to any BS it can hear. Participating miniTelcos accept the request and establish the wireless channel. At this point, UEs are only provisioned for sending traffic to bridges available in the cloud for negotiations. This traffic is called the *seed data* and is exempt from billing.

The seed data carries the miniTelco ID and is transmitted by the UE's Bridge Client once the RRC is configured (❹ in Figure 1). The bridge responds with the costs of the available slices. The UE chooses a slice and notifies the bridge with the initial payment and the signature. The bridge relays this payment to the miniTelco after deducting a commission. Once the miniTelco receives the payment, it provisions the UE for the network slice with the negotiated QoS.

When the UE no longer requires connectivity, it requests a termination from the bridge which is forwarded to the miniTelco to disconnect the UE. If the UE does not pay as expected, the miniTelco may unilaterally terminate the session as well. We explain the payment expectations next.

3.1 Verification & Two-sided Measurements

One concern for a trust-free cellular network is making sure the miniTelco supplies the agreed-upon QoS to the UEs upon payment. Similarly, miniTelcos need to be assured payment for the services supplied. To achieve these and incentivize

honest behaviour, we propose *incremental SLAs* where the service is divided into small billing units. For example, the usage can be billed every 10MB which is significantly smaller than the total amount of service needed by a typical UE. Then, both the UE and the miniTelco should prefer a socially optimum (i.e. honest) strategy for long-term connectivity [37]. Otherwise, the honest party quickly detects the adversary with minimal loss (i.e. service or payment worth at most 10MB) and stops collaborating in the future.

As a consequence, both entities must measure the service they provided (or consumed) and map it to an equivalent payment. We call this mechanism *two-sided measurements*. Any service can be offered in a trust-free environment as long as it is verifiable with two-sided measurements. In §4, we describe usage and bitrate as services. Two-sided measurements for other kinds of services are discussed in §5.1.

3.2 Blockchains as the Source of Trust

MNOs perform the critical task of authorizing UE access to the cellular network via centralized checks on the UE's credit and subscription plan. In a decentralized setting, providers can not do this as the UE is not a subscriber at all. Instead, a public and immutable database can be used to provide an unassailable proof of identity and credibility. When a UE attempts to attach, the provider can check this database to get assurance for future payments. We design an interface that utilizes a blockchain for authorizing UEs and orchestrating payments. Any blockchain can be used for this purpose as long as the bridge supports its APIs. Implementing a Bridge Client that also negotiates which blockchain to use is a promising direction of future work.

Prior work has already proposed incentivizing communication networks with blockchains [8, 9, 13, 25, 43, 54]. Yet, proposals focus on routing and packet forwarding and leave QoS verification an open research problem [36]. Global payment systems of credit card companies can also host custom payment channels to provide authorization as a service. However, only a few such companies exist, making it a fertile ground for rent-seeking [3, 48] and gate-keeping [21]. In addition, their proprietary infrastructure is against the factors listed in §2. Instead, blockchains are trust-free, secure, and open databases that provide the same service. Indeed, a careful bridge design between the blockchain and the cellular network can allow scalability at low costs.

3.3 Bridge & State Channels for Scalability

Blockchains usually finalize very few transactions per second with high costs [53]. Therefore, cellular networks can not commit every incremental SLA (e.g. 10MB of download) as an on-chain transaction. Instead, state channels aggregate many small transfers into two on-chain transactions [4]. The

first commit opens the channel with a certain escrow amount. The second commit announces the final balances of the two participants after many off-chain payments in between.

Opening a state channel can take minutes to finalize on the blockchain. In our design, UEs and base stations open these channels with a subset of bridges in advance to hide this latency (Steps ❷, ❸, ❺, and ❻ in Figure 1). The state channels are governed by *smart contracts* to define conditional payments from the UE to the bridge (consumer contract) or from the bridge to the miniTelco (supplier contract) while removing trust from the system. Thus, a direct payment channel for every pair of UE and miniTelco is not necessary.

When a UE connects to a base station, it simply sends payments to a bridge through the state channel. The bridge immediately sends this payment to the state channel of the miniTelco after deducting a commission. Those deductions incentivize bridges to send incoming payments to miniTelcos. Otherwise, miniTelcos would not continue serving UEs and micro-payments would stop accordingly.

The micro-payments are handled by the bridge without interacting with the blockchain. This has two main benefits: (i) The bridges can be deployed physically closer to the miniTelcos compared to blockchain nodes for smaller RTTs. (ii) The micro-payment commissions of bridges would be much cheaper than on-chain transactions. Defining the commission rates is out of scope for our work. We expect it to be dynamic based on the number of bridges serving miniTelcos in the area, and the types of slices negotiated.

Fortunately, the barrier to deploying a bridge is quite low as developers can utilize open-source blockchain APIs and start running one at a low cost thus preventing monopolies. As more bridges are deployed in the region, the market share decreases for each bridge while increasing competition. This balances the number of bridges serving the same area and lowers the commissions.

In addition, a UE can utilize the consumer contract with a bridge to send payments for multiple miniTelcos. Therefore, maintaining the same state channel for a long time is a cost-effective and scalable way of handling payments in the system. The settlement time of the channels depend on the escrow amount and cost of committing into the blockchain itself. Yet, there is no risk of losing payments when the settlement is delayed because each micro-payment is signed by the payer under the escrowed amount. We estimate that settling once a month makes the system feasible for use by millions of users despite the transaction rate limits of blockchains.

4 PROTOTYPING AND EVALUATION

We are building a miniTelco prototype with three Tejas Networks model TJ1600 base stations around our campus. They connect to an Evolved Packet Core (EPC) in our lab which
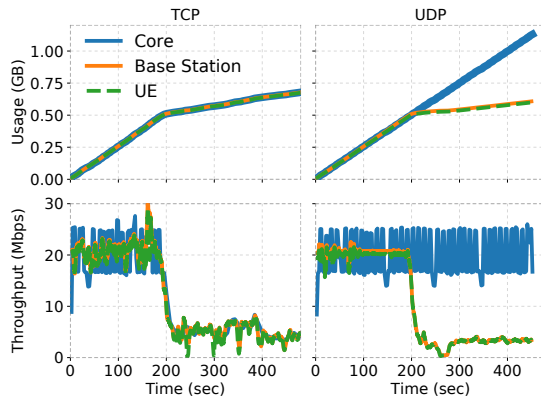
Figure 2: Two-sided measurements from different locations at the miniTelco and the UE. Channel conditions deteriorate after $t = 200sec$

will soon be upgraded to 5G. Our UEs are Linux based laptops connected to the network using USB dongles. We test our network with various channel conditions simply by moving around the campus. Finally, the bridge prototypes are deployed on AWS EC2 instances [5].

The UE's Bridge Client and Measurement Services are user space programs which poll `sysfs-class-net-statistics` (exposed by Linux) every 50 ms to monitor the data usage on the Ethernet interface of the device[1]. On the other hand, the miniTelco's Bridge Client is a network function that queries transport block (TB) sizes and queue occupancy from the MAC and RLC layers of the base stations respectively every Transmission Time Interval (TTI). For a TB size exceeding the queue occupancy in a TTI, the entire queue for a UE is transmitted and the rest of the TB is padded with arbitrary values [2]. Hence, we take the lesser of the TB size and the queue occupancy as the usage at the base station for the UE. Further, the Measurement Services also fetch charging information from the Online Charging System (OCS) to infer data usage at the core. Note that the throughput can be obtained as a ratio of the usage and the elapsed time.

To investigate the challenges to reconciling two-sided measurements for usage and throughput, we connect a UE to the miniTelco and run a congestion-controlled TCP flow from an independent server in our lab to the UE for 500 seconds via `iPerf`. The UE is stationary at a location near the base station for the first 200 seconds of the experiment for good channel conditions whereas we take the UE further away and move around in the second half for worse channel conditions. We also repeat the experiment with constant-rate UDP traffic and collect the same set of data described above.

Figure 2 shows the usage and throughput measured by the UE and the miniTelco for TCP and UDP. The measurement of the UE's usage made at the miniTelco's core is misleading for

UDP as packets can be dropped somewhere between the P-GW and the UE, i.e. at the BS. Since a UE would be unaware of these, it would not pay for them in a decentralized setting. Yet, centralized MNOs charge users based on the measurements from the core network (P-GW or UPF).

In the case of TCP, the flow adjusts itself to the channel conditions and slows down as needed to achieve a negligible loss rate. Even then, we observe noisy throughput measurements at the core which double count retransmissions and do not match the UE measurements exactly for high throughput. Estimating a small and bounded mismatch margin is harder with such noisy measurements.

On the other hand, measurements from the closest point to the UE (i.e. the RLC layer) provide the most accurate data about the actual service provided. Low mismatch rates enable the miniTelco to adjust its payment expectations in a robust way. We observe that any mismatch is bounded below 1.5% in usage across various channel conditions when 4 second averages are calculated. It can be further reduced if the base stations expose more granular physical layer telemetry such as the loss rate at the wireless channel. Hence, we conclude that precise telemetry exposed by the base stations, i.e. nRT-RIC by ORAN [40], is vital for enabling robust two-sided measurements and dynamic slice control.

Next, we investigate the scalability of the interactions between the bridges and the blockchain. We use Ganache [27] to simulate a local Ethereum blockchain for our experiments, but any blockchain with enough programmability on smart contracts would work in our design. First, a state channel is opened by a miniTelco (or UE) sending a `request` to the chain followed by the bridge sending a `confirmation`. It takes 30 seconds for the blockchain to finalize these transactions and open the state channel with a fee of $8.00[2]. Luckily, this cost is incurred only when opening and settling the state channels. Further, we assert that frequent micro-payments cause minimal extra load. Each micro-payment from a UE to a bridge is a packet of size 294 Bytes. Hence, downloading at a rate of 40 Mbps with a payment every 2 seconds for 10 MB utilizes a mere 1176bps from the channel capacity.

5 DISCUSSION AND FUTURE WORK

5.1 Diversifying Two-Sided Measurements

Although our preliminary experiments focus on two-sided measurements for data usage and throughput, we are working towards verifying other QoS metrics. The performance of cellular services is dictated by the standard QoS Class Identifiers (QCI) [1]. They determine the packet forwarding behavior on the BS by defining targets or limits for metrics-exposed via specific interfaces [40]-like bitrate, delay, and

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[1]Similar statistics are also available for iOS and Android [15, 19].

[2]Each on-chain transaction costs $0.005 in Polygon blockchain. Prices estimated by etherscan.io/gastracker on June 21st, 2022.

packet loss rate. If a UE is equipped to make its own measurements, it can negotiate for a particular QCI with a miniTelco.

Bitrate is already measurable in our prototype. However, it does not detect whether the bottleneck of the flow is within the miniTelco's network. When the negotiated bitrate is not achieved, either the miniTelco is not providing the promised bitrate or the bottleneck is somewhere else that the miniTelco cannot control. In any case, a UE would rightfully discontinue paying for exclusive high bitrate service.

Delay and loss rate are harder to measure at the UE. For example, in the case of delay, a packet's wait time at the BS is not visible to the UE. Similarly, monitoring the time a packet spends waiting at the UE before it is sent requires root access to the networking stack of the UE. MobileInsight [34] exploits this root access to collect telemetry on various metrics. However, relying on it would be against the requirement of compatibility described in §2.3 as most smartphones do not grant users root access. Instead, an analysis tool in the user-space is required to infer delay and loss due to the wireless service. According to [7], RTT variations in a TCP flow can help infer the scheduling behavior of the BS, assuming the load for the rest of the network is stable. We defer the design of such inference mechanisms to future work.

5.2 Quantifying Overhead of Measurements

In a decentralized network, the UE must spend precious energy on negotiating directly with the miniTelco to authorize policies and verify service. We argue that the overhead of two-sided measurements would cost the UE a negligible amount of power due to three reasons: (i) Negotiation procedures take only two requests per session which limits the communication overhead. (ii) Our proposed measurements are passive and in the user-space. (iii) The computations just involve reading already present variables[3] and simple calculations. Nevertheless, the design and evaluation of an optimized Bridge Client on the UE remains as a future work.

5.3 Mobility with Decentralization

As observed in [35], the current telecommunications infrastructure, with its oligopolistic market of expansive MNOs, operates on the premise that handovers within a network are routine and that a UE is unlikely to switch networks. Further, coordination among base stations and the core enables the careful optimization of mobility mechanisms by grouping cells, and employing core assistance during handovers and paging. However, this coordination can no longer be guaranteed in the decentralized setting where switching cells might imply switching miniTelcos. CellBricks [35] tackles this by requiring the UE to detach from the current service provider

and attach to the new one using the Secure Attachment Protocol (SAP) they propose. Connectivity is maintained despite IP changes by relying on MPTCP [49] which uses distinct subflow identifiers to delineate connections.

UE driven mobility in [35] is promising for many decentralized architectures. While the design of a mobility scheme for our system is beyond the scope of this paper, we find the structuring of incentives to make miniTelcos willing participants in network assisted handovers to be an interesting direction of work. This will not only enable more intelligent handovers and resource management but also prevent interoperability from being a barrier to new entrants.

5.4 Privacy with Decentralization

Currently, carriers can locate a UE and record who it is communicating with, and users simply trust them to not spy on their traffic. Several countries have laws (i.e. [45]) that strictly regulate these few large centralized carriers. However, with decentralization, we expect many independent miniTelcos to exist which makes auditing each one harder. Nevertheless, there are decentralized mixnet solutions like [12] that aim to provide privacy over the Internet. Further, bridges can also collect data about the miniTelco connections of UEs by tracking their payments. We invite the community to start a discussion around the level of information that would be safe to expose in decentralized environments and expect it to lead to the design of a secure protocol for slice negotiations as well as payments in the future.

6 CONCLUSION

A decentralized architecture was pivotal to the growth of the Internet. Recently, similar principles are being applied to cellular networks. In this work, we introduced two-sided measurements as a primitive fundamental to realizing the promise of this approach. While two-sided measurements are intuitive, implementing the framework requires careful consideration of numerous technical subtleties of the cellular stack. Further, it enables a dynamic marketplace for on-demand network slicing where users have the power to negotiate with providers in real-time. Our design builds on a permissionless and trust-free ecosystem that incentivizes entities to participate fairly in this marketplace. To the best of our knowledge, this is the first proposal to enable on-demand network slicing for purchase. We believe that the diversity of the measurable slices as well as the adoption of the marketplace will rise with greater contribution from the community, aligned with the spirit of decentralization.

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[3]Metrics such as data usage, and RTT are traceable values from the Ethernet or socket interfaces of the networking stack

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