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;

KEYWORDS

Cellular Architecture, Decentralization

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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 properties.

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

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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 user empowerment in these networks. 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 prevents the UE to pay a large amount without getting the expected service while the provider avoids supplying a substantial amount of service without getting paid. 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 with a months-long waiting list for purchase. Instead, *permissionless* systems where anyone can deploy software on off-the-shelf hardware without any 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 a clean slate approach 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 base stations – may even have just one. Their core network can be co-located with the base stations similar to dLTE [30], deployed in a central office or in the cloud [18]. They declare cellular resources and available slices on the smart supplier contracts with the bridges (❶ in Figure 1) and accept any UE into their network as roamers.

Bridges are the intermediaries that manage payment channels in a scalable manner. Each bridge interacts with many miniTelcos and UEs in the region. Further, a miniTelco (or a UE) can also have smart supplier (consumer) 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.

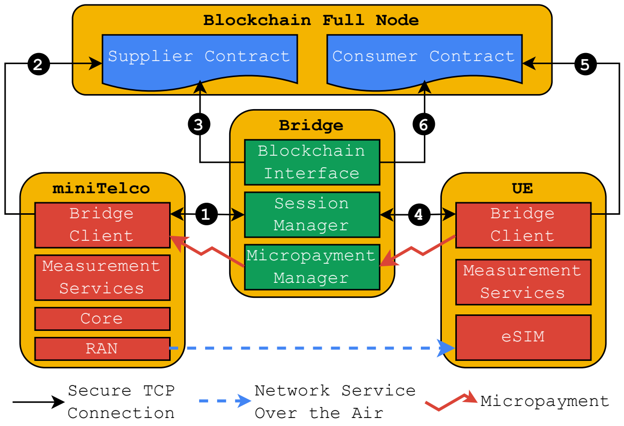

Figure 1: Decentralized cellular networks. Each orange block can be owned by a different entity without trust in others.

During the discovery phase, UE sends attach requests to any base station it hears per the standards. 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 ID of the miniTelco 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 does not require connectivity any more, 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 Two-sided Measurements for Payments

One concern for a trust-free cellular network is making sure the miniTelco supplies the agreed-upon QoS to the UEs per the payments. Similarly, miniTelcos need to be assured payment for the services supplied. To address these and incentivize both parties to behave honestly, 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 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. max 10MB worth of service or payment) and stops collaborating in the future.

As a consequence, both entities must measure the service they provided (or consumed) and map it to the associated 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 a service. 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 the subscription plan. In a decentralized setting, providers can not check these as the UE is not a subscriber at all. Yet, they need an unassailable proof of identity and credibility. A public and immutable database can be used for this purpose. When a UE is trying to connect, 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 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 mostly 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 transactions [4]. The first commit opens the channel by declaring 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 is still an on-chain transaction and can take a few minutes to finalize. In our design, all 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 miniTelcos (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 (and UEs) compared to real blockchain nodes for smaller RTTs. (ii) The commission of bridges for micro-payments would be much cheaper compared to the on-chain transactions. Defining the commission rates is out of scope for our work, but we expect it to be dynamic based on the number of bridges serving miniTelcos in the area, and the types of network slices negotiated.

Fortunately, deploying a bridge doesn't require a spectrum licence which significantly lowers the barrier to entry into this business. Developers can utilize open-source blockchain APIs and start running their own bridge at a low cost while preventing monopolization. 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 base stations [1] around our campus. The base stations are connected to an Evolved Packet Core (EPC) located in our lab which will be upgraded to 5G in the near future. 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 Measurement Services along with the Bridge Client of the UE is developed as a user space program. It polls `sysfs-class-net-statistics` exposed by Linux every 50 milliseconds to monitor the data usage on the Ethernet interface of the device[2]. On the other hand, the Bridge Client at the miniTelco is developed as a network function that queries transport block (TB) sizes and queue occupancy, respectively, from the MAC and RLC layers of the base stations every Transmission Time Interval (TTI). If the allocated TB size is larger than the queue occupancy in a TTI, the entire data in the queue for a UE is transmitted and the rest of the TB is padded with arbitrary values [2]. Therefore, we take the minimum of the TB size and the queue occupancy as the usage at the base station for the UE. In addition, the Measurement Services also fetch charging information from the Online Charging System (OCS) to infer data usage at the core. Note that the usage can be converted to throughput by dividing it with the elapsed time.

We investigate the challenges for matching the two-sided measurements from the UE and the miniTelco for usage and throughput. In this regard, 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 both of the cases. Note that the measurements at the core of the miniTelco are misleading for the UDP scenario in terms of the actual amount of data delivered to the UE because packets can be dropped somewhere between the P-GW and the UE, i.e. at the base station. Since a UE would not be aware of these packets, 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).

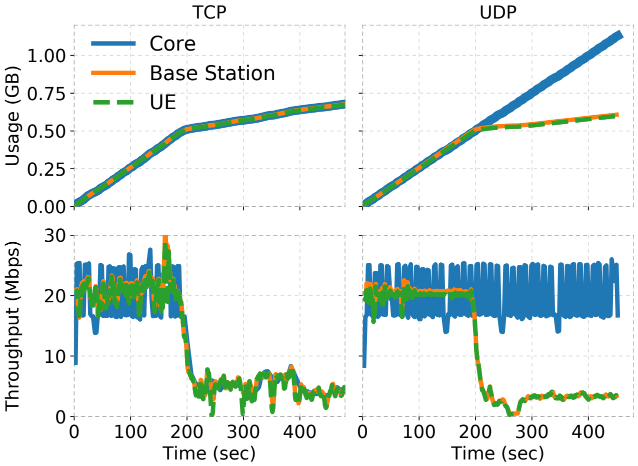

Figure 2: Two-sided measurements from different locations at the miniTelco and the UE. Channel conditions deteriorate after $t = 200sec$

In the case of TCP, the flow is able to adjust itself to the channel conditions and slow down when needed, so that loss rate is negligible. Even then, we observe noisy throughput measurements at the core which double count retransmissions and fail to match the UE measurements exactly when the throughput is high. 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, miniTelco (or UE) sends a `request` to the chain which is complemented with the `confirmation` from the bridge to open state channels. It takes 30 seconds for the Ethereum blockchain to finalize these transactions and open the state channel with a cost of $8.00[3]. Fortunately this cost is incurred only when opening and settling the state channels.

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[1] Model TJ1600 from Tejas Networks

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

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

Second, one can argue against the extra load created by frequent micro-payment packets. Each micro-payment is a notification packet of 294 Bytes sent to the bridge by the UE. We find that downloading at a rate of 40Mbps requires a UE to send a micro-payment for 10MB every 2 seconds which utilizes only 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]. It determines the packet forwarding behavior on the base station by defining targets or limits for metrics such as bitrate, delay, and packet loss rate. Those metrics are exposed by base stations via specific interfaces [40]. 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 trickier metrics to measure at the UE. For instance, in the case of delay, the time a packet spent waiting at the base station is not visible to the UE. Similarly, monitoring the time a packet spent 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. Unfortunately, most smartphones do not grant users root access, so relying on it would be against the compatibility requirement of decentralization described in §2.3. 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 could provide hints about the scheduling behavior of the base station, assuming the load for the rest of the network is stable. We leave the detailed analyses for such an inference mechanism in a decentralized network as a future work.

5.2 Quantifying Overhead of Measurements

Decentralization empowers a UE to authorize and verify policies itself by negotiating directly with the miniTelco. Hence, it needs to actively participate in the two-sided measurements and spend precious energy. All of these procedures are normally handled by the core network of the telco in monolithic architectures.

We argue that the overhead of empowering the UE via two-sided measurements would cost a negligible amount of power due to three reasons: (i) Negotiation procedures take only two requests for each session which limits the communication overhead. (ii) We propose passive measurements in the user-space to minimize extra power consumption. (iii) The computations are limited to read operations for already existing variables[4] and simple mathematical 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

In central architectures, the carrier has the power to locate a UE and record the destination it is communicating with. Then, the user simply trusts the carrier to not spy on her traffic. In several countries, legal regulations (i.e. [45]) define strict rules for auditing these small number of large carriers. With decentralization, we expect many independent miniTelcos to exist which makes it harder to audit every single one of them. Nevertheless, there are decentralized mixnet solutions like [12] that aim to provide privacy over the Internet.

In addition to miniTelcos, bridges can also collect data about miniTelco connections of UEs by simply tracking the payments. Therefore, we invite the community to start a

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

discussion around the level of information that would be safe to expose in decentralized environments. We expect this discussion 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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