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SERVICE COMPETITION AND DATA-CENTRIC PROTOCOLS FOR INTERNET ACCESS

A Dissertation Presented

by

THIAGO TEIXEIRA

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
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Electrical and Computer Engineering

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DEDICATION

To my wife Cavaille and my parents Norma and Jose Roberto.

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I would like to thank my advisor, Professor Tilman Wolf, for his much valuable guidance and lessons learned during my doctorate. I would also like to thank Professor Michael Zink for supporting, guiding, and working together in many exciting projects. My achievements would not have been possible without them. I would like to thank the remaining committee members, Professor Anna Nagurney, and Professor Jay Taneja for accepting my invitation. I am honored to have you in my committee.

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ABSTRACT

SERVICE COMPETITION AND DATA-CENTRIC PROTOCOLS FOR INTERNET ACCESS

SEPTEMBER 2019

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The Internet evolved in many aspects, from the application to the physical layers. However, the evolution of the Internet access technologies, most visible in dense urban scenarios, is not easily noticeable in sparsely populated and rural areas.

In the United States, for example, the FCC identified that 50% of the census blocks[1] have access to up to two broadband providers; however, these providers do not necessarily compete. Additionally, due to the methodology of the study, there is evidence that the number of actual customers without broadband access is higher since the FCC considers the entire block to have broadband if any customer in a block has broadband. Moreover, the average downstream connection bandwidth in the United States is 18.7 Mbps, according to the Akamai State of the Internet report, which places the US in the 10th position in the global rank. It's worth noting that modern applications such as Ultra High Definition (UHD) video streaming requires a bandwidth of at least 25 Mbps. Newer applications

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[1] Census blocks are the smallest unit of geography defined by the Census Bureau

such as virtual reality streaming require at least a 50 Mbps bandwidth. Additionally, urban scenarios are dominated by monopolistic and duopolistic markets, whereby network providers have little incentives to offer innovative services. In this work, we propose an open access network infrastructure along with a novel Internet architecture that allows dynamic economic relationships between users and providers through a marketplace of network services. These economic relationships have a finer granularity than today's coarse and lengthy contracts, allowing higher competition and promoting innovation in the access market. We develop an agent-based simulator to evaluate our proposed network model and its various competition scenarios. Our simulations show that competition greatly benefits users and applications, creating the necessary incentives for providers to innovate while also benefiting consumers.

The trend that resulted in sparsely populated areas lagging of the latest innovations in the access networks is also observed in wireless access networks, where the investments are focused on densely populated areas. Moreover, the rapidly increasing number of mobile devices coupled with the increasingly bandwidth demanding applications are posing a significant challenge to cellular network operators that have to increase OPEX/CAPEX and deal with higher complexity in their networks.

The advances in the access technologies that brought higher speeds and lower latency also reduced the area of coverage of cellular base stations. To cope with the increase in traffic, cellular network operators have been deploying more base stations. In addition, cellular providers have adopted "all-you-can-use" price models, which led users to ramp-up their usage, further worsening congestion in the network.

To address this issue, we propose a scheme that uses Device-to-Device (D2D) communication along with Information-Centric Networking (ICN) to offload traffic from cellular base stations. Then, we build on this scheme and propose a cross-layer assisted forwarding strategy to enhance communication in the MANET. In D2D communication, users can retrieve content directly from their nearby peers. However, this type of communication poses challenges to the current connection-oriented communication model, as devices can move in and out of the communication range at any time, constantly changing routing state, and nodes are subject to hidden and exposed terminal problems. ICN addresses some of these issues with inherent support for transparent caching and named content retrieval, making the network more resilient to disconnections. Our proposed scheme can offload up to 51.7% of the contents from the backhaul cellular infrastructure when requesting the content from nearby peers first.

Finally, we combine the concepts of the marketplace, D2D communication, and ICN to propose a platform for decentralized and opportunistic communication that uses COTS radios to relay packets, extending the reach of the Internet to sparsely populated areas with low cost and without the lengthy contracts from commercial network providers. Our platform can potentially link the remaining part of the population that is not currently connected to the Internet.

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INTRODUCTION

Since its conception in the 1960's, the Internet evolved from an academic networking experiment of a few hosts into a global utility network connecting billions of devices, organized in more than 89,000 autonomous systems (AS).[1] Most of its success is attributed to the Internet Protocol (IP), that provides an interconnection between many existing heterogeneous networks, that may operate over different protocols, while hiding the underlying technologies from the applications. This allowed many networks to interact over a wide variety of physical layers, such as fiber optic, coaxial cable, wireless, or twisted copper wire. The growth in the number of ASes was accompanied by an increasing number of devices connected to the network, which in turn was accompanied by an increasing demand for bandwidth.

This interconnected mesh of networks, each operated by a different profit-seeking actor, created a rich environment where providers offer a variety of services and compete for customers. Some of these services include voice, video, gaming, artificial intelligence (AI), cloud, targeted advertising, and e-commerce. Autonomous Systems also collaborate to exchange traffic (peering) or operate as transit (carrying traffic from other networks). This interconnection is usually done via an Internet Exchange Point (IXP). IXPs provide a neutral facility where different networks can exchange traffic, either via a revenue-neutral peering, or a customer-provider relationship. Current IXPs can host thousands of providers[2], which attracted Content Providers (CP) and Content Delivery Networks (CDN) to deploy their

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[1] according to Caida AS Ranking (`http://as-rank.caida.org/`).

[2] Brazil Internet Exchange (`http://ix.br/`)

servers and Points of Presence (PoP) at the IXP to offer lower latency to subscribers and reduce transit traffic. Business agreements between these entities are translated into inter-domain routes, using the Border Gateway Protocol (BGP-4) [66], then implemented on the routers. This process can take weeks to complete and it is subjected to configuration errors. One demonstration of such misconfiguration was when the telecommunications ministry of Pakistan ordered the state run ISP Pakistan Telecom to censor the online video platform YouTube over an anti-Islamic video.[3] Pakistan Telecom then changed the BGP entry for YouTube, which was propagated over the Internet, bringing down YouTube traffic globally for several minutes. This incident happened in 2008 and it is a known exploit called BGP injection. Similar incidents happened in 1997 (deemed the Internet Black Hole[4]), 2004[5], and 2006.[6] These examples illustrate how vulnerable parts of the Internet are due to its decade old protocols.

Nevertheless, the Internet is a vibrant ecosystem that led to the deployment of many new technologies. For instance, initially, the widely available twisted copper wire from the Public Switched Telephone Network (PSTN) was used for Internet access (dial-up connections). Dial-up connections used the voice channels for communication – sampled at 8 kHz with an 8-bit Pulse Code Modulation (PCM), thus the 64 kbps frame size used in T1 and E1 carriers. As the link layer technologies evolved and more modern ones became available, named Integrated Services Digital Network (ISDN) and the Digital Subscriber Line (xDSL) family, providers started to upgrade their networks to offer differentiated services (this refers to product differentiation and it is not to be interpreted as the DiffServ from the IP header). Coaxial cable was introduced for TV services, but also capable of carry-

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[3] `https://dyn.com/blog/pakistan-hijacks-youtube-1/`

[4] `https://www.nanog.org/mailinglist/mailarchives/old_archive/1997-04/msg00380.html`

[5] `https://dyn.com/blog/internetwide-nearcatastrophela/`

[6] `https://dyn.com/blog/coned-steals-the-net/`

ing data traffic at higher speeds (coaxial cables allow higher bandwidth than twisted pair). Fiber optics were mainly used in the backbone to carry large traffic and at long distances. The increase in computing power and bandwidth demanding applications created a need for faster connections also at the last mile. Therefore, network providers started offering Fiber-to-the-Premises (FTTP) in dense urban areas. However, some of these innovations lagged in reaching sparsely populated regions and rural areas, creating a gap where broadband[7] is still not available. This issue affects countries such as China, Brazil, India, and even developed countries such as the United States.

One of the reasons for this delay in upgrading the physical infrastructure is the lack of economic incentives, where in some cases the return on investment (ROI) is too long (network providers have to invest large amounts of money in laying out the infrastructure to a few customers per mile). The lack of economic incentives is also visible within cities, where some areas are served by only one or two broadband providers [1] (monopolistic and duopolistic markets, respectively). In fact, the FCC reports that 18% of the developed census blocks (blocks that contain housing units) have one broadband provider and 32% have two broadband providers; however, these providers do not necessarily compete. i.e., one provider can offer services to a share of the census block and the other provider offers services to another share of customers. While the FCC reports that 24.7 million Americans do have access to broadband, Microsoft estimates that this number can reach 162.8 million.[8] The main difference between the two studies is that the FCC considers the whole census block to have broadband access if any customer in that census block has broadband access while the Microsoft study is of much finer granularity. In the aforementioned scenarios where providers do not compete, there are little or no incentives to offer innovative and better network services.

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[7] As of the writing of this dissertation, the FCC defines a broadband connection as a minimum of 25 Mbps downstream and 3 Mbps upstream.

[8] `https://blogs.microsoft.com/on-the-issues/2019/04/08/its-time-for-a-new-approach-for-mapping-broadband-data-to-better-serve-americans/`

To demonstrate the costs of deploying new infrastructure, the U.S. Department of Transportation Research and Innovative Technology Administration (RITA) maintains a database of installation costs for various projects across the country. It estimates that a new fiber optic infrastructure installation alongside a highway can cost up to $40,000 per mile.[9] The authors in [19] estimated the cost of new aerial (i.e., utility poles) installation in urban scenarios to be on the order of $132,000 per mile. In sparsely populated areas, these costs can be a significant investment for the network provider. In addition, it does not create incentives for a competitive market, i.e., providers that take the risk of creating or upgrading the infrastructure usually prefer to operate as monopolies.

1.1 Background of Open Access Networks and Novel Internet Architectures

Open access networks (OAN) separate the roles of the owner of the infrastructure, the network operator, and Internet service provider. This business structure shifts away from the vertical model where one provider owns everything and allows a fair competition between multiple ISPs that can focus on offering innovative network services to subscribers, creating a vibrant market. The OAN model can be achieved by slicing the physical layer to different providers, also called virtual network operator or VNO, and the infrastructure owner is also referred to as dark fiber provider.

Open access networks are more commonly implemented by the public sector (commonly known as municipal broadband networks). Communities where open access networks were deployed have seen an increase in economic development and have been successful in fostering innovation. Moreover, broadband penetration is linked to economic development. The authors in [41], present studies that found that a 10% increase in broadband penetration can lead to an increase in up to 1.5% in a country's GDP. Perhaps the most

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[9] Available at `http://www.itskrs.its.dot.gov/`

prominent case is in the city of Stockholm in Sweden, where in 1994 the local government decided to launch a municipally owned dark fiber provider, called Stokab [30]. Since then, the Swedish city figures among the highest Internet qualities (in terms of average bandwidth and penetration) in Europe and among the most business-friendly, being considered a technological hub for the region. More recently, Google Fiber cities [9] in the US experienced a similar trend where an eco-system of start-ups and small business flourished at higher Internet speeds. Open access networks are becoming more popular in the US. A study by the Berkman Klein Center at Harvard University [75], found that community-owned networks that offer broadband services charge lower prices than private providers and generally do not offer the initial teaser price where the price can increase sharply after the first year (the authors of [75] found a price hike of up to 42.8% after the initial teaser price).

In the first part of this work, we focus on creating the necessary economic incentives for network providers to upgrade their infrastructure. We believe that if customers can easily switch away from their Internet Service Provider (ISP), the ISP has an incentive to offer better services, consequently addressing the issue of lack of competition in urban scenarios and lack of incentives to upgrade or extend the infrastructure. We combine open access networks with novel Internet architecture concepts proposed in recent years, allowing a richer set of interactions between participating parties.

The Internet was built on top of the telephony network, and it was designed for a specific type of communication. As the Internet and its applications evolve, we are experiencing the growing pains of its design decisions [24], which were based on the technologies available at that time. For example, host mobility and inherent security are two of these limitations. In recent years, a number of innovative projects[10] have arisen to address the shortcomings of the Internet, some of which enable a richer set of economic interactions. Among those

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[10] NSF Future Internet Architecture Project (`http://www.nets-fia.net/`)

projects, we can highlight the eXpressive Internet Architecture (XIA) which uses service choices and fallbacks [15] and ChoiceNet [89] that provides choices through an economy plane. These new architectures allow fine-grained and dynamic economic interactions between users and providers, more specifically, they enable users to establish a short-term, on-demand contract on a per-connection base.

In summary, the first part of this work proposes a combined approach with concepts of open access networks and novel Internet architectures to create incentives for network providers to upgrade their infrastructure [80]. To study whether switching to an open access network infrastructure with dynamic contracts is beneficial for the eco-system (subscribers, ISPs, and transit providers), we developed an agent-based simulator that implements key concepts of ChoiceNet, in particular, a marketplace for fine-grained network services. The specific research challenges that this work addresses on this topic are the following:

- How should network services be instantiated in a marketplace with dynamic contracts?
- Encouraging competition can result in a race to the bottom scenario, assuming that providers do not collude. Given this scenario, we would like to understand whether providers will be able to profit in a competitive market while offering better network services.
- Network providers operating over an open access network have more incentives to innovate, given that the shared infrastructure offers lower operational costs while fostering competition. We would like to understand the outcomes of such a scenario in the access market.

1.2 Introducing Device-to-Device Communication in the Wireless Domain

The trends that let sparsely populated areas lagging in innovations in the network are also visible in the wireless domain, for the same reason stated before (long ROI). The advances in the radio access technology created a market for data delivery, which started to ascend with General Packet Radio Service (GPRS), also known as 2.5G, including High Speed Packet Access (HSPA/+), Long-Term Evolution (LTE), LTE-Advanced (4G), and most recently 5G. These improvements are the direct result of enhancements and new techniques used in the Third Generation Partnership Project (3GPP) standards that were not available at earlier releases. For instance, the LTE and LTE-Advanced standards saw the debut of carrier aggregation and multiple input multiple output (MIMO – also referred to as Spatial Multiplexing) technologies, which allowed download speeds to reach up to 3 Gbps [7]. These advances in the access technologies have opened possibilities for a more diverse set of applications, such as content streaming and video conferencing. Network operators, in contrast, have seen the traffic in their networks increase as devices and applications continue to demand more bandwidth.

The OpenSignal State of Mobile Networks: USA [2] reports more than 5 billion data points collected from April to June of 2017 from more than 170 thousand users in the 32 largest metropolitan areas in the country. Among their main findings, the average download speeds decreased from the previous report, as the four main cellular network providers migrated to unlimited data plans, which caused users to ramp-up their usage. The increasing number of devices is also challenging network operators, especially in urban scenarios where the concentration of users is higher, which may result in overloaded base stations, which in turn can result in network operators deploying more base stations to cope with the demand. Although smaller cells provide higher throughput and require less energy for the uplink transmission (from the mobile device to the base station), cost, complexity, and management for the network operator may increase to a level higher than what is desired.

One of the possible solutions to this issue is to allow users to try to fetch content from nearby peers first via Wi-Fi or Bluetooth interfaces, that are widely deployed in modern devices and operate over the Industrial, Scientific, and Medical (ISM) unlicensed bands. This device-to-device (D2D) communication can offload traffic from the base station; however, it also poses challenges as nearby devices can move in and out of communication range at any time, breaking the end-to-end connection. Collisions are another challenge in mobile ad hoc networks, as the medium is shared by multiple users with no resource reservation, creating hidden and exposed terminal problems.

Another issue is that the current communication model led to an underutilization of resources, i.e., if multiple users are accessing the same content simultaneously, the network will carry multiple copies of it, wasting valuable bandwidth in the communication channel, especially at the core. This is due to the ultimate goal of these networks, which is to establish a communication channel between two hosts, much like the telephony networks which the Internet was built on. To address this issue, overlay networks such as Content Delivery Networks (CDN) [59] were developed. Content producers use CDN to reduce latency to end-users by deploying caching servers at the network edge. Then, the CDN platform provides a DNS service to map each request to the nearest content replica. This model has been very successful, despite its complexity, with an increasing number of content providers developing their own CDN. IP multicast also addresses this issue by combining traffic into one stream, then replicating it to multiple downstream routers. It is more commonly deployed in private networks and multimedia applications, such as IPTV. IP multicast, however, faces deployment issues and limitations [63, 29], including the initial deployment cost for operators to enable the network to speak the protocol and the possible loss of revenue from transit ISPs that charge customers based on the amount of traffic they carry. A more detailed description of IP multicast issues is presented in [29].

1.3 Introducing Information-Centric Networks

Information-Centric Networks (ICN) propose to change this connection oriented paradigm and move to content-centric, reflecting the changes in the current utilization of the network (i.e., the web is mostly used for retrieving content). ICN works directly on the network layer, which simplifies the forwarding request for content to the nearest replica, compared to CDN which works on the application layer. Moreover, ICN supports transparent en-route caching (TERC) that is helpful when a link breaks or multiple requests for the same content are made (in both cases content will be located closer to the user). Therefore, ICN is disruption tolerant, inherently supports multicast, and it is loop-free, which makes its application in mobile ad-hoc networks (MANET) appealing.

There are several architecture proposals for ICN.[11] Among those, Named Data Networking (NDN) [96] is one of the most prominent open source proposals, led by multiple research institutions. NDN is a publisher/subscriber model, where the requester manifests an interest to the network in retrieving a certain content. NDN is a clean-slate protocol stack that can work natively on top of Ethernet, Wi-Fi, or LTE, or can work as an overlay on top of IP networks. Moreover, content is immutable, i.e., once created it cannot be modified (applications cannot change data packets, but create newer versions of it).

In NDN, the *Consumer* application initiates the communication by sending an *Interest* packet upstream. It does so by using namespaces, an hierarchical name structure used by intermediate routers to select the next hop. The UMass ECE webpage (https://ece.umass.edu/welcome) could be translated to the namespace */edu/umass/ece/welcome*, where *welcome* is one uniquely identifiable content signed by the originator (*Producer* node). Every node in the network that speaks NDN deploys the following data structures:

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[11] A list of ICN designs is available at the Internet Engineering Task Force - Information-Centric Networking Research Group (IETF ICNRG) page: `https://trac.ietf.org/trac/irtf/wiki/icnrg#RelatedResearchProjects`

- A *Content Store* (CS) that caches incoming data packets that can be used for further requests (either by other nodes or when there is a link failure). This is the first step in the forwarding process after the node receives an Interest request. If the requested data is available, the node can immediately send the data packet downstream. For instance, if a node receives an Interest request for "/edu/umass/ece/welcome" and it has a cached copy, it can reply with the content without sending the request further upstream. The NDN routers can implement different caching eviction policies, such as Least Recently Used (LRU), Least Frequently Used (LFU), and First In First Out (FIFO).

- A *Pending Interest Table* (PIT) that is responsible for the stateful data plane and for preventing loops. The PIT keeps a record of Interest requests, incoming and outgoing interfaces, aggregating similar requests. For instance, if a router receives a request for "/edu/umass/ece/welcome" on its interface 1, it checks the FIB and forwards the request to the outgoing interface 4. If at a later time, but before the PIT entry expires, the router receives another request for the same content on its interface 2, it will append another entry to the PIT, but it will not send the request forward. This mechanism prevents loops and aggregates similar Interests. When the data packet comes back, the forwarder sends the packet to the corresponding interfaces.

- A *Forwarding Information Base* (FIB). Similar to the IP FIB, the NDN FIB holds the information on which interface to forward incoming Interest requests, however, in this case the IP prefixes are replaced by name prefixes. In our previous example, the FIB entry to "/edu/umass" would be egress interface 4. In case the node has no routes installed for the requested prefix, it may send a negative acknowledgment (NACK) back to the requester.

- A *Forwarding Strategy*, which is one of the key components of the NDN stack, deciding when and how to forward packets. It is worth noting that each namespace can have its own forwarding strategy, and each network operator can decide the best strategy for its network.

1.4 Organization and Contributions

The main focus of this dissertation is to enable innovations in the Internet access technology – in the wired and wireless domains – as discussed in the previous subsections. In the remaining chapters, we provide a detailed discussion and present solutions to the research challenges previously described. The remainder of this dissertation is organized as follows:

In Chapter 2 we present the detailed implementation of our economic simulator, simulation scenarios, and results; more specifically we describe a concrete model relating users and providers in an environment with dynamic network services and network infrastructure virtualization. We design a simulation system that yields quantitative results for a given economic scenario, offering insights on how users and providers can benefit from competition in the access market. Finally, we evaluate the concepts of marketplaces to ensure that network services are properly advertised and implemented.

In Chapter 3, we propose, implement, and evaluate an approach to offload cellular base stations using D2D communication and NDN over LTE, whereas in Chapter 4 we propose a cross-layer approach that combines D2D communication and ICN concepts to improve data retrieval from nearby peers in urban scenarios. In Chapter 5 we propose a framework that provides financial incentives for deployment of the necessary infrastructure in dense urban scenarios, as well as rural and low-density areas for collaborative communication.

Chapter 6 summarizes and conclude the work. In addition, we provide a discussion of future research directions.

CHAPTER 2

MARKET COMPETITION IN WIRED INTERNET ACCESS

2.1 Introduction to Economic Interactions on the Internet

In the Internet, many entities interact and establish economic relationships, spanning the entire protocol stack, i.e., from access to light paths in the physical layer to access to video content in the application layer. In [25], Clark et al. have defined these relationships between different stakeholders with conflicting interests as tussles and that the future of the Internet will be increasingly defined by the relationships between these parties. Our work focuses on the relationship between a set of actors, more specifically the relationship between users and network providers and between network providers (inter-domain routing business models). In the latter case, autonomous systems interconnect by advertising External Border Gateway Protocol (EBGP) routes, which are translated from business agreements, e.g., routes are usually configured to send traffic to customer ASes first, then through peer ASes, and finally via provider ASes. These inter-domain relationships are illustrated on Figure 2.1. BGP configurations can be much more complex, but its discussion is beyond the scope of this work.

Newer Internet architectures, such as ChoiceNet [89] and Nebula [16], bring these economic relationships to the architecture design, enabling the instantiation of network services and negotiation of payments. The main idea of ChoiceNet is to provide alternatives to services with different qualities and price, making it explicit for users to choose among them. These services can be composed of multiple parts (traffic traversing multiple networks, for instance), where payments are distributed accordingly to the participating parties.

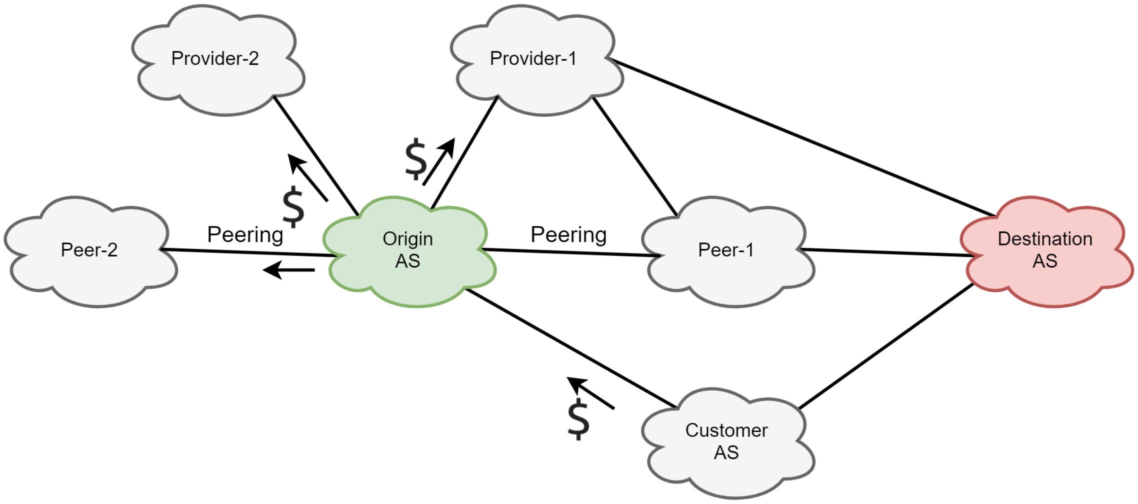

Figure 2.1. Example of an inter-domain routing business model. The Origin AS (green) wants to send traffic to the Destination AS (red). It learns routes to the destination through Provider-1, Peer-1, and Customer AS. Since the Customer AS pays the Origin AS for traffic, the Origin AS most preferred route is through the Customer AS. This route is advertised to Provider-2 and Peer-2. The second preferred route is through Peer-1. This is a settlement-free peering. The least preferred route to reach the destination is via the Provider-1 AS, which receives money from the Origin AS for traffic.

Technological advances facilitated network slicing, which is a virtualization technique where multiple logical networks operate on top of a physical infrastructure. The key benefits of a virtualized provider are that each operator can create and maintain a different set of rules, QoS parameters, and security levels, independently from other tenants on the physical infrastructure. This creates new business opportunities for operators and developers. For instance, one can create a slice in the network to carry traffic related to sensors on a highway, whereas others can create a low latency and high throughput slice to carry augmented reality traffic. In our work, we implemented an agent that resembles an open access network, allowing multiple providers to operate on top of its physical infrastructure. The operation of this entity is described in Subsection 2.5.2.

Using Agent-Based Modeling (ABM), described in Section 2.3, we build an ecosystem where entities interact to buy and sell network services via marketplaces. A brief description of our complete ecosystem is described as follows, and its economic interactions are depicted in Figure 2.2.

- Subscribers (or consumers) are entities that contract network services in order to access the Internet (i.e., consumers *pay* providers for network services). They can also buy multimedia services from content providers. To better reflect users' preferences in our simulations, subscribers select services based on their different choice of price and quality of network services.

- Access providers are organizations that provide last mile Internet access to consumers. They can employ different physical technologies, such as fiber optics, cable modem, DSL, microwave, and satellite, to name a few. Besides Internet access, these providers can offer different services to consumers (e.g.: email hosting, VPN services, media content, etc.). Access providers can also engage in peering with other ASes.

- Transit providers are entities that own network infrastructure, carrying other providers traffic through their network. They can engage in *revenue neutral peering*, whereby providers of the same size exchange traffic at no cost (the assumption is that the incoming and outgoing traffic are roughly equivalent, therefore, there is no need for payments), or a *customer-provider relationship*, whereby the customer AS pays the provider AS for carrying traffic. These cases are depicted in Figure 2.1. Transit providers can own long haul infrastructure spanning a wide geographical area (Tier-1), also referred to as the Internet backbone.

- Marketplace is a new entity in our ecosystem. The marketplace is responsible for mediating transactions between network providers and consumers. The former advertises network services in the marketplace, making them visible to consumers. The latter contracts network services from providers through the marketplace. The marketplace serves as a trust entity between consumers and providers, enforcing the implementation of the contract. In addition, multiple marketplaces may coexist to provide diversity. It is worth noting that marketplaces of this type are already present on the Internet. Perhaps the most prominent case is in the advertising industry, where companies such as Rubicon Project[1] and Google Ad Services[2] query advertising servers for the highest bid to fill the content provider's advertisement space within a certain latency (usually a few milliseconds). The winning bid then gets its advertisement rendered and displayed at the end-user's screen, while the content provider and the mediator get a share of the revenue. Another example is the social media influencer marketplace, where companies can hire the influencer of their choice to promote their product. Other possible applications of our marketplace include cross-reference links to improve a web page's search engine ranking (search engine optimization - SEO) and the exchange of one's marketing preferences to receive personalized advertisements (account-based marketing - ABM).

- Content providers are organizations that handle the distribution of content to end-users via the Internet. News networks, video on-demand (VOD), music, and blogs are among organizations inserted in the content provider class. The most common sources of income are advertisements and subscription services. Content providers play a major role in the Internet, being responsible for more than 70% of Internet traffic. Our work however, is concerned with network access services responsible for carrying this traffic. Therefore, we leave the instantiation of the content provider agent for future work.

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[1] `https://rubiconproject.com/`

[2] `https://ads.google.com/home/`

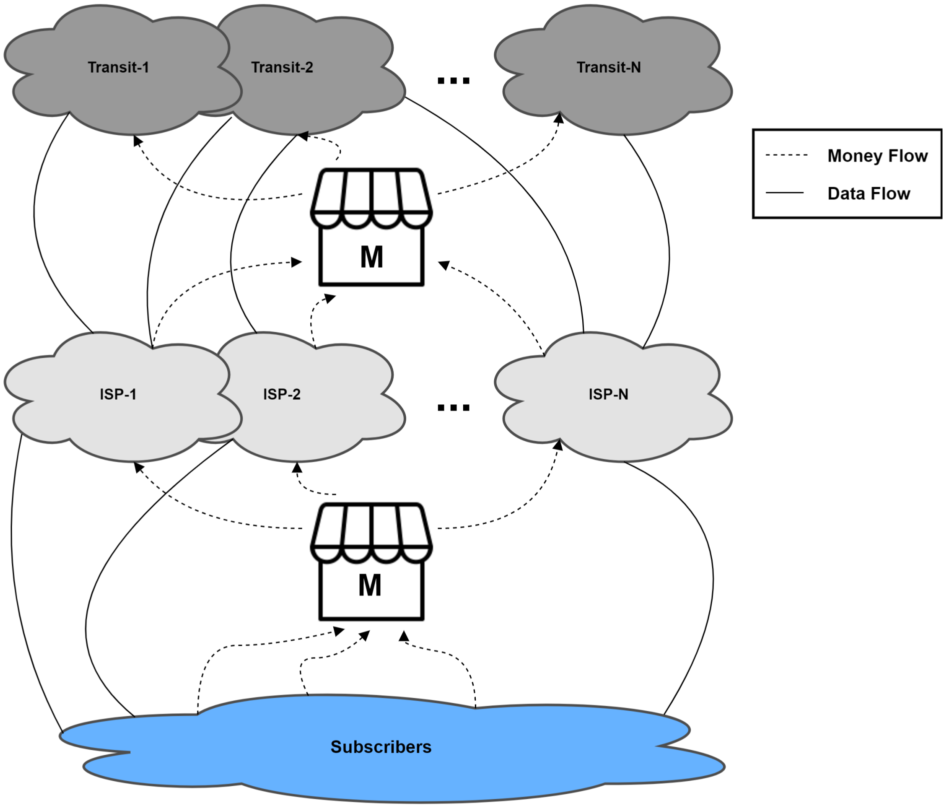

Figure 2.2. Economic interactions between subscribers, access providers, transit providers, and marketplaces. The dotted lines show the flow of money from the users to the marketplace. The marketplace acts as a trusted entity, assuring that the network service is delivered and that the providers get paid. The solid lines show the data flow.

2.2 Background

Previous works have studied pricing network services in the current Internet model. MacKie-Mason and Varian [47] have introduced a two part tariff price model for modeling the relationship between providers and customers. They show that different quality levels create more profits for the providers as they capture specific groups of customers. In addition, scenarios where a provider has a strong market force (e.g. monopoly), the capacity is constrained and prices are increased. Shakkottai and Srikant [72] have examined how services are priced in a network comprised of multiple ISPs. They have shown that multiple ISPs competing in the same market lead to price wars. Also, multiple ISPs can participate in a non-cooperative game, where different ISPs compete in different markets and do not compete for the same customers; however, they are economically linked through a series of other providers, forming a hierarchy. In [71], authors model prices on the Internet related to network congestion and resource access control.

For more complex network scenarios, where providers auto-organize in layer structures, research has been done to understand alternatives to cooperate. In [36], the authors present a cooperative pricing scheme where providers offer joint network services. Providers with less capacity have an incentive to cooperate in the revenue-fair allocation scheme, increasing the profitability of network services. A practical mechanism based on the Shapley value to enable cooperation is presented in [46]. Authors show that providers agree on optimal decisions for the global routing. Valancius et al. [84] studied the bundling of network services and how these new network services are priced based on the cost of the links. Among their findings, the market efficiency can be improved by selling network services with fine-granularity. The economic outcomes of this richer scenario, where multiple providers compete in a networked market with transparent network services have been studied in [49]. Economic models for this environment have proven to be stable by presenting derivations for Nash equilibria [55, 57, 68, 56]. Though, as Valancius et al. suggest, the implementation of these complex scenarios encounters resistance from ISPs.

The technical foundations of an Internet architecture of such fine-grained and dynamic economic relationships have been described in [89]. Wolf et al. describe an architecture where providers compete for customers in a marketplace that enables short timescale contracts for network services. This not only makes fine-grained agreements between end-users and ISP providers plausible but it also forms the foundations to establish cooperation mechanisms between providers.

In [95], Yiakoumis et al. proposed a scheme that uses programmable network elements to customize slices of the network for different applications. Our work introduces the marketplace entity, where consumers can buy network services dynamically. Moreover, we study the economic outcomes of interactions in this scenario.

Our work differs from the previous studies in the sense that we explore the implications of short-term dynamic contracts for the agents involved in different networked scenarios. In addition, we price network services and establish quality parameters that are transparent to the users, via the marketplace. Furthermore, our work considers a virtualized underlying infrastructure that is used by multiple virtual network operators.

2.3 Implementation Details

We developed an Agent-Based Model (ABM), which is capable of analyzing and understanding the behavior of systems with multiple independent interacting agents. ABM allows behavior observation not only when a stable state is reached, but throughout the process, according to [26]. In economics, ABM has been used to model a variety of scenarios ranging from transaction cost economics [42] to electricity markets [64]. The authors in [23] present a survey on different strategies for agent modeling and its roots in contributions from various disciplines. For the specific topic of network economics, [44] study the dynamics of Internet topology formation, while [45] propose a model for understanding best pricing mechanisms in a multi-tier spectrum re-seller market. Our model follows these approaches and applies ABM to network service environments with highly dynamic contracts. In the following subsection, we present the results for the simulator. The remainder of this section describes the behavior of each entity in our simulation. Additionally, we present the implementation details of the simulator and its deployment on a research testbed that resembles a real network environment.

2.3.1 Subscriber Behavior

In order to buy network services, subscribers query the marketplace for available offers. Subscribers scan all available offers, choosing the one that yields the best outcome based on its preferences, contracting one service at a time. Each agent is assigned a uniformly distributed random variable, which is used to determine its preferences in terms of quality of service and the price that an agent is willing to pay for that service (e.g., agents that are assigned a value below 0.5 will prefer low-quality services). In addition, it defines how much that agent is willing to compromise between price and quality, compared to its preference. This random variable is then used to calculate a region of offers in the *quality-price* space that a certain agent is willing to buy. Subscriber agents then calculate the Euclidean distance between their preference and the closest non-dominated offer, based on Equation 2.1, from [49]. The procedure to calculate non-dominated offers is explained in Section 2.3.3.

$$B_{co} = R_c - \sum_{a \in \mathcal{A}} cs_a * \max\left(0, \frac{o_a - c_a}{c_a}\right), \tag{2.1}$$

where R_c is the threshold measuring how much the disutility created by an offer is accepted or not by the agent. $\mathcal{A}$ is the set of attributes a within an offer (i.e. price and quality), and c denotes a subscriber (or consumer). For each attribute a, we calculate the distance between the attribute of an offer o_a and the consumer preference denoted by c_a, weighted by the sensitivity of the users to that attribute cs_a. The term (cs_a) follows a second uniformly distributed random variable, which models the heterogeneity of subscriber to attributes.

Once an offer is selected, the subscriber issues a purchase order to the marketplace. The offer is then calculated as $o^* = \text{argmin}\{B_{co} | o \in \mathcal{O}_{\mathcal{A}}\}$. Since there is no reservation of resources at the time when the subscriber queries the marketplace, it may occur that the selected offer is no longer available. In this case, the second best offer if selected, and so on. The consumer behavior is formalized in Algorithm 1.

2.3.2 Transit and Access Provider Behavior

In the real Internet, one network service may be implemented as an aggregation of services that are transparent to the user. However, this service may traverse multiple ASes. Our model considers the last mile provider and the transit AS, which can be interpreted as an aggregation of paths traversing multiple ASes. Attributes offered to consumers might

Algorithm 1: Consumer Behavior

```
Initialize Consumer agent;
Configure Consumer behavior;
Query Marketplace for available offers;
Sort offers based on weighted distance between offers and desired region
  (Equation 2.1);
Send purchase order to Marketplace;
while true do
    if purchase completed then
        go idle;
        return;
    else
        Choose next best offer;
        Resend purchase order to Marketplace;
    end
end
```

be translated into another service at the transit network. Access providers have to maintain at least two sets of attribute values for the services in the network. In order to coordinate multiple services, an aggregation process is performed via offer's attributes, so that transit and access providers should agree on offers that are viable to the subscriber. We include, as part of our model, the possible mismatch that can occur in these interactions.

In our simulations, we assume that both transit and access providers behave rationally and that their main goal is to maximize profits by selling network services. Providers can create multiple offers in the *quality-price* space, depicted in Figure 2.3, and advertise them in the marketplace. We assume that access providers update their offers taking into account available offers given by transit providers.

To maximize profits, providers (sellers) can switch between a price-oriented and a market-oriented strategy. This orientation can be influenced by the available capacity at the moment or can be randomly chosen for a specific period. Providers oriented on price move their offers towards lower quality or higher prices, while providers oriented on market share will move their offers towards segments of the market where more customers (buyers) are located, information which can be retrieved from the marketplaces. The ef-

Figure 2.3. Price and quality quadrants showing service providers strategies.

fectiveness of the strategy in time is computed by a moving average of the previous (f) updates of each offer.

Each provider has limited capacity and a minimum operational cost, creating a boundary in the *quality-price* space where offers are not profitable. In addition, we limited the ability that an agent has to copy other offers by a random variable called adaptation factor (af). If a provider has the ability to follow other providers' strategy, $af \rightarrow 1$, or if a provider does not have the ability to do so, $af \rightarrow 0$. The provider behavior is formally described in Algorithm 2.

2.3.3 Marketplace

The marketplace is responsible for clearing transactions and payments. It receives offers that are advertised by multiple network providers and are not dominated by another offer, i.e., offers that are strictly better in the quality-price space. In this way, the marketplace pre-selects the offers that fall into a Pareto frontier where offers are valid and are optimal for any subscriber. We call this structure a non-dominated offers Pareto front.

Algorithm 2: Provider Behavior

```
Initialize Provider agent;
Initialize offers;
Send offers to Marketplace;
while True do
    Evaluate current offers' performance;
    if Increase profit then
        if Provider is oriented on price then
            Decrease quality;
        else if Provider is oriented on quality then
            Increase price;
        else if Margin increased then
            Continue;
        else
            Return to previous offer;
        end
    end
    if Increase market share then
        if Current offer is best offer then
            Try to improve best offer;
        else
            Follow best offers;
        end
    end
    Send updated offers to Marketplace;
end
```

Once a transaction is completed, the resources listed on that order are reserved, maintaining the provider's availability in real time. Offers with higher quality consume more resources than those with lower quality, i.e., by increasing the offer's quality, the provider will have to reserve more resources. In order to model this relationship, we assume different functional forms including linear, quadratic, and logarithmic.

The marketplace ensures that the service is properly delivered to the other end, releasing payments to the participating actors. The marketplace behavior is described by Algorithm 3.

Algorithm 3: Markeplace Behavior

```
Start Marketplace agent;
Start bidding period;
while Bidding period do
    Receive Provider bids;
    Receive queries from consumers;
    Reply to consumer queries;
    Receive consumer bids;
    if Provider resources > bid quantity then
        Execute order;
    else
        Deny order;
    end
end
```

2.3.4 Implementation on the GENI Testbed

The Global Environment for Network Innovations (GENI) [21] is a federated research testbed that provides a virtual laboratory for educational and research institutions by allowing researchers to reserve physical computing resources across the United States, as well as other federated testbeds such as Cloudlab [67] and Fed4Fire.[3]

Figure 2.4 shows the topology of our ABM simulator implemented on the GENI research testbed. All nodes are connected through shared physical links. Each node in that topology implements one or more instances of an agent, e.g. the provider nodes implement multiple network providers that will communicate with the marketplaces. The communication between agents is done via sockets. Concurrency in these agents is implemented using the reactor pattern [70], which is highly scalable when transactions are short, as it is in our case. Messages exchanged between agents are composed of a message header that establishes the type of transaction being requested and an XML body. Network providers and consumers agents are implemented in Python while the marketplace and the simulation engine are implemented in C++. The backend is implemented on Django with a SQL

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[3] `https://www.fed4fire.eu/`

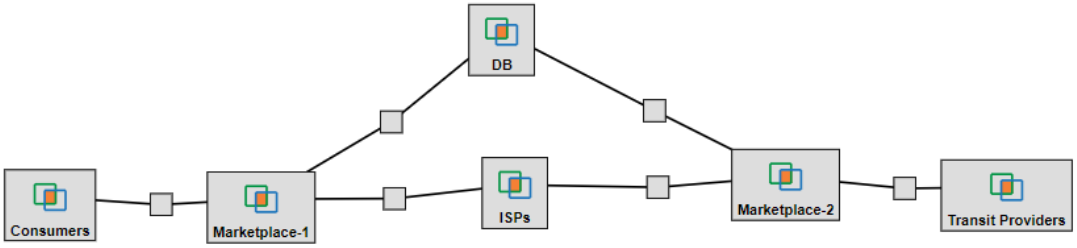

Figure 2.4. Implementation of agents on GENI testbed. Each GENI node can implement multiple instances of the agents.

database. The database node stores transactions, offers, bids, and all other information regarding the simulation operation.

The simulation engine (co-located with the database node in Figure 2.4) controls processing intervals and activates consumers. The simulation engine sends to providers and the marketplace a broadcast message in order to initiate a new exchange session. Then, it reads the aggregated demand for the period and converts it to a consumer level, which includes not only the number of consumers to activate but also the expected quantity to consume. Information is used to send an activation message to idle consumers. At the end of the exchange session, the simulation engine broadcasts an end period message to all agents. Finally, when the specified number of session periods is reached, the simulation engine transmits a terminate message, which ends the agents processing.[4]

2.4 Simulator Results

We evaluated our simulator on the following three competition scenarios:

A *Monopoly* scenario where one ISP alone sells network services to subscribers. Figure 2.5 shows the evolution of price, quality, and profits over time for the monopolistic provider. Each data point in the *Price* and *Quality* plots correspond to an offer that was

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[4] An open-source implementation of the agents can be found at `https://github.com/lmarent/EconomicSimulator`

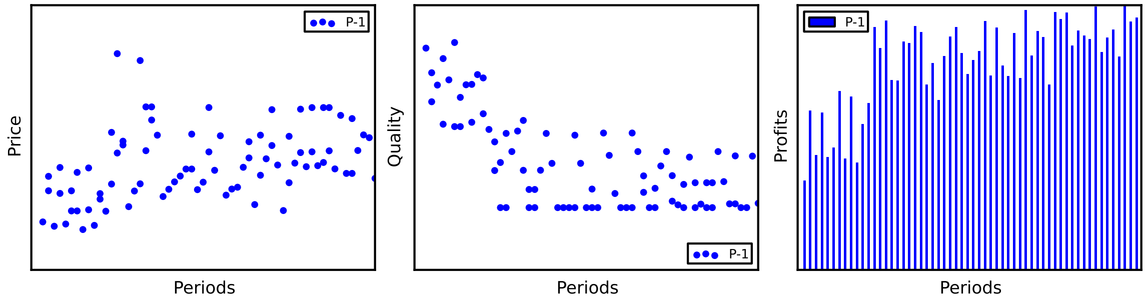

Figure 2.5. Price, quality, and profit evolution in monopoly. In this scenario, one monopolist network provider with more capacity than demand.

satisfied by the provider (seller). The *Profits* are the aggregated profits of all the offers in a bidding round. The units in the graphs are intentionally not shown since the price and quality metrics are hypothetical and we can draw conclusions based on their relative value.

As can be seen, sellers adapt their strategy over time to maximize profits. Because monopoly firms are price makers, the ISP increases prices over time, while reducing the overall quality of each offer. The provider follows this strategy until the marginal revenue equals the marginal cost. Additionally, the provider creates offers in different areas of the price x quality plane to obtain market knowledge, which is used to determine the limits of price and quality where consumers continue to purchase. It is worth noting that consumers do not benefit in a monopolistic scenario, as they pay higher prices over time.

The second scenario is the case where two ISPs operate in the access market (duopoly). In this case, providers can compete or can collude. We observe that collusion behavior is directly related to the total capacity available to providers. Figure 2.6 shows the simulation results when the capacity exceeds the customer demand. We can observe that when a provider reaches a given threshold, the offer adaptation process becomes more oriented on maximizing profits, as opposed to increasing market share. This behavior is unchanged whether testing with providers in different strategies or adaptation factors. Figure 2.6 shows a typical offer evolution pattern.

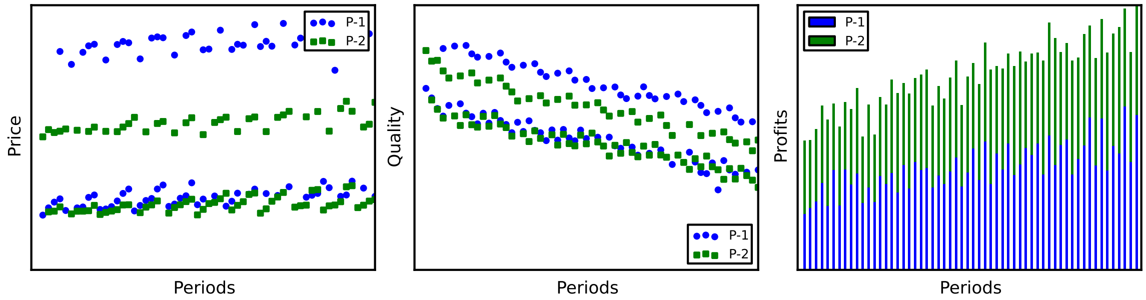

Figure 2.6. Price, quality, and profit evolution in duopoly. In this scenario, two network providers with summed total capacity 120% more than demand, low adaptability, and quality orientation. 70% of consumers desire high quality, 20% medium quality, and 10% low quality.

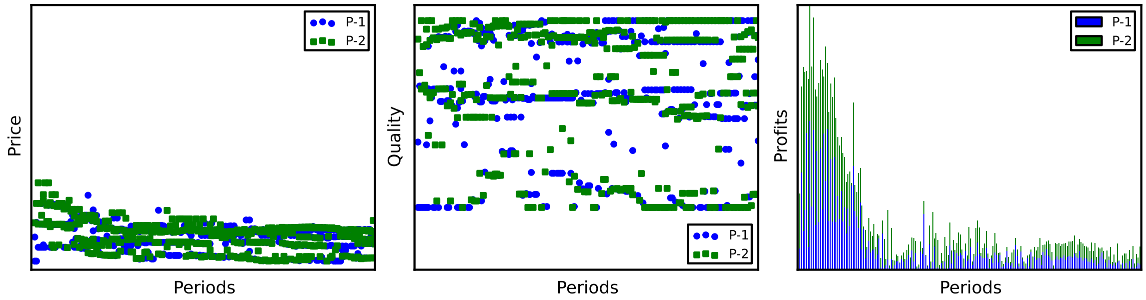

Figure 2.7. Price, quality, and profit evolution in duopoly. In this scenario, providers P-1 and P-2 try to capture market share and have a combined capacity of 120% more than the demand. 70% of consumers desire high quality, 20% medium quality, and 10% low quality.

Figure 2.7 depicts the simulation results when ISPs do not collude, i.e., network agents engage in a non-cooperative game. In this case, providers try to adapt to consumers by offering services that are as close as possible to their expectations. Competition in this case drives prices down (race to the bottom effect). Consequently, profits decrease as well, where quality parameters are adapted to consumer desires. This result is aligned with results in [55]. These outcomes illustrate that in steady state, providers develop equivalent offers, in cost terms, with different values of quality and price targeting different market segments.

Table 2.1. Simulation scenarios

	Scenario		
Type	**Monopoly**	**Oligopoly**	**Open Access**
Subscribers	many	many	many
Access providers	one	few	many
Transit providers	few	few	one

2.5 Extended Simulation Scenarios

The results of Section 2.4 indicate that competition benefits consumers, increasing quality of services and reducing prices. In contrast, competition can lead to race to the bottom effects that do not benefit the providers, therefore, providers will not be willing to move to that model without proper incentives.

The authors in [98] have evaluated numerically the economic outcomes of mobile virtual network operators (MVNO) along with Open WiFi (e.g. Google Project Fi). They found that cross-carrier MVNO increases competition in the mobile market and creates a complex set of interactions among the participating entities. Moreover, the MVNO operator can profit while users are able to save money on their subscriptions. Our work evaluates the outcomes of similar scenarios in the wired domain, evaluating the results via simulations.

In order to assess whether switching to an open access infrastructure model provides the necessary incentives for operators (to expand or upgrade their networks) and consumers (to enjoy better services), we evaluate the two most common models today, along with the open access infrastructure. Table 2.1 presents these simulation scenarios. In Section 2.7 we present and evaluate the simulation results.

2.5.1 All Private Networks

This model evolved from the telephone companies. It is the status quo, where private networks own the infrastructure and sell network services to subscribers, with the majority of users having access to only one provider. This model is referred to as vertical business model [31] (one provider owns the infrastructure, operates, and sells network services).

In other cases, two or more providers compete, but there are not enough economic incentives for them to innovate [49]. New providers face a high initial cost to enter the market by building new infrastructure. Incumbent network providers can temporarily lower their prices to prevent customers from switching to the new provider. Smaller providers often do not survive the competition as they do not have the economies of scale of large networks unless the smaller provider offers an innovative service that attracts a niche. Moreover, when new players enter the market by offering new network services, either by deploying fiber infrastructure from scratch or making use of wireless links, the outcome is that established providers adapt to the new terms to retain their customer base.

2.5.1.1 Case I: Monopolistic Multihomed ISP

In this scenario, consumers have only one choice of ISP. This is the second most common case in the US, according to the FCC statistics [1]. Since providers have no competition in the last mile, the expected outcome of this scenario is for the provider to offer average to low-quality services at a higher price, resulting in higher profits. The ISPs however, can have multiple points of presence (PoP) with different transit providers or participate in an Internet Exchange Point (IXP). ISPs therefore, can forward their traffic via multiple providers. Competition in the transit market tends to drive prices down, thus, we expect transit providers will have lower profits.

2.5.1.2 Case II: Oligopolistic Multihomed ISPs

This is the most common scenario in the US. Consumers have multiple choices to contract network services; however, contract granularity is usually on an annual basis with cancellation fees or installation fees for switching between providers. Our assumption is that competition in the last mile will drive prices down, as providers seek to capture a larger share of the market by lowering prices. Each ISP can also participate in multiple PoP or IXP, thus, the scenario in the transit market remains unchanged.

2.5.2 Case III: Open Access Networks with Virtual Network Operators

Slicing the physical network opens opportunities for multiple providers to offer network services to subscribers under the same physical infrastructure. Figure 2.8 depicts this scenario. Open access networks are proliferating across the United States[5], but some states still have laws that prevent their implementation.

Our assumption is that this scenario creates competition with network providers focusing on services with reduced operational costs, therefore, providers will have more incentive to innovate (e.g.: providing services with guaranteed latency, caching services, and video delivery, to name a few). At a recent poll[6], 56% of respondents support a publicly owned Internet.

In our simulation model, we are interested in the ISP competition and its outcomes. Hence, we model the virtual network operator as pursuing social welfare, resembling a municipal broadband provider. Once the virtual network is implemented, consumers have the option to sign up with the ISP that best fits their needs, switching providers at any time (i.e., consumers will be able to seemingly choose network services in the marketplace)

As a result of our simulation, we expect that competition in the access market is beneficial for subscribers, as providers may seek a lower price and may try to distinguish themselves from the competition by offering better services. This scenario does not discriminate smaller providers that can enter the market by offering innovations to consumers.

2.6 Implementation Details

To evaluate these scenarios, we developed a new simulator in Python that implements each agent as follows:

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[5] `https://muninetworks.org/communitymap`

[6] `https://tabsoft.co/2DC1ATZ`

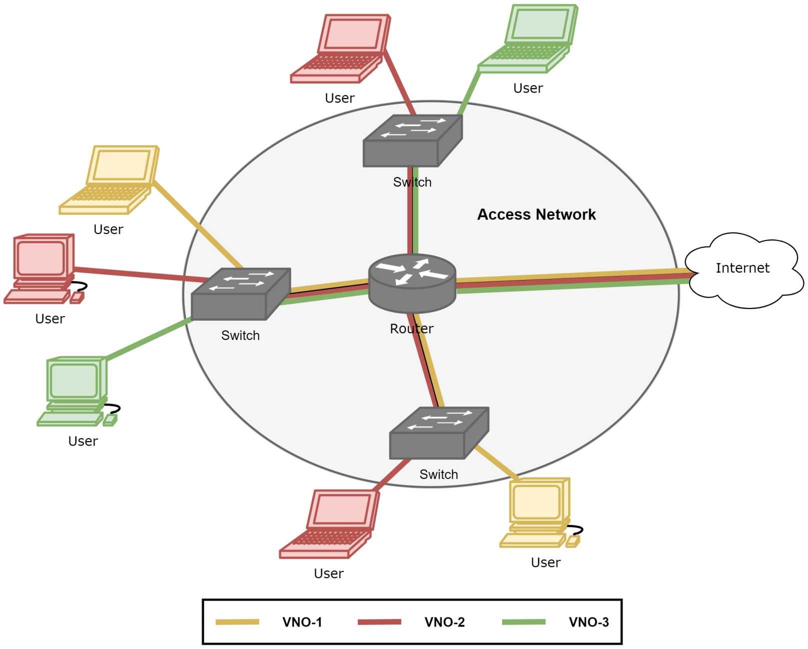

Figure 2.8. A sample scenario of an open access network with virtual network operators (VNO). Each VNO uses the same physical infrastructure to serve different subscribers.

- **Offers –** Offers are composed of a capacity, price, and quality parameters, as well as an offer id, e.g. *[1, 0.47, 0.33, '5c8e97b8']*. For an offer to be profitable, the price has to be greater or equal than the quality parameter, creating an frontier where offers are constrained. All ISP offers have a capacity of one and can only be bought once per round; however, ISP buy offers from transit providers with a higher capacity and split those offers into multiple ones.

- **Consumer Preferences –** At the beginning of each simulation, consumers are assigned a price and quality preferences that remain fixed throughout the simulation. These preferences are randomly assigned following a uniform random variable. Consumers will only buy offers that are equal or better than their preference and will distinguish the best offer to buy by calculating the Euclidean distance between their preference and the provider's offer, buying the offer with the highest distance that satisfy their preference, thus, maximizing their utility function.

- **Firms Preferences –** Firms randomly create offers at the beginning of each simulation. Based on the result of the previous round, providers can choose to improve profits by incrementally putting their offers closer to the consumers (consumer preferences are not known to providers) or improve quality if an offer was not sold.

  Non-profit providers create offers at the frontier and can only move the offers along the curve, i.e., price is equal to quality.

- **Marketplace –** Agents send their preferences and offers to the marketplace that compiles and orders them by distance between consumer preference and provider offer. The marketplace will clear offers with highest Euclidean distance first, maximizing the consumer utility. At the end of each bidding round the marketplace will broadcast all offers that were sold by all providers to all providers. This way, the providers are aware of the competition and have some information of the market, but do not know the whole market (e.g., where consumers are located).

2.7 Simulation Results and Evaluation

This section presents the simulation results for the three aforementioned scenarios. We present additional simulation results in Appendix A. There are 100 consumers in each scenario that buy services from up to ten ISPs. The ISP on the other hand, buys transit services in the marketplace. Table 2.2 presents a sample list of connection types and requirements that can be translated to multiple price and quality parameters.

We report the results as the mean and 95% confidence interval of the offers price, quality, and providers profits. Also, for each scenario, we present the percentage of customers that were satisfied and the average customer satisfaction. Customer satisfaction is measured as the distance from the consumer preference to the offer that it buys. For instance, if an offer is exactly at the consumer preference, the customer satisfaction metric will be

Table 2.2. Examples of connection types and their requirements.

Type	Latency	Price	Description
Timely	High	Low	Static web browsing File transfer (e.g. FTP, still image) Messaging E-mail
Responsive	Medium	Medium	Dynamic web browsing Low-quality video streaming Audio streaming
Interactive	Low	High	High definition video streaming Conversational voice Video conferencing Gaming

zero. If the consumer buys a better offer than its preference (lower price, higher quality, or both), the customer satisfaction metric will be positive.

2.7.1 Case I - Monopoly

Figures 2.9 and 2.10 show the price, quality, and profit evolution for three transit and one ISP providers, respectively. As can be seen, competition in the transit market drives profits down as providers compete for one customer. On the access market, the ISP provider operating as a monopoly increases prices while reducing quality. As a result, profits increase. The higher level of profits compared to other scenarios is due to the fact that the provider is acting alone in the market, capturing all the market share and the offers are more profitable. It is worthwhile to note that this scenario does not benefit the consumers, who pay a higher price for worse network services. Figure 2.11 shows the market share of consumers that buy network services and their satisfaction. Because of the higher prices and lower quality, only 21.5% of consumers are satisfied and buy network services with customer satisfaction decreasing.

2.7.2 Case II - Competition

Figures 2.12 and 2.13 show the price, quality, and profit evolution for the transit and ISP providers, respectively, when there is competition in both markets. In this case, there are three transit and ten ISP providers. As can be seen, competition among providers quickly

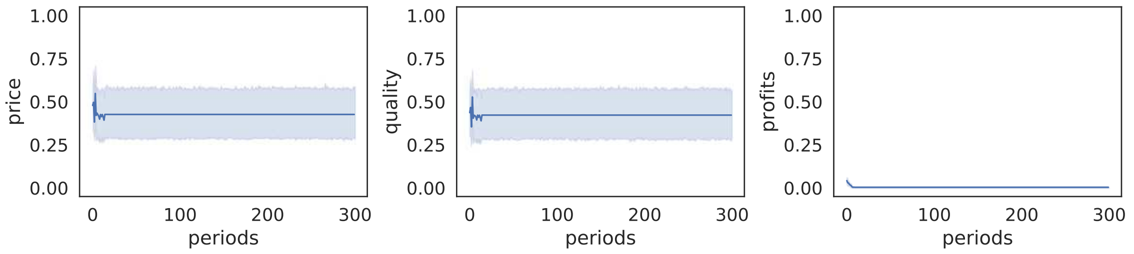

Figure 2.9. Mean and 95% confidence interval of price, quality, and profits for the transit provider.

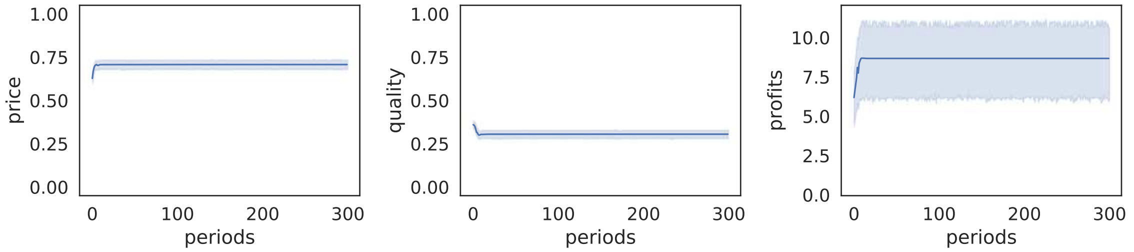

Figure 2.10. Mean and 95% confidence interval of price, quality, and profits for the ISP provider operating as a monopoly.

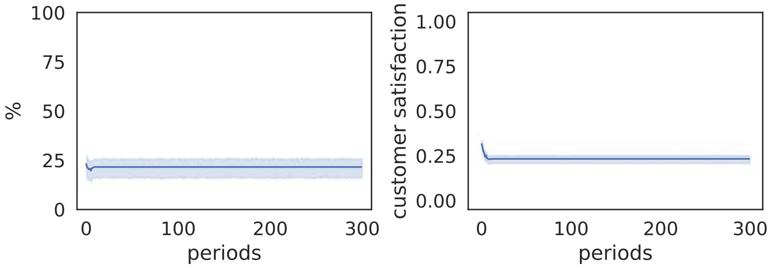

Figure 2.11. Mean and 95% confidence interval of share of customers served by the ISP provider and customer satisfaction.

drives profits down; however, in the ISP market (Figure 2.13) quality increases more than price, as providers try to capture more market share by moving their offers closer to the frontier. As a result, more consumers buy network services. Figure 2.14 shows this effect, with more than 62% of consumers buying network services and higher overall satisfaction. As mentioned previously, providers profit less than if they were operating as a monopoly. Therefore, their preferred mode of operation is a monopoly, despite competition benefiting consumers the most.

2.7.3 Case III - Open Access Network

One way to achieve competition in the access market is to deploy an open access provider. In our case, this provider is non profit-oriented, resembling an municipal broadband network. Figure 2.15 show this type of provider in our simulation. Since offers only move along the *price x quality* frontier, any changes in one parameter reflects on the other. Figure 2.16 shows the competition in the access market between ten ISP providers. Similarly to the Case II, competition in the access market quickly drives profits down while improving quality. Because the open access provider is non-profit oriented, more consumers are able to buy network services (64.7% versus 62.5% in the competition scenario). The market share and customer satisfaction are depicted in Figure 2.17.

2.8 Concluding Remarks

This chapter explores the economic relationships of transit, ISP providers, and customers in current Internet models using a custom developed simulator. In addition, we incorporate novel Internet architectures capable of implementing dynamic fine-grained contracts. More specifically, we deploy a marketplace of network services, whereby providers (ISP and transit) and consumers interact by buying and selling network services. We implement our simulator in the GENI research testbed, a research network that resembles the real Internet (the communication between GENI racks at different locations is done via Inter-

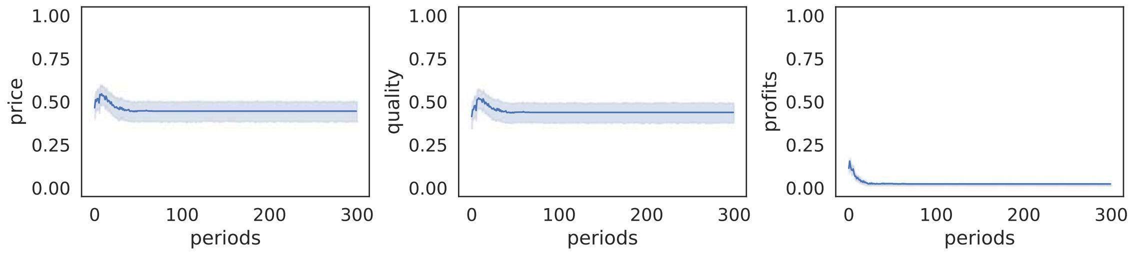

Figure 2.12. Mean and 95% confidence interval of price, quality, and profits for the transit provider.

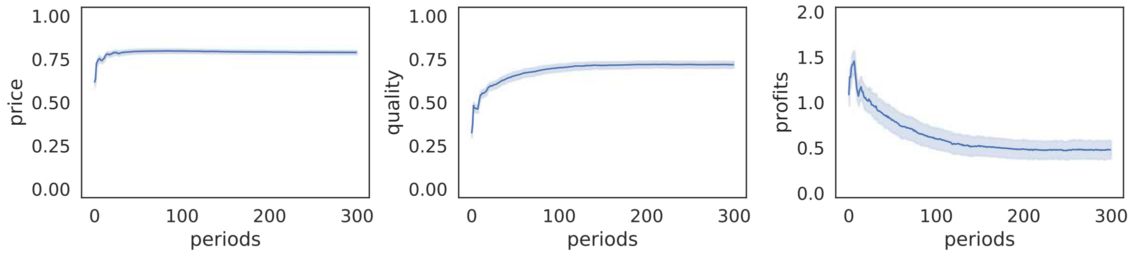

Figure 2.13. Mean and 95% confidence interval of price, quality, and profits for the ISP providers.

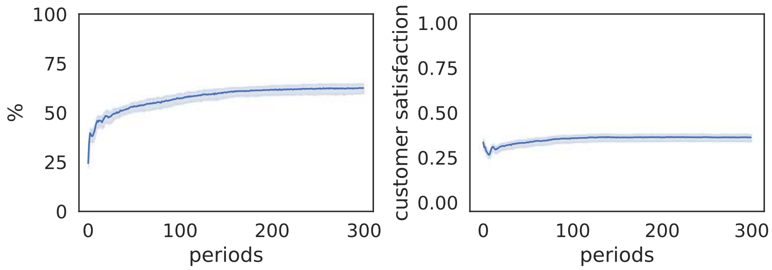

Figure 2.14. Mean and 95% confidence interval of share of customers served by the ISP provider and customer satisfaction.

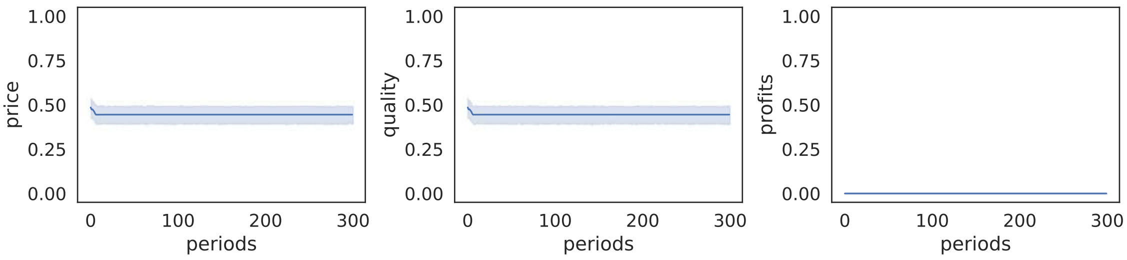

Figure 2.15. Mean and 95% confidence interval of price, quality, and profits for the provider operating as an open-access.

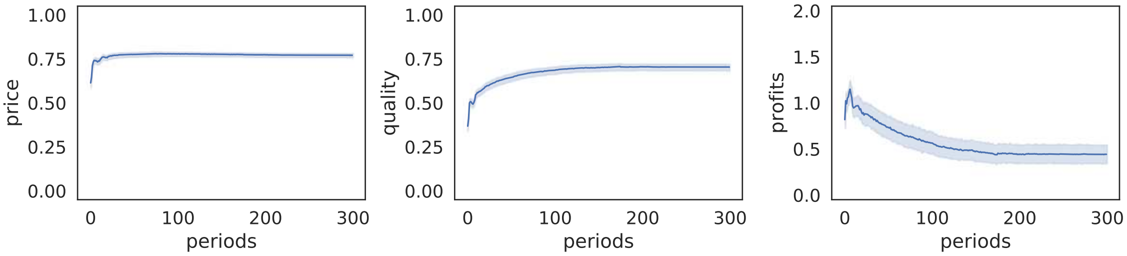

Figure 2.16. Mean and 95% confidence interval of price, quality, and profits for the ISP providers.

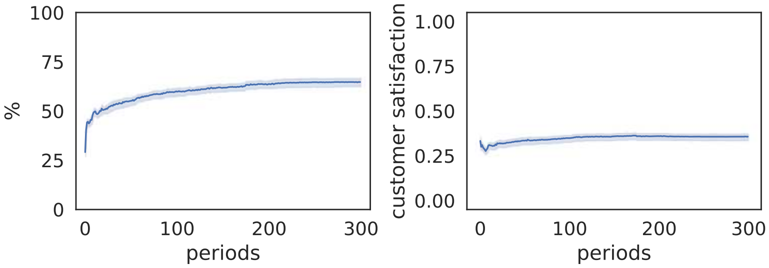

Figure 2.17. Mean and 95% confidence interval of share of customers served by the ISP provider and customer satisfaction.

net2). Using this setup, we evaluated different competition scenarios in the access market, identifying that competition is beneficial for the customers if the ISP providers do not collude. Also, related work shows that providers are not willing to switch to a competitive model without incentives, as it would reduce their profits.

In the second part of this chapter, we developed another simulator that instantiates an open-access network provider that leases shares of its infrastructure to multiple providers. With our new simulator, we evaluate the two most common business models in the US, as well as the emerging open-access provider with multiple virtual network operators to increase competition in the last mile. Our simulation results show that the ISP providers operating as a monopoly raises prices and reduces the quality of services, resulting in fewer customers joining the market (21% of consumers buy network services). Nonetheless, the provider thrives in this market model. When there is competition, providers try to capture market share by offering better services, resulting in more consumers joining the market (62% of consumers buy network services). The providers however, achieve a lower profit level than the monopolistic market, thus, providers will prefer to operate as monopolies if they can and will have no incentives to participate in or foster competition. In fact, providers lobby the FCC against collecting pricing data,[7] obfuscating information from the public. To address the competition issue, we evaluated open-access networks with a non-profit provider (or a community-owned network provider). Our simulation results showed that we can achieve a higher level of participation of customers in the market by having better services.

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[7] `https://bit.ly/2i9SoO3`

2.9 Network Neutrality

Internet service providers generally charge their customers a fixed amount of money for a monthly subscription in exchange for unlimited access to the Internet through their networks. They act as mere traffic carriers.

With the increasing popularity of video streaming services, network providers saw the traffic in their network expand dramatically. Video streaming (sometimes referred to as elephant flow) represents almost 60% of the downstream volume of traffic on the Internet [69]. In response, ISPs started to apply data caps to downstream traffic, i.e., once customers exceed their data cap, ISPs would lower their data rate. Additionally, ISPs also started to charge content providers, such as Netflix, in exchange for not having their traffic throttled, which would result in a bad user experience for the content providers' customers.

This situation sparked a discussion about the power of network providers over their networks and their ability to discriminate traffic. In 2015, the Federal Communications Commission (FCC) voted to regulate that all traffic should be treated equally (or neutral) [4], by reclassifying Internet access in the same category of telephone services, the so called Title II telecommunication services of the 1934 Communications Act. This ruling meant that network providers could no longer slow down (*no throttling*) or block traffic (*no blocking*). Moreover, network providers could no longer charge content providers for prioritizing their traffic, delivering to their customers faster (*no paid prioritization*). This ruling incurred loss of revenue for network providers that argued against the ruling.

In 2018, under a new administration, the FCC revoked the previous network neutrality ruling, allowing network providers to discriminate traffic among applications and services.

In our proposed work, customers can evaluate a set a network services that are advertised in the marketplaces using price and quality parameters, including latency, jitter, and bandwidth. These parameters would fall under the category of discriminatory services. Based on customers' preferences for quality and price, they can then choose the services from a set of providers that best fit their needs.

In fact, [94], Yiannis et al. have shown that users prefer their applications to receive this differentiated treatment, and their preferences are heavy-tailed. For instance, some users prefer their favorite social network application traffic to receive preferential treatment over a background application. The authors implemented a mechanism that uses network cookies to give priority to certain applications in the local network. Open access networks create more opportunities for different actors to offer innovative services over the same physical infrastructure.

2.10 Future Research Directions

Interconnection and settlements between ASes on the Internet, discussed in this chapter, are complex and the implementation of these contracts can take several days to weeks. In addition, the protocol for inter-domain routing (BGP) is subject to a variety of misconfigurations and stability problems, which can lead to route oscillations [85]. Among the most common interconnection points are the Internet Exchange Points (IXPs), connecting dozens to hundreds of ISPs, transit, content providers, and other private networks (university, business, etc.). Having a way to implement contracts on demand is crucial to the implementation of our proposed scheme of open-access networks with novel Internet architecture.

With the advent of software-defined networks (SDN), that implement the control plane in software and decouple it from the data plane, some of the shortcomings in the IXP can be circumvented. By implementing an SDN-enabled switch at the IXP, network operators can have direct control over their egress and ingress traffic via a set of match/actions on packet headers. This concept was described by Gupta et al. [35].

A Software-Defined Internet Exchange Point (SDX) [35] allows the implementation of other entities in the IXP ecosystem, such as a marketplace for interdomain routes where network operators can instantiate settlements and enforce rules on a per-flow granularity.

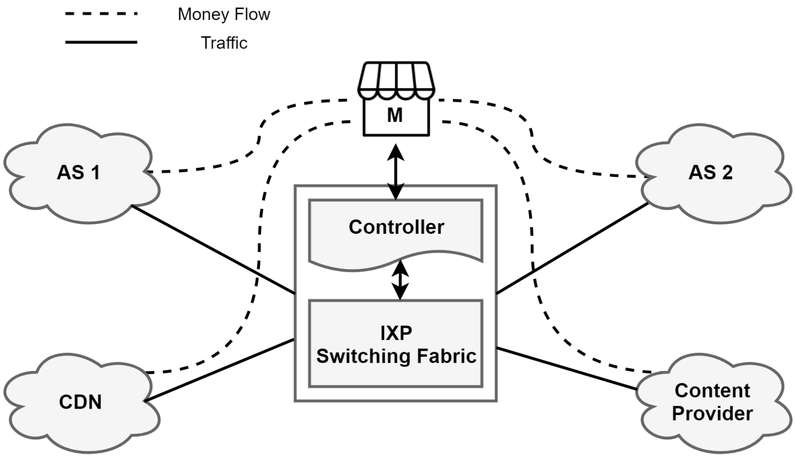

Figure 2.18. Software-defined exchange point with a marketplace for inter-domain routing where different entities can dynamically buy and sell network services.

The SDX that facilitates the establishment of dynamic contracts was described in [34], where Griffioen et al. devised a Coin-Operated SDX prototype, and more recently in [90].

A future research direction is to adapt our simulation model to incorporate content providers and IXP agents into a marketplace that implements dynamic routes using SDX [50]. This extension is depicted in Figure 2.18, where we have autonomous systems, representing transit and ISP providers connecting to customers, CDN agents that can deploy caching services along with the IXP, and content providers, that want their traffic traversing the fewest possible ASes before arriving at the destination. This scenario simplifies the relationship between these entities while facilitating the implementation of forwarding rules.

CHAPTER 3

OFFLOADING NEXT GENERATION CELLULAR BASE STATIONS VIA AN INFORMATION-CENTRIC MOBILE CLOUD

The current connection-oriented model used in the Internet is inefficient when multiple users, located at a short geographical distance, are downloading the same content. In this case, the content (e.g., a popular video) is likely to traverse the same path and likely to be served from the same router. A common solution used by content providers to reduce latency and cost is to use an overlay network, placing content closer to end-users, usually at the network edge or at an IXP.

In cellular networks, the traffic goes through the Radio Access Network (RAN) until it reaches a cached copy of the content (in the upstream case) or the destination user equipment (UE), in the downstream case. In LTE for example, traffic is unicast from the UE to the base station and to the Evolved Packet Core (EPC) via a GPSR tunnel (GTP – GPSR Tunneling Protocol), which adds an extra communication overhead. Additionally, IPSec is often used for security, especially if the traffic goes through a third-party backhaul provider. IPSec combined with tunneling can add a communication overhead of up to 23% [74]. This overhead, along with the increasing demand for traffic can be challenging to the cellular network operator, where it may result in overloaded base stations and blockages for users if not managed properly.

Due to the broadcast nature of the wireless channel and the shared media, our goal in the next two chapters is to increase the probability that a node can retrieve the desired content from the nearby peers, while reducing the utilization of the cellular infrastructure. In this chapter (Ch. 3), we propose a scheme that tries to download content from nearby peers prior to sending the request to the cellular network. In Chapter 4 we augment our scheme to consider information about the wireless channel, geographical location of the nodes, as well as the energy level to improve the communication.

3.1 Introduction

The ubiquitous presence of smartphones and mobile devices brought convenience and entertainment to users' hands, enabling access to services such as video on demand (VOD), online banking, and social media virtually anywhere. As these applications continue to evolve, they require more bandwidth (e.g. video streaming with higher quality, higher definition photos and videos in social networks, virtual and augmented reality videos, and 360° streaming to name a few), stressing the already congested cellular networks. Moreover, in the future, cellular networks are expected to see a wider deployment of Internet of Things (IoT) and other connected devices. In fact, the Cisco VNI report forecasts that there will be more than 27 billion networked devices by 2021[1] with most of the IP traffic being video. Smartphone technology and wireless networks also play a key role in emergency and disaster scenarios, where first responders need to communicate among themselves, command posts, and the public to perform emergency management tasks (e.g., to perform triage in the case of many significant injuries). With the current infrastructure reaching its capacity limits in dense urban scenarios, it is fundamental that communication in the case of an emergency can be performed in a timely and reliable manner.

The evolution of Radio Access Networks (RAN) is mostly focused on increasing capacity and reducing cost for network operators. For instance, the Third Generation Partnership Project (3GPP), the body responsible for cellular network standards, adopted carrier aggregation and multiple input multiple output (MIMO) technologies in the LTE and LTE-Advanced standards [6, 7] that specifies data rates on the order of 3 Gbps. The higher

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[1] According to the Cisco Visual Networking Index (VNI): `https://www.cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/index.html`

uplink and downlink speeds enabled the evolution of mobile applications, but at the cost of a smaller cell size to increase throughput. To help visualize this phenomena, we provide a short explanation of frequency allocation/reuse and cell size in cellular networks in subsection 3.2.1. This increase in capacity aims at supporting the rapid increase in demand from the user-side; however, the rate at which mobile devices and traffic are growing outpaces the growth of the capacity of cellular networks. According to the Cisco VNI report, global mobile traffic expanded 18-fold from 2011 to 2016, and it's expected to grow another 7-fold until 2021. Consequently, mobile network operators (MNO) have been deploying more base stations and femtocells to accommodate this increase in traffic, an approach that increases complexity, cost, and management for the MNO. In an attempt to alleviate the infrastructure, the 3GPP formalized in releases 13 and 14 the LTE Licensed Assisted Access (LTE-U/LAA/eLAA), that allows the coexistence of LTE in unlicensed 5 GHz ISM-bands to expand the capacity of current networks.

We believe that Device-to-Device (D2D) communication has the potential to address the challenge in providing extra capacity to the edge of the network, while reducing capacity requirements at the core. Additionally, by deploying fewer antennas we reduce the exposure to radiation in urban areas [79]. However, a reliable communication is challenging as nodes can enter and exit the communication range at any time, breaking end-to-end paths and altering routing state. Additionally, in larger ad hoc networks, nodes are subject to hidden terminal problems.

In this chapter, we present a scheme that combines Information-Centric Networking (ICN) with D2D communication to offload traffic from cellular networks. In ICN, data is immutable and decoupled from its location, enabling a node to fetch content from any other node in the network that has a cached copy of the requested data. In-network caching is supported as part of the architecture. Furthermore, ICN supports multipath communication and prevents loops. These characteristics make ICN more tolerant to delay and disruptions than host-centric architectures. The work presented in this chapter is based on Named-Data Networking (NDN) [96], one of the many flavors of ICN.

We assume that mobile nodes have at least two wireless interfaces (e.g. Wi-Fi and cellular) which is a common case on modern smartphones. Therefore, when a node sends out a request to fetch data, we first query nearby devices for a cached copy. If the request times out, we retransmit to the cellular network. We simulate our scenarios using NS-3 and ndnSIM [52] simulators.

The specific contributions of this chapter are the following: first, we propose a scheme that utilizes D2D communication and ICN to offload increasingly congested base stations, also facilitating the communication between peers when the infrastructure is impaired. Additionally, our scheme considers energy saving measures and reduces content flooding in the MANET by suppressing the propagation of requests when the energy on the node falls under a threshold. Our solution successfully offloads traffic from the base station, consequently reducing cost and complexity for the MNO.

3.2 Background

3.2.1 How Channel Allocation Works

Frequency spectrum is a scarce and expensive resource. For instance, in an auction in 2015 the Federal Communications Commission (FCC) collected more than $40 billion from cellular operators for the rights to use the frequency bands in certain geographical areas in the US.[2] These frequency bands are further segmented into smaller channels and allocated to cells. To better utilize space and manage interference, cells are organized in a hexagonal shape (honeycomb layout) and allocated to non-contiguous frequencies to avoid interference between cells. The choice of hexagonal shape, which closely approximates a circle, is ideal for macrocells. Figure 3.1 shows the frequency reuse pattern for $N = 7$,

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[2] Available at FCC AWS-3 Auction - Auction ID: 97.

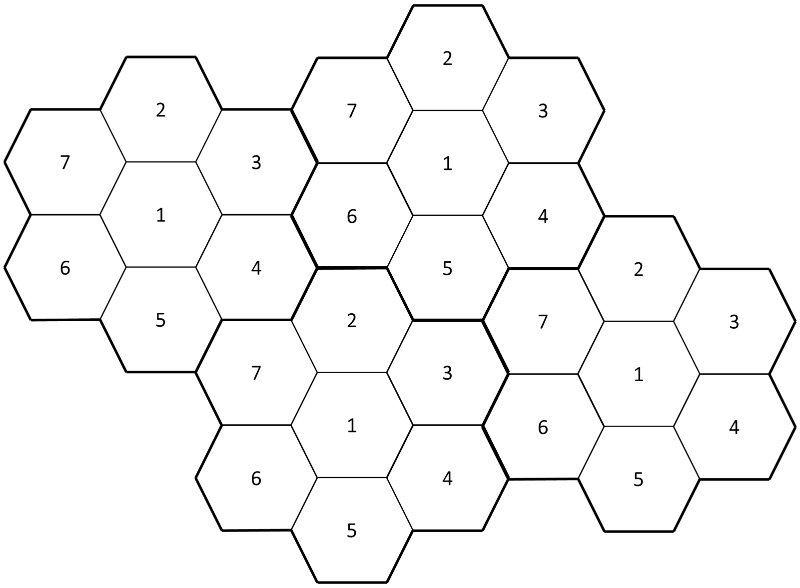

Figure 3.1. Frequency reuse factor N = 7 and clusters (shown in bold).

where N is the number of cells in a repetitious pattern (each cell uses a unique set of frequency bands). The reuse pattern is defined by Equation 3.1.

$$\frac{D}{R} = \sqrt{3N}, \tag{3.1}$$

where D is the minimum distance between two centers that use the same frequency, and R is the radius of the cell. Additionally, N can be calculated by Equation 3.2.

$$N = I^2 + J^2 + (I \times J), \tag{3.2}$$

where i and j are two integers representing the arm length between two cells with the same frequency. Figure 3.2 illustrates this approach. Therefore, possible values of N are 1, 3, 4, 5, 7, 9, 12, and so on. As more users join the system, the available frequency bands might not be sufficient to accommodate all users at a certain cell, building up congestion. There are a number of approaches to address this issue, from reducing the cell size to cell-sectoring to the use of femtocells (which departs from installing antennas on top of

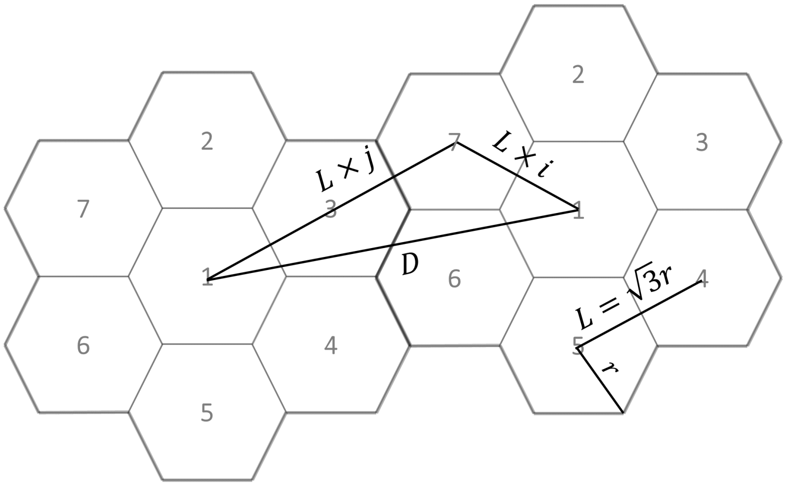

Figure 3.2. Illustration of the arm lengths i and j, as well as r and L.

buildings to place them inside buildings). For instance, a system with 32 cells of radius $r = 1.6km$ (13.9 km × 17.6 km, or 213 km^2) with reuse pattern of 7 can handle up to 1536 channels. By reducing the cell radius to $r = 0.8km$ we can increase the system capacity to handle up to 6144 channels [81]. Besides increasing the system complexity, in dense urban scenarios this number of channels is susceptible to blockages as the number of users connecting to the network simultaneously can exceed the capacity.

3.2.2 The Need for a New Model

Increasing the capacity of the cellular network by shrinking the base station coverage leads to the deployment of more base stations and more handoffs between cells, increasing management and complexity for the network operator. Additionally, this approach can be costly. Due to this limitation, the 3GPP and the research community started to look at D2D communication as an option to offload base stations. In IP, the most common protocols used for D2D communication are Wi-Fi Direct [5] and Bluetooth [3], which operate on unlicensed bands (ISM bands) and are available on a variety of devices. More recently, the 3GPP formalized the operation of LTE in 5 GHz unlicensed ISM-bands.

We propose a combined strategy to offload cellular networks via D2D communication and LTE. Our scheme takes advantage of the benefits of ICN in wireless networks to try to fetch content from nearby peers first. If the desired content is not found in neighboring nodes within a certain number of hops, the consumer forwards the request to the LTE network. Possible applications to our proposed scheme include the following: *flash crowds* (e.g., sports events and concerts) where hundreds of users can fetch content related to the event; *emergency situations*, where the cellular infrastructure is impaired or not available; mobile traffic in *densely populated areas* (e.g., touristic attractions) where users can fetch content that is common to a large group (e.g., restaurants, points of interest, and "stories" on social networks); and *sparsely populated and rural areas* to extend the reach of the network. Details of our proposed implementation are given in Section 3.4.

3.2.3 Introduction to Named-Data Networking (NDN)

NDN [96] is one of the many implementations of the ICN paradigm. It is a publisher/subscriber model, where the requester manifests an interest to the network in retrieving a certain content. NDN is a clean-slate protocol stack that can work natively on top of Ethernet, Wi-Fi, or LTE, or can work as an overlay on top of IP networks.

In NDN, the *Consumer* application initiates the communication by sending an *Interest* packet upstream. It does so by using namespaces, a hierarchical name structure used by intermediate routers to select the next hop. The UMass ECE webpage (https://ece.umass.edu/welcome) could be translated to the namespace */edu/umass/ece/welcome*, where *welcome* is one uniquely identifiable content signed by the originator (*Producer* node). Every node in the network that speaks NDN deploys the data structures explained in Section 1.3. An overview of the NDN router is depicted in Figure 3.3. From the figure, we can easily see that the content store saves upstream bandwidth by not forwarding the request further. Similarly, the PIT has a similar effect by aggregating duplicate requests as well as preventing loops.

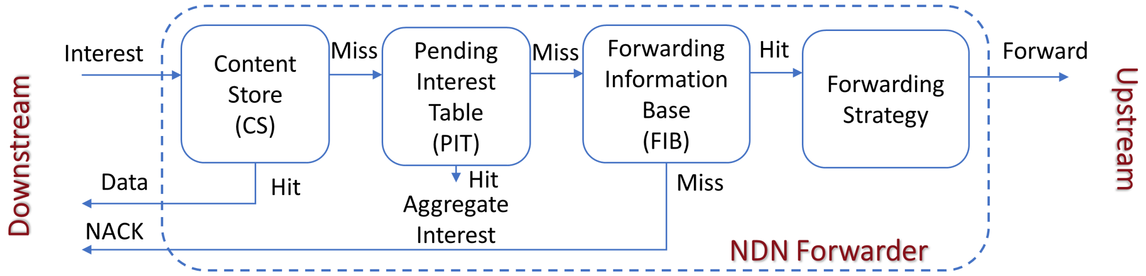

Figure 3.3. An overview of the NDN forwarder and its packet processing iterations

3.3 Related Work

There have been a number of studies focused on using D2D communication to offload cellular base stations in the TCP/IP domain. In fact, the authors in [65] survey the literature to classify existing offloading approaches into two main categories: AP-based (where traffic is offloaded via IEEE 802.11 networks) and Terminal-to-Terminal (or simply D2D communication). In the latter, we can further segment the techniques into timer-based (where nodes delay forwarding to reduce collision) [54, 13], geographical-based (where farther nodes re-broadcast first) [88, 33], randomized broadcasting (again to reduce collisions by making nodes re-broadcast at random times) [13], contact-based (based on the number of neighbors (degree of a node) or number of visited nodes) [17], and a combination of two or more approaches [40]. On the contrary, there have been few studies to use *ICN over LTE* to take advantage of in-network caching to decrease traffic in the backhaul network.

In [14], Lopes et al. developed an application whereby messages are stored in a *Content Manager* module, much like a cache. In the case that the destination is not in the vicinity of the sending node, the *Routing* module consults the *Social Proximity* of the neighbors to decide which node to forward the packet to. This decision is based on the frequency that each node meets the destination node (thus, social proximity). Therefore, the sending node creates a socket-like connection via WiFi-Direct and transfers the message to the node that will most likely meet the destination node in the future. Every node can also carry other nodes' messages (data muling). Although this scheme implements concepts of ICN, it uses MAC addresses to route messages instead of content names. Moreover, it does not support multicast, as only the node that has seen the destination more often carries the request.

The authors in [32] expand an LTE-based architecture to include NDN routers, which are co-located with eNBs to implement caches at the backhaul network, then address the problem of content allocation optimization. In particular, the problem of content allocation optimization is addressed by determining where, when, and how content should be migrated. Their approach enhances the network response to user mobility via a set of parameters derived from the LTE network. Among the results, Gomes et al. [32] found that latency can be reduced by using NDN default caching strategies (e.g. LRU). In addition, considering the amount of free space at the destination cache when placing content yields the most benefits. The authors, however, do not consider D2D communication as part of their design. In our work, we leave content migration to the LTE handover process (which was not considered in [32]).

In the vehicular network domain, Navigo [33] proposes a location-based packet forwarding mechanism to reduce disruption and path changes. The main idea is to forward requests to geographical regions where the content might be located. The location of contents is computed using a broadcast strategy, called exploration phase. Navigo is purely ad hoc as it does not consider base stations in their topology. Our approach is comprised of ad hoc and infrastructure components. In [87], Vigneri et al. propose an augmented architecture where public service vehicles serve as relay points to offload traffic from the backhaul network. In this architecture, MNOs can place content on these vehicles that can later be retrieved by end-users. This approach showed improvements of up to 50% in the traffic offloaded from the backhaul network. The authors in [28] use an ICN approach to disseminate road emergency information (e.g. flooding and crashes) to other vehicles in an ad-hoc fashion. They do so by translating the 2-D coordinates of the emergency area into one value using a mapping function (more specifically, the Cantor pairing function used by the authors in [62]) and appending this information directly to NDN packet names. Then, the NDN forwarding strategy is modified to consider the geographical coordinates and velocity of the nodes to delay the re-broadcasting of packets with a timer-approach.

In contrast, our approach differs from previous works in the sense that we modify the NDN protocol stack to develop a custom forwarding strategy to better take advantage of D2D communication that improves the reliability of cellular networks, making it more resilient to failures, as well as providing extra capacity to current infrastructure.

3.4 Design and Implementation

Our application scenario is focused on data dissemination in urban environments, including pedestrian and vehicular nodes. We assume that all nodes have at least two wireless interfaces, one Wi-Fi and one LTE, that they are willing to join the MANET, and share storage space for collaborative caching.

In our first scenario, nodes move along a Manhattan grid (shown in Figure 3.4) generated using BonnMotion [18], a widely used mobility generation tool. We implement two other scenarios: the vehicular cloud proposed in [87] and a pedestrian crowd (e.g.: concerts and sports events). For evaluation, we use the ndnSIM simulator [52], a NS-3 based NDN simulator.

We customized the NDN forwarder to our application scenarios as follows. First, when a node sends out an Interest request to the network, it attaches a retransmission tag (*Retx tag*) to the outgoing packet. The Retx tag informs the forwarder whether the packet is a retransmission, i.e., if the desired content was not found in the MANET within one timeout period, it sets the Retx tag. All retransmitted packets are forwarded directly to the cellular network. We use the hop count tag (*HopCount*) to identify if a node is the originator or a forwarder. If a node is a forwarder, it may drop packets based on its energy level, which we will described next.

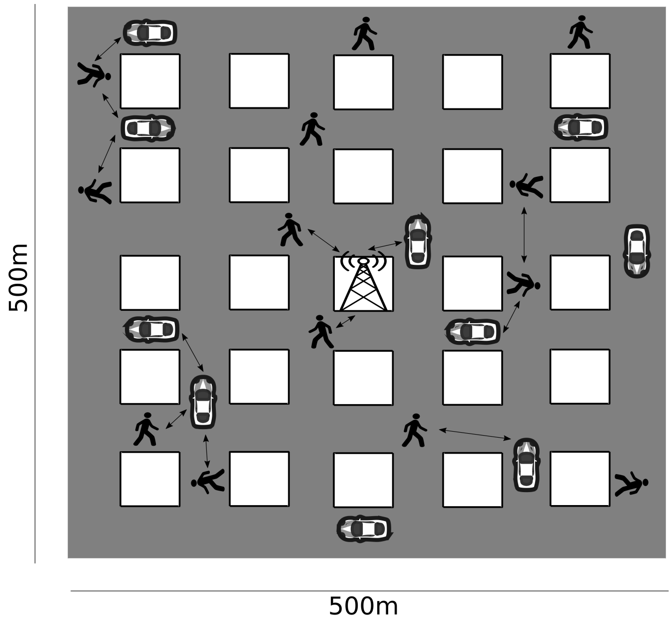

Figure 3.4. Manhattan grid mobility model. Nodes (cars and pedestrians) can only move along the gray roads.

Considering the energy consumption of the nodes, we create two thresholds where nodes change their forwarding behavior based on the current energy level. The first threshold, E_{th_1}, is at 35% and the second threshold, E_{th_2}, is at 25%. These thresholds were chosen based on a common Li-Ion battery discharge curve [83]. At the beginning of our simulations, each node is randomly assigned an initial energy level ranging from 5% to 100%. When the energy at a certain node falls under E_{th_1}, it stops forwarding packets with hop count greater than three. In our initial tests, we found that more than 90% of the packets retrieved from the MANET come from within 3 hops. Therefore, this threshold aims at saving energy by reducing a packet's reachability while still being able to serve the majority of contents. Furthermore, when the energy level falls under E_{th_2}, the node leaves the MANET by forwarding all Interest packets to the cellular network. The described behavior is formalized in Algorithm 4.

For the consumer application, we gathered real data from Twitter's trending topics in the United States, analysing the popularity of each tweet to create our content request pattern. Through maximum likelihood estimation, we found that the popularity in our dataset

Algorithm 4: Modified behavior of NDN forwarder

```
Input  : Interest packet
Output: Interface to forward
if $HopCount = 0$ then
    if $E_n \leq E_{th_2}$ then
        return LTE;
    else
        return WiFi;
    end
else
    if ( $E_n \leq E_{th_1}$ and $HopCount \leq 3$ ) or
    ( $E_n > E_{th_1}$ and $HopCount \leq 6$ ) then
        return WiFi;
    else
        return Drop;
    end
end
```

follows a Zipfian distribution with $\alpha = 0.7$ and $q = 0.7$, described by Equations 3.3 and 3.4. Other works have characterized Internet content to follow the Zipfian distribution as well, among them [11, 22]. The assumption is that some tweets will have lots of followers (fetched more often), while others will have very low visibility.

$$f(k; N, q, \alpha) = \frac{1/(k+q)^{\alpha}}{H_{N,q,\alpha}} \tag{3.3}$$

$$H_{N,q,\alpha} = \sum_{i=1}^{N} \frac{1}{(i+q)^{\alpha}} \tag{3.4}$$

Our content catalog (N) is composed of a total of 1,000 contents. Each node requests an Interest every 20 ms, and can cache contents varying from 0.1% to 10% of the content catalog. We simulate three scenarios where the infrastructure is being challenged by the rapidly increase in traffic:

Table 3.1. Summary of simulation parameters for scenario I - Urban

Parameter	Value
Node count	25, 50, 100, 150
Area	500 x 500 m^2
Access technology	IEEE 802.11g and LTE
Communication range	Wi-Fi: 100 m, LTE: To base station
Node cache (CS)	1, 5, 50, 100 kB
Cache Policy	LRU
Data payload	1 kB
Total contents	1,000

3.4.1 Urban Scenario

This scenario resembles an urban environment where nodes can only move along the grid (streets). Due to the large number of users, MNO turned to small cell densification to cope with the increase in traffic. For our simulations, half of the nodes are pedestrians (moving at 1 m/s) and half are vehicles (moving at 13 m/s). Node count and simulation area were calculated using the framework in [43]. There is one base station located at the center of the grid that is used only when end-users cannot fetch the requested content from neighboring nodes. Table 3.1 summarizes the simulation parameters.

3.4.2 Vehicular cloud

Following the findings in [87], we implemented the concept of a vehicular cloud where utility vehicles serve as data mules to assist end-users in fetching content. In our implementation, nodes move according to the Manhattan-Grid model. First, the vehicular nodes randomly request contents from the backhaul network to fill up their caches (i.e., a node will sequentially request as many contents as it can store in its cache, with the first requested content being randomly selected), then consumer nodes request contents from the vehicular cloud. If that request times out, pedestrians retransmit to the cellular network. In this scenario, the only communication allowed is device-to-vehicle and device-to-infrastructure. We vary the number of utility vehicles from 25 to 100 nodes in increments of 25, while the number of pedestrians remain static at 25 nodes. Moreover, we evaluate the effects that different cache sizes on the vehicular node have on the network. The expectation is that as the number of vehicular nodes increase, pedestrians will be able to fetch more contents from them. Similarly, as the vehicle's cache sizes increase, the pool of contents available to pedestrians will be greater.

3.4.3 Large crowds

Another possible application for our model is large crowds, where often the influx of people exceeds the capacity of the infrastructure. In [58], the authors reported that terabytes of data were transfered via cellular networks (AT&T, Verizon, and Sprint) by in-stadium fans during the 2015 Superbowl. We develop a scenario where spectators at an arena are able to watch on-demand replays, reducing the load on the infrastructure. Our scenario comprises of 200 users in one section of a stadium. Users can communicate with the LTE base station (in this case a femtocell) as well as other users in the same stands to fetch contents. The replay videos have a total duration of 20 seconds each, segmented into 2-second chunks (following the MPEG-DASH standard [73]). The chunk size is 100 kB. We leave the question of fetching different quality levels for future work. In total, five replay videos are requested by all users, with the video segments being requested in order. However, each user will start requesting the videos at a random time within a short interval (10 seconds). The reason for this interval is two-fold: in reality, not all spectators request videos at the same time; second, by using slightly different times, nodes can take advantage of caching.

3.5 Simulation Results and Evaluation

We first analyze the Manhattan-Grid scenario (Section 3.4.1). Figure 3.5 shows the average percentage of traffic that was successfully offloaded from the cellular network with different node densities and different cache sizes (CS). The remaining requests that could not be satisfied from the MANET were served by the cellular network. The error bars are the standard deviation of ten runs. According to Figure 3.5, our model can offload up to 51.7% of traffic from the infrastructure. We attribute this result to the combination of inherent in-network caching in NDN (enabled by named-content) and the Zipfian request pattern described earlier. We can also observe a higher variation in lower density scenarios. This is due to the social proximity of the nodes, i.e., in low densities, nodes are more susceptible to the presence of neighbors, as for higher densities the pool of content from neighbor caches is greater. Additionally, we see an increase in the traffic being offloaded as the density increases. This can also be attributed to the higher social proximity in higher densities (more neighbors translate to a greater set of contents to choose from). Figure 3.5 confirms our expectation that the network performance increases as cache size increases.

In applications that are more tolerant to a higher latency (e.g., where the infrastructure is partly unavailable), the fraction of offloaded traffic can be improved by increasing the number of retries injected in the MANET. Figure 3.6 shows the percentage of traffic that is offloaded when the consumer application rebroadcasts the Interest request to the MANET, instead of sending it directly to the cellular network. Our experiments show improvements of up to 16.61% (68.31% offload in total) when resending up to four requests to neighboring nodes before sending it to the cellular network.

Figure 3.7 depicts the PDF of data packets' hop count in all node densities when the cache size per node is 0.5% of the total content catalog. We can see that in all cases, less than 5% of contents comes from the nodes' own cache (when the hop count equals to zero), while the majority of contents comes from nodes that are three hops away. It is important to note that as MANET grows, the PDF becomes wider. We do not limit the propagation of data packets (as we do with Interest packets); therefore, in some occasions, the data packets travel multiple hops back to the consumer node before the Interest timeout expires. Figure 3.8 shows the CDF for latency for different node densities. We compute latency as the elapsed time from the first Interest requested by a node until the data packet returns, either via the MANET or via the cellular network. We also distinguish between vehicular

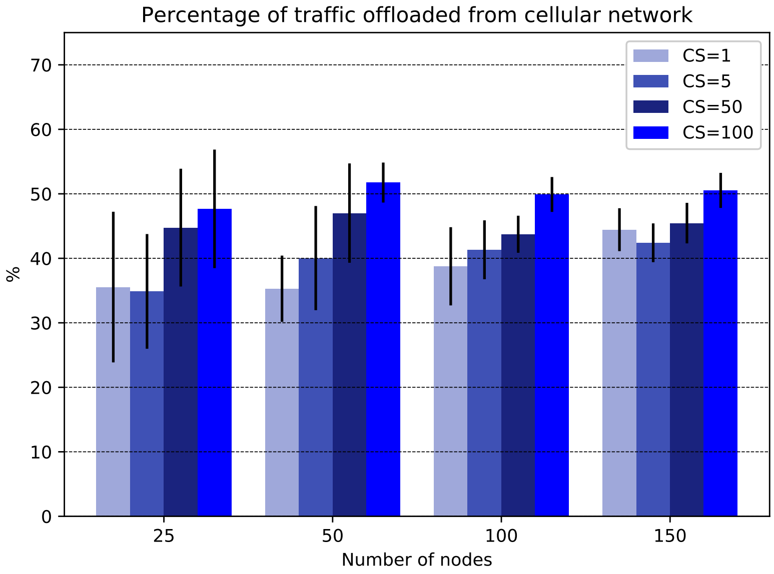

Figure 3.5. Percentage of traffic offloaded via the MANET, illustrating the effect of varying cache size and node density.

and pedestrian nodes to study the effects of mobility on latency; however, the graphs do not show a significant difference in latency between pedestrian and vehicular nodes with both curves overlapping in most cases. Figure 3.8 also shows that in approximately 80% of the cases the latency is below 50 ms. The retransmission timeout in NDN varies according to the number of satisfied (timeout decreases) and lost requests (timeout increases); thus, the tail in the CDF in the MANET cases. The LTE CDF shows the sum of the first timed-out request plus the retransmitted request to the cellular network. Moreover, the shallower slope in the LTE case reflects the variation of the Interest timeout in the MANET.

We also evaluated the energy consumption on the nodes. Our simulation results showed that nodes below the first ($25\% < E_n \leqslant 35\%$) and second ($E_n \leqslant 25\%$) threshold consume 5.8% and 2.9% less energy than other nodes, respectively. Nodes that are in the low power range have a steeper drop in the energy levels due to the battery discharge curve. This energy saving approach provides a longer battery life for mobile user equipment, which is specially important when the infrastructure is impaired (e.g. power outages).

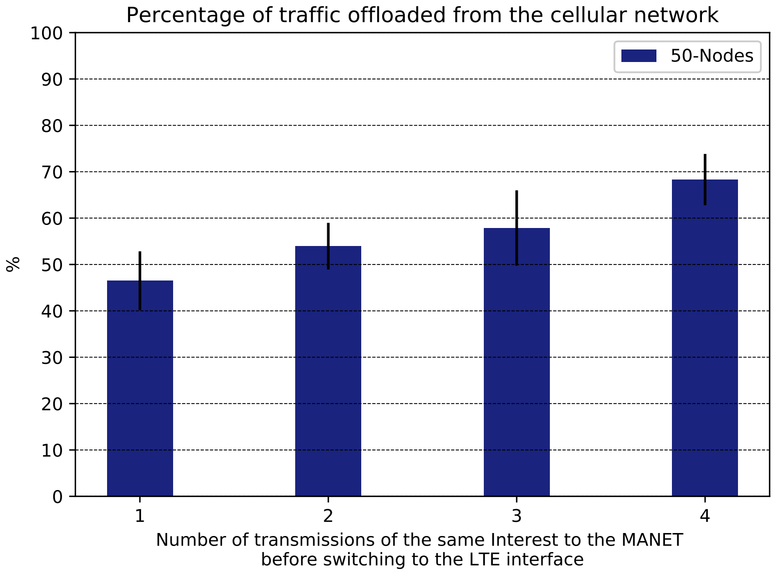

Figure 3.6. Percentage of traffic offloaded from the cellular network when the consumer application retries to send Interest requests to the MANET. The figure shows up to 4 transmissions of the same Interest to the MANET for the 50-Node case.

The vehicular cloud case (Section 3.4.2) is presented in Figure 3.9. The *x-axis* represent the number of utility vehicles, while the bars show the average percentage of traffic that was offloaded from the cellular network for different cache sizes used in the simulation. The error-bars represent the standard deviation of ten runs. Figure 3.9 shows the effect of increasing the number of vehicles, increasing the cache size, and a combination of both. As expected, increasing the number of vehicular nodes that cache content for the MNO has a positive impact on the amount of traffic that can be offloaded from the LTE network as more cache space becomes available. Similarly, increasing the cache size on the available nodes also has a positive impact on the offloaded traffic. It is important to note that increasing the number of vehicles is more effective than increasing the cache size on the vehicles, suggesting that the network benefits from more nodes joining the MANET, but without the necessity of having large caches. This result can be explained because increasing the number of vehicles increases cache diversity in the network, since end-users benefit from the short contact time (when communication between vehicles and consumers

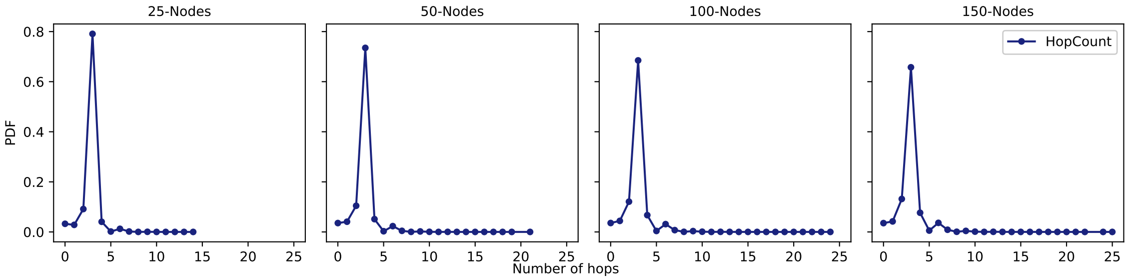

Figure 3.7. Number of hops from successfully retrieved data packets.

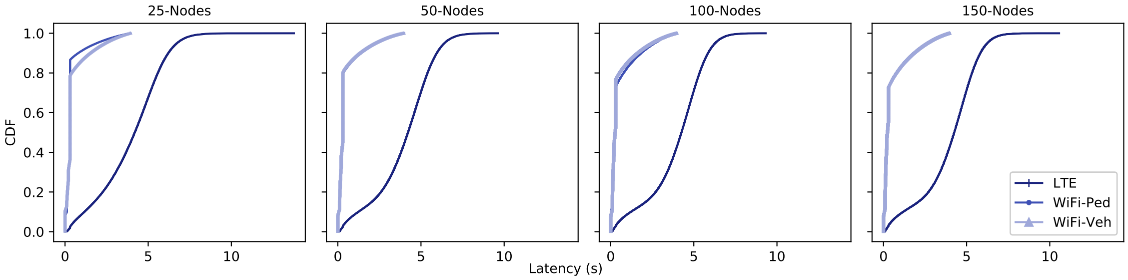

Figure 3.8. Cumulative distribution function of latency for different node densities.

happens) with the utility vehicles. Furthermore, our simulation results are aligned with the findings in [87], where the authors experienced an offload ratio of approximately 50% in their vehicular cloud.

The third scenario (Section 3.4.3) focuses on large crowds, where spectators at a sports event have the capability to watch instant replays at their mobile devices. Figure 3.10 (a) shows the percentage of traffic offloaded by the MANET, as well as the percentage of the video that was downloaded for different request rates. Figure 3.10 (b) shows the average and standard deviation of latency to fetch one segment. According to Figure 3.10 (a), 10.3% and 16.59% of traffic was offloaded by the MANET for request rates of 1 and 5 Interest/s, respectively, showing that we can alleviate traffic from the backhaul network. It is important to note that as we increase the request rate, the network saturates and we are no longer able to download the entire video, leading to re-buffering. Moreover, we see a lower offload traffic compared to the two urban scenarios, which reflects the sequential request pattern used in this case (as opposed to the Zipfian pattern used previously). Figure 3.10 (b)

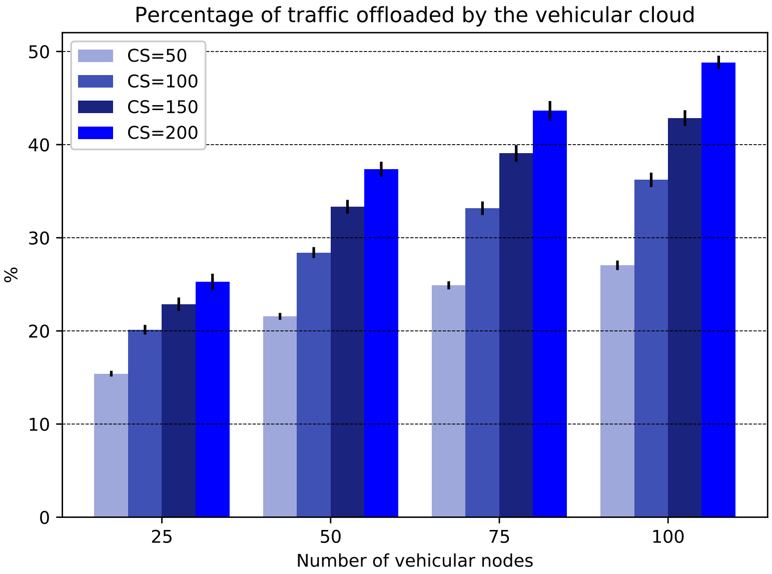

Figure 3.9. Percentage of traffic offloaded by the vehicular cloud for different node densities and cache sizes.

shows the average and standard deviation of latency for each 2-second video segment. In all cases the latency remained under 1.2 seconds and decreases as the request rate increases, suggesting a smooth playback for lower request rates. This decrease in latency reflects the variation in the retransmission timeout (RTO), that reduces as more packets that are in flight are served by the producer or neighbor caches.

All of the above results are also available on the project website.[3]

3.6 Conclusion

This work proposes and evaluates a custom ICN design tailored to environments where the infrastructure is being pressured by the surge in traffic. Our forwarding strategy seeks to empower D2D communication so users can download contents directly from the MANET, easing the burden on the wireless access network as well as the core. We assessed our model in two urban scenarios using real data from social media to create our request pattern,

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[3] `http://people.umass.edu/tteixeira/icn-adhoc.html`

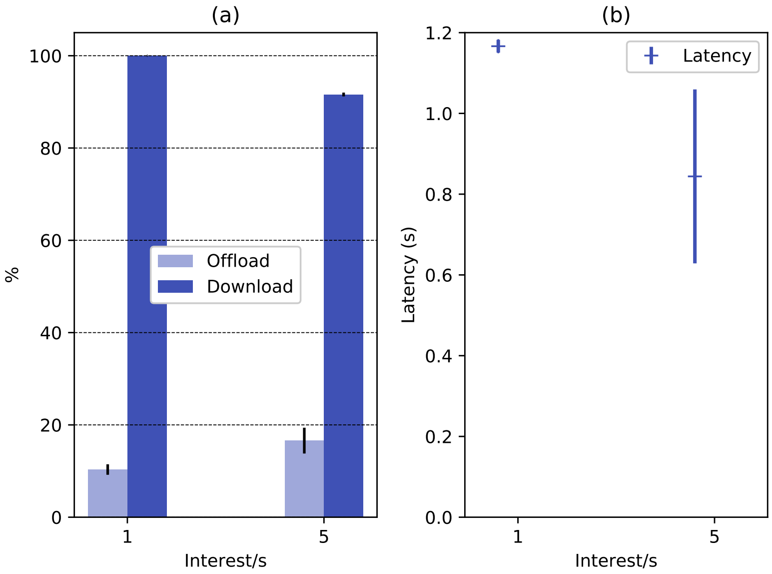

Figure 3.10. Percentage of traffic offloaded, video download completion (a), and latency (b) for 200 nodes in sports events.

and one indoor in-stadium scenario where users can view on-demand replays directly on their devices. Our simulation results showed an improvement of up to 51.7% in traffic being offloaded from the cellular network in the urban scenario. Moreover, our energy saving approach reduces the average consumption by up to 5.8% compared to the normal operation, despite the steeper decrease in the battery discharge curve towards the end of its cycle. In the in-stadium scenario, our approach successfully downloads 20-second replay videos where 10.3% of the contents are fetched from nearby devices. We believe that offloading traffic from next-generation cellular networks (5G and onward) is a promising solution to accommodate the traffic generated from new applications without increasing the complexity and capacity for the MNO.

3.7 Future Work

During the development of this work, we have identified limitations and improvements in our model that we plan to address in the near future. For instance, since the MNO has more information about the overall contents that are being requested in the network, it can have control of what content gets cached in the nodes to maximize cache hits. Optimizing the wireless channel to reduce the probability of collisions is another improvement addressed in Chapter 4, approach that was demonstrated to be efficient in ad hoc networks [13, 54]. Moreover, [93] developed a scheme based on named-data correlation to more accurately calculate the retransmission timeout of NDN packets, which greatly benefits vehicular and ad hoc networks. Additionally, in lieu of the high potential that ICN has to offer to D2D communication (in-network retransmissions for example), a future research direction to our model is to develop it on real smartphones to collect more realistic data.

CHAPTER 4

IMPROVING D2D COOPERATIVE COMMUNICATION IN URBAN SCENARIOS WITH ICN

4.1 Introduction

In the early days of the Internet, connected mobile nodes were rare, therefore support for mobility was not yet an issue. Fast-forward to a few decades later where things connected to the Internet include light bulbs, toasters, vehicles, and the almost ubiquitous presence of smart phones, the need to support mobile connectivity is paramount.

As the number of mobile devices keeps growing, developers and users are starting to feel the pains of the end-to-end model of the TCP/IP. For instance, instead of using the broadcast nature of the wireless channel, a variety of mesh applications accomplish multicast via a replicated unicast tunnels[91], limiting the number of devices in a multicast group due to the high latency created by this approach. Moreover, existing MANET routing protocols, either reactive (such as AODV [61]) or proactive (such as OLSR [38]), generate extra communication overhead to maintain the network state, that in some cases require 73 control packets per data packet [12].

The work presented in this chapter proposes a new approach that uses a cross-layer assisted forwarding strategy in Information-Centric Networking (ICN) to accomplish opportunistic communication in MANETs. ICN decouples information from its location by allowing any node in the network to answer with a copy of the requested data. This feature is due to *transparent caching* and *named-content forwarding*. Additionally, ICN provides a *loop-free* data plane by deploying an extra data structure that keeps a record of pending requests and network interfaces that it has sent the packet to (this data structure is explained in more detail in Sections 1.3 and 3.2.3). These features are useful to control traffic in a MANET, disseminating information closer to the requester. Recently, Cisco and Verizon joined forces to demonstrate the benefits of ICN in next generation cellular networks and IoT.[1]

We augment the packet forwarding process by enabling each forwarder to be more aware of the surrounding environment. More specifically, we develop a timer-based solution that accounts for the distance to the originator, signal to interference and noise ratio (SINR), and the energy level of the node (mobile nodes are battery operated). These metrics provide more context to forwarders to select their back off time, also acting as a tie-breaker between neighboring nodes to avoid collisions.

Our goal is to improve communication in multi-hop opportunistic networks. In such scenarios, end-to-end paths are intermittently available due to node mobility or, at times, are not available at all (some nodes are periodically out of range of any other nodes in the network). Examples of such scenarios include disaster response where the infrastructure is impaired, low-cost extension of access networks via COTS radios to low-density and rural areas, and device-to-device communication in dense urban settings where cellular base stations are congested (traffic offloading).

To design, test, and evaluate our forwarding strategy, we used the ndnSIM [51] network simulator, an extension of NS-3. We simulated topologies with up to 150 nodes (divided into vehicles and pedestrians) in dense urban settings using the Manhattan-grid mobility.

The main contributions of our work are the following: first, we propose a cross-layer forwarding scheme that combines ICN with opportunistic networks to improve communication in MANETs, moving towards a hybrid cellular network that allows D2D communication, reducing complexity and cost for the network operator. Second, we design and evaluate our scheme in dense urban scenarios, where our scheme achieved a 13X im-

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[1] https://bit.ly/2TrLvFn

provement over our baseline comparison when the cellular network is present, and a 1.83X improvement in low density when the base station is replaced with an access point.

In the remainder of this chapter, we present the related work (Section 4.2), design and implementation (Section 4.3). Section 4.4 presents and discusses the simulation results. We conclude the chapter and discuss future work in Sections 4.5 and 4.6, respectively.

4.2 Background on Opportunistic Wireless Networks

Opportunistic wireless networks over IP have been studied extensively. However, networks of this type suffer from the issues discussed in the introduction section (end-to-end connections break, large routing overhead, loops, and inefficiency). This subsection focuses on approaches that use multi-hop wireless communications over ICN.

In [88], Wang et al. present a set of timers to disseminate traffic information in a linear topology that resembles a highway. The main idea is based on the assumption that traffic information, such as traffic jams, construction work, and accidents are more valuable farther away from the source. The authors then devise a set of four timers that prioritize the dissemination of packets by nodes that are farther away from the source, so they can take appropriate measures (e.g., changing the route to avoid a traffic jam). The first is a *collision avoidance timer* to randomize transmissions between neighboring nodes, a *pushing timer* to prioritize nodes that are farther away from the source, an *NDN-layer retransmission timer* to ensure that the packet is broadcasted further, and an *application-level retransmission timer* if the request does not reach the destination before it times out. Simulation results showed that with adequate node density, this approach can successfully disseminate traffic information. The topology and traffic patterns used to evaluate this approach are rather simple, which requires further investigation.

A more general approach was developed by Amadeo et al. in [13], where a timer-based scheme was also used to reduce the broadcast storm phenomenon in the MANET. The main idea is that nodes use a random timer to listen to the channel for transmissions. If during that waiting period the node overhears the transmission of the same packet, it cancels its own transmission. This mechanism was also used for the pushing timer presented in [88]. This approach allows an adjustment on the magnitude of the waiting period, called defer window. Simulation results showed that reducing the defer window improves completion time (time for retrieving all data packets); however, when the defer window becomes too small, it degrades the performance. This scheme was evaluated using pedestrian random mobility, with 50 and 100 nodes where up to 20% were consumer nodes, and one producer. The broadcast storm control mechanism seems to be effective, as packet retrieval latency stabilizes after some time. This work, however, does not compare the timer-based approach with any other scheme. We use Amadeo's approach as our baseline comparison for the second scenario variation of our simulations.

In Chapter 3 of this work and in [77], we devised a new forwarding strategy that enables device-to-device communication (D2D) over ICN in emergency and urban scenarios. The assumption is that content requests follow a Zipfian distribution (according to the findings in [11] and [22]), i.e., popular contents are requested more often than not so popular ones. The authors then performed simulation studies where nodes first request contents from the MANET, forwarding the requests to the infrastructure when the content is not found in the nearby nodes. With this approach, 51.7% of the requested contents were able to be retrieved from the MANET, saving bandwidth in the backhaul network. In this chapter, we propose a forwarding strategy to make the direct communication between nodes more effective, possibly complementing the findings in [77]. We use the approach presented in [77] as the baseline comparison for the first scenario variation of our simulations.

In [76], Tavares et al. propose an opportunistic network on top of NDN by deploying an NDN face on top of Wi-Fi direct, called NDN-OPP. NDN-OPP encapsulates the NDN forwarding daemon (NFD) to allow its operation in intermittent environments. While the previous works focused on the forwarding strategy, this scheme modifies the NDN Forwarder shown in Figure 3.3 to support longer timeouts and implements a queue to store packets until a wireless channel becomes available. The connectivity manager monitors the wireless channels, forming and maintaining Wi-Fi direct groups. This scheme is an extension of the NDN Android forwarding daemon, but its performance evaluation is not yet available. To evaluate this approach, one would need multiple Android devices, which can become expensive, and possibly multiple people to test different topologies.

In the the following sections we lay out our proposed design, simulation scenarios, and evaluation.

4.3 Design and Implementation

In crowded urban centers, the number of mobile devices connected to cellular networks increased dramatically, generating a surge in traffic that expanded 18-fold from 2011 to 2016, according to the Cisco VNI report [8]. D2D communication serves as an alternative to alleviate the pressure on the cellular last mile. We propose a forwarding strategy that tries to download data from the MANET first, only using the infrastructure when the requested data is not found on neighboring nodes [78]. This section presents our design goals and challenges in D2D communication that we address with our cross-layer assisted forwarding strategy.

4.3.1 Challenges in D2D Communication

The challenges in D2D communication include short-lived end-to-end connections, changing topology due to node mobility, and a lossy channel. The distributed coordination function (DCF), employed on IEEE 802.11, often does not prevent collisions in MANET scenarios [92]. Moreover, the overhead created by current MANET routing protocols, such as OLSR [38], AODV [61], and DSR [39] may overwhelm the benefits of maintaining the network topology [86]. Therefore, we use a timer-based approach that does not require nodes to keep track of the network topology, instead, we gather information available at the node to make forwarding decisions.

4.3.2 Our Design

Our goal is to design a forwarding strategy that uses minimal coordination between nodes resulting in reduced communication overhead. We aim to maximize the usage of the wireless channel by allowing nodes to rebroadcast Interest packets randomly, but according to a set of priorities. These priorities are based on the nodes' power level, the signal to interference and noise ratio (SINR) at the node, and the distance from the node to the originator. We then assign weights to each parameter, according to Equation 4.1.

$$\begin{aligned} T_{delay} = & w_1 * d_{norm} + \\ & w_2 * Energy + \\ & w_3 * SINR_{norm} \end{aligned} \tag{4.1}$$

Where d_{norm} is the normalized distance from the current node to the originator, given by the Equation 4.2. The distance between the forwarder and the sender is calculated as follows: when sending out an Interest or data packet, the consumer or producer applications attach a packet tag with its location. Upon receiving the packet, the forwarder reads the tag and calculates its Euclidean distance to the sender. This metric can be easily implemented in modern mobile devices with the help of GPS. In our simulations, we used $d_{max} = 500\ meters$.

$$d_{norm} = \frac{d_{max} - min(d_{max}, d_{N_i,sender})}{d_{max}} \tag{4.2}$$

$SINR_{norm}$ is the normalized signal to interference and noise ratio, given by Equation 4.3. SINR is a common metric to measure channel quality in wireless networks, as it relates the desired signal with noise and interference. We used $SINR_{max} = 22$ in our simulations, according to the guideline used in [82].

$$SINR_{norm} = \frac{min(SINR_i, SINR_{max})}{SINR_{max}} \tag{4.3}$$

The $Energy$ is the power level on the node, ranging from 0 to 100%. Since mobile nodes are battery operated, we implement two thresholds at 35% and 20% to save energy. After the first threshold (at 35%) the nodes stop forwarding packets with hop count greater than 3. Our simulation results show that over 90% of the data packets retrieved from the MANET come from within 3 hops. After the second threshold (at 20%) the nodes leave the MANET. These thresholds were chosen based on the battery discharge curve described in [83].

The rationale behind these variables is to disseminate packets farther away from the source, while any node along the way that has the content can immediately reply. The SINR gives priority to nodes with a better channel quality.

4.3.3 Implementation and simulation setup

To implement and evaluate our scheme on up to 150 nodes, we decided to use the ndnSIM simulator, which is an extension of the NS-3 simulator, allowing us to evaluate our protocol in different mobility scenarios. Moreover, ndnSIM implements the NDN forwarding daemon (NFD), facilitating the transition of the forwarding scheme to real mobile devices in the future. The overview of the ndnSIM node that implements the NDN protocol is shown on Figure 4.1, where the shaded blocks were modified to introduce our approach.

We modified the consumer and producer applications to implement a retransmission tag (*Retx tag*), that is used to direct packets towards the MANET or towards the cellular network. The application sets the Retx tag on the Interest packet after the first request times out. When the packet is retransmitted, the forwarder reads the tag and sends the packet to the cellular network. Moreover, the application implements the *HopCount* tag, used by intermediate nodes to read how many hops the Interest packet has travelled. Depending on the node's energy level, it may decide to drop the packet to save energy. To help reduce traffic in the MANET, nodes drop Interest packets with hop count greater than five.

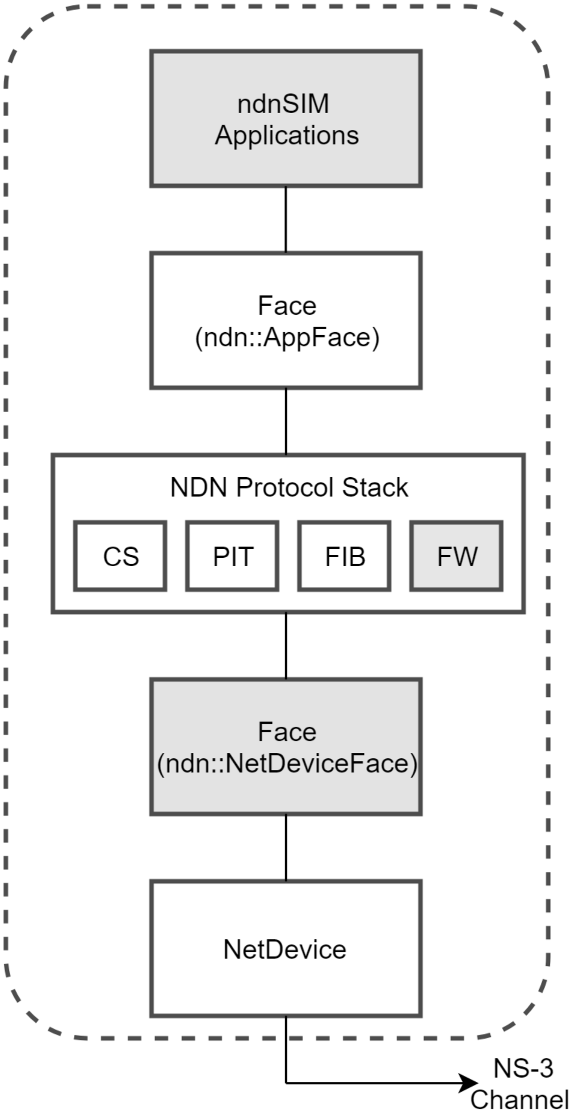

Figure 4.1. A block diagram of the NDN node in NS-3 with the modified blocks in grey.

At the beginning of the simulation, each node is randomly assigned an energy level. Following the battery discharge curve from [83], nodes implement two energy saving thresholds. The first (E_{th_1}) is at 35% at which nodes stop forwarding packets with a hop count greater than three. The second (E_{th_2}) is at 25% at which nodes leave the MANET, i.e., all requests are directly forwarded to the cellular network. This process is formalized in Algorithm 5.

Algorithm 5: Modified behavior of NDN forwarder

```
Input  : Interest packet
Output: Interface to forward after back off time
Calculate $d_{norm}$
Get $Energy$
Calculate $SINR_{norm}$
Calculate back-off timer $T_{delay}$
Get node's interfaces
Initialize interface
if $HopCount = 0$ then
    if $E_n \leq E_{th_2}$ then
        interface = Cellular;
    else
        interface = WiFi;
    end
else
    if ( $E_n \leq E_{th_1}$ and $HopCount \leq 3$ ) or
    ( $E_n > E_{th_1}$ and $HopCount \leq 6$ ) then
        interface = WiFi;
    else
        interface = Drop;
    end
end
SendAfterDelay (interface, back-off time);
```

In our simulation scenario, nodes move along a 5x5 grid, following the Manhattan-grid mobility pattern generated using the BonnMotion tool [18]. Nodes are divided into pedestrians (moving at walking speed – 1 m/s) and vehicles (moving at 13 m/s). This scenario is illustrated in Figure 4.2. Urban scenarios with a high node density are a common use case for D2D communication. Mobile network operators (MNO) are deploying more

Table 4.1. Summary of simulation parameters for each variation.

Parameter	Scenario-I	Scenario-II
Node count	25, 50, 100, 150	
Area	500 x 500 m^2	
Access technology	Wi-Fi & Cellular	Wi-Fi only
Number of Consumers	All nodes	10
Node cache (CS)	10	100
Cache Policy	LRU	
Payload	1 kB	
Total contents	1,000	

and more base stations to accommodate the ever increasing traffic. However, this approach increases CAPEX/OPEX and increases complexity for the MNO, while our approach can prevent the deployment of new base stations.

We simulated two variations. First, the producer node can be reached from the cellular network, represented by the base station at the center of the scenario. Second, the producer is behind an access point, also located at the center of the scenario. The main difference between the two variations is that the cellular network has a much larger range (nodes can reach the base station from any point on the grid) than the access point. The consumer application requests content during 600 seconds (though we report the results starting at 100 seconds to allow the caches to warm-up) following the Zipfian distribution from a library of 1,000 contents. For each scenario, we vary the number of nodes from 25 to 150 (node count and simulation area were calculated using the framework in [43]). The content replacement policy is Least-Recently Used (LRU). Although the authors are aware of caching strategies that outperform LRU, such as Adaptive Replacement Cache (ARC) [53], the current implementation of the NDN Forwarding Daemon (NFD v0.6) does not support ARC, as the only operation allowed is storing an entry, not tracking. A summary of the simulation parameters is available on Table 4.1.

For the first simulation scenario, our baseline comparison is the scheme presented in [77], which we refer to as *Offloading*. Offloading sends every request to the MANET, only retransmitting it to the cellular network when the request times out. It also employs similar

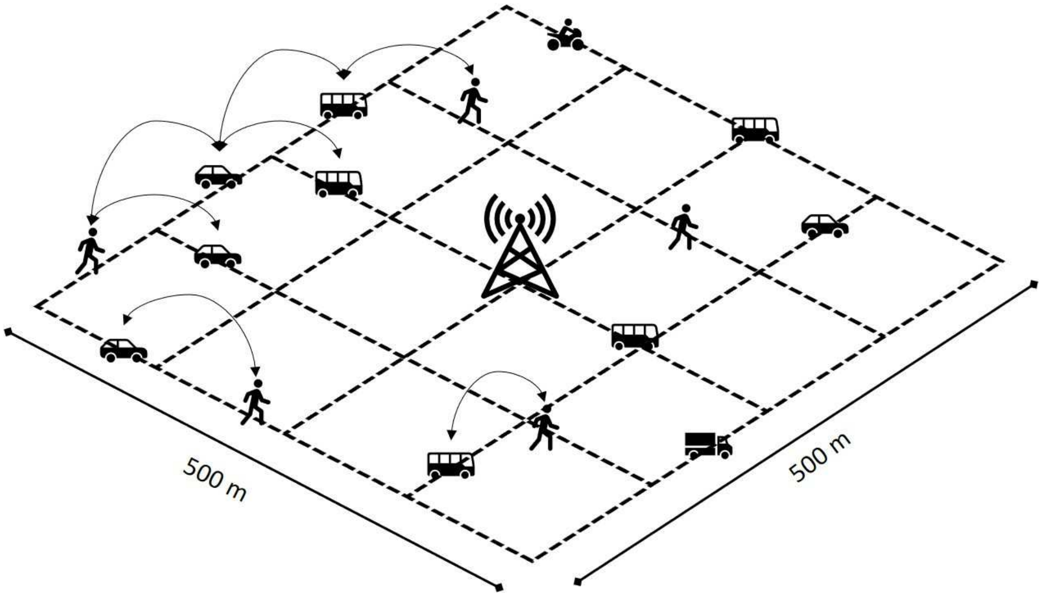

Figure 4.2. Sample simulation scenario showing pedestrians, vehicles, and infrastructure nodes. The arrow represent bidirectional links between nodes. Note that the node count in this case is lower than our simulations for presentation purposes.

approaches to energy and hop count constraints, but it does not implement a back off timer. Each node is able to cache up to 10 contents (1% of the content library). In this simulation scenario, all nodes act as consumers.

For the second simulation scenario, our baseline is the scheme presented in [13]. We refer to this scheme as *Controlled Flooding*. Controlled Flooding implements a random back off timer and packet overhearing, meaning that, if during the back off timer a node overhears the transmission of the same packet by another node, it cancels its transmission. The back off timer is given by Equations 4.4 and 4.5 [13]. Nodes implement a cache size of 100 contents, or 10% of the total content library. The higher cache size is due to the lack of the cellular network. In this simulation scenario, ten nodes are consumers.

$$T_{Data} = rand[0, DW - 1] - DeferSlotTime \tag{4.4}$$

$$T_{Interest} = (DW + rand[0, DW]) * DeferSlotTime \tag{4.5}$$

Where, $DeferSlotTime = 28\mu s$ (from the IEEE 802.11g DCF Interframe Space (DIFS)) and $DW = 127$.

4.4 Results

This section presents the simulation results for the two variants of our scenario. Among the performance metrics we analyze are *latency*, *retransmissions*, *total number of contents downloaded*, and *cellular offloading* (for scenario-I only).

Latency is defined as the elapsed time from the first Interest request until the application receives the corresponding data packet, including retransmissions. Retransmissions are the total number of Interests requested, including the first transmission (i.e., an Interest that was transmitted, timed out, and retransmitted will count as two). The total number of contents downloaded is the sum of all data packets for all nodes in a simulation scenario. Cellular offloading is the percentage of data packets served by neighboring nodes (MANET) instead of being served from a base station.

During our experiments, we observed that varying the weights on Equation 4.1 has little effect on the overall performance metrics. Moreover, shorter back off times seemed to improve the overall latency. Therefore, we used $w_1 = w_2 = w_3 = 15$, meaning that a node will wait up to 45 ms before re-broadcasting an Interest.

4.4.1 Scenario I – Urban with cellular network

In this scenario, mobile nodes first try to communicate among themselves to download popular content from neighboring nodes. As stated in section 4.3.2, our baseline comparison is *Offloading*.

Figures 4.3 and 4.4 show the empirical CDF of latency and retransmissions for both Cross-layer and Offloading, respectively, for different node distributions. As can be seen in Figure 4.3, the Cross-layer scheme can sustain a lower latency throughout the entire simulation, either in low or dense scenarios, while Offloading struggles with lower densi-

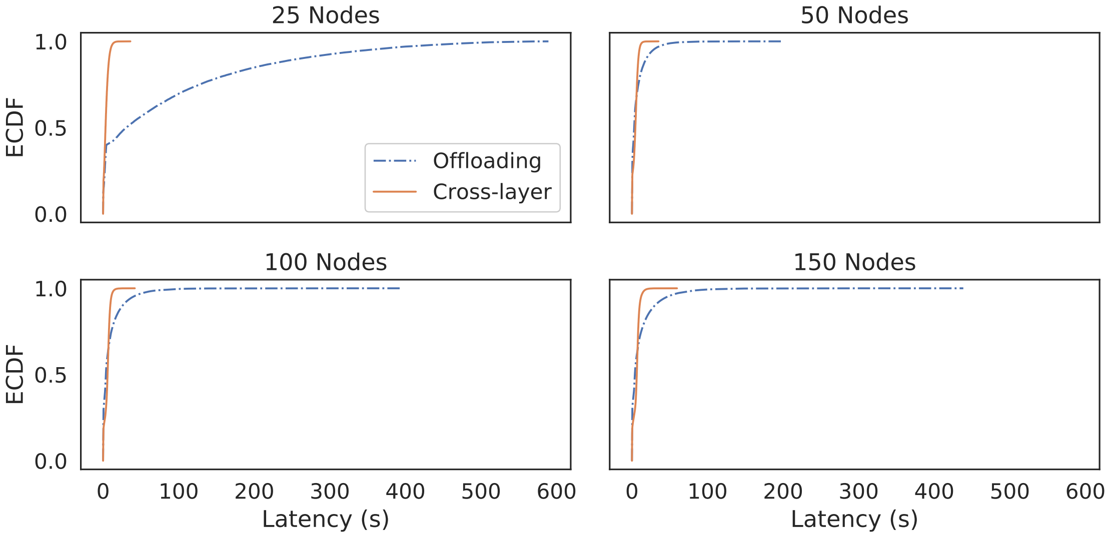

Figure 4.3. Empirical CDF of latency for scenario I

ties. Since Offloading lacks a back off timer, forwarders become congested, forcing the application to retransmit several times, as seen in Figure 4.4. As the number of nodes in the simulation area increases, it facilitates the creation of paths to a copy of the requested content, as well as it increases the availability of caches in the network, resulting in an overall lower latency. Additionally, as more nodes are added to the network, the hop count traversed by data packets gradually increases. For instance, 30% of the data packets come from neighbors that are two hops away in the 25-node case, increasing to roughly 40% in the 150-node case for Cross-layer. Similar trends apply to Offloading. Increasing the number of nodes increases the probability of collisions, which contributes to a higher latency and retransmissions, thus the increasing tail in the CDFs.

Figure 4.6 demonstrates the percentage of data packets that were delivered by neighboring nodes. According to the graph, Offloading is capable of fetching more contents from the MANET than Cross-layer. This result is due to the more flooding-like approach of Offloading with no back off timer, taking advantage of short-lived paths. However, the more flooding-like approach of Offloading has the disadvantage of creating more traffic in the network, resulting in fewer data packets being retrieved from the network, as can be

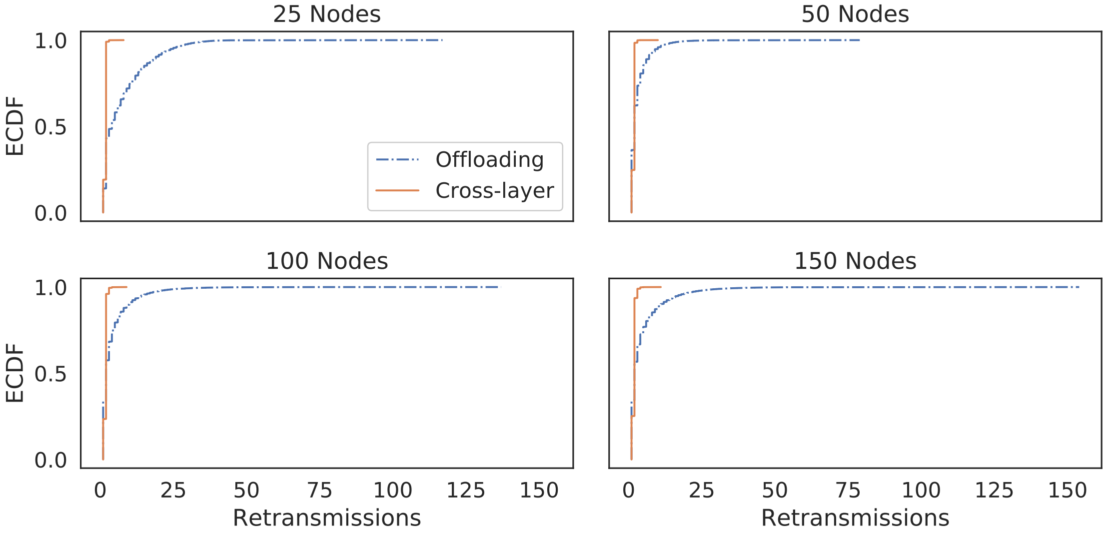

Figure 4.4. Empirical CDF of retransmissions for scenario I

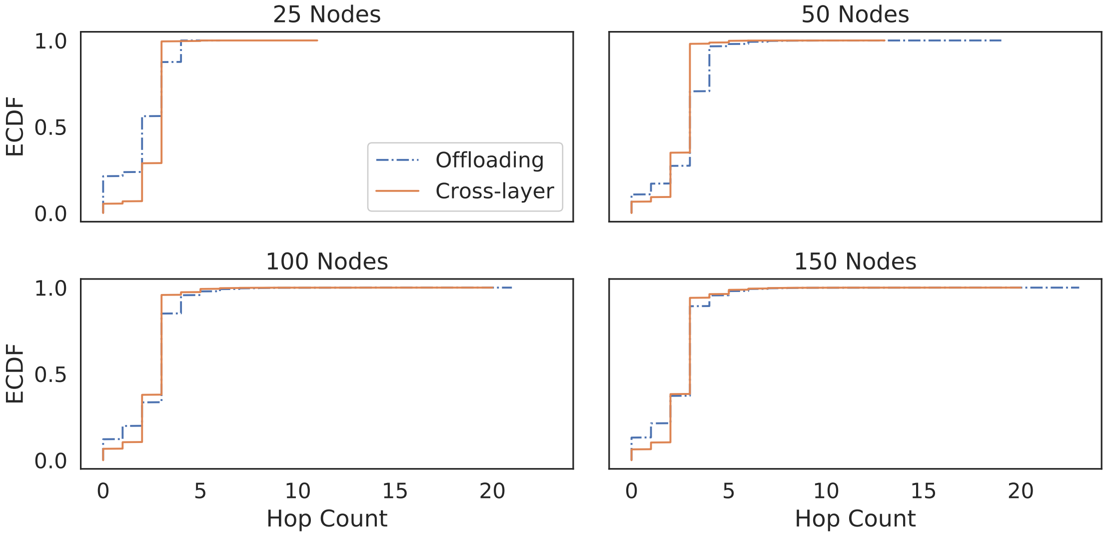

Figure 4.5. Empirical CDF of hop count for scenario I

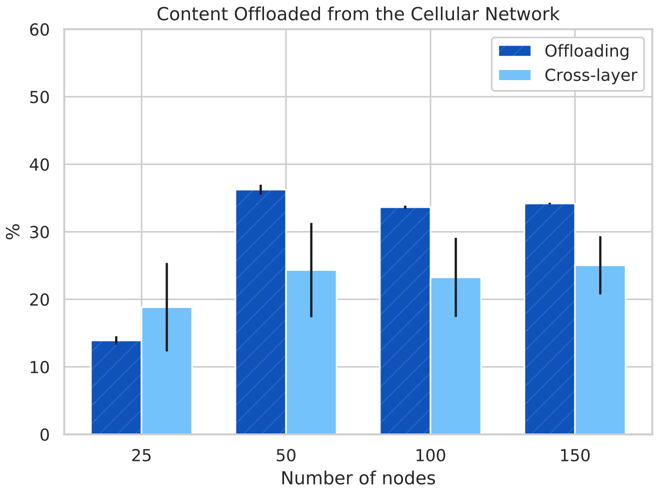

Figure 4.6. Percentage of data packets retrieved by the MANET, offloading the cellular base station.

seen in Figure 4.7. According to Figure 4.7, Cross-layer can retrieve data packets up to 12.98 more times than Offloading in the 25-node case.

4.4.2 Scenario II – Urban with access point

Scenario II differs from scenario I with regards to the type of infrastructure node. The cellular base station is now replaced by a wireless access point. To compensate the absence of the cellular network, mobile nodes have a larger cache size to accommodate more contents. We compare our approach with *Controlled Flooding*.

Figures 4.8 and 4.9 depict the empirical CDF of latency and retransmissions, respectively, for Controlled Flooding and Cross-layer in different node densities. As shown in Figure 4.8, Cross-layer can download about 50% of the contents with low latency in the 25-node case, gradually increasing until reaching about 80% in the 100-node case, while Controlled Flooding is able to download more than 90%. We attribute the lower latency of Controlled Flooding to the shorter back off timer that takes advantage of short-lived connections in the MANET. The Cross-layer, however, can download 43.5% and 83.7% more contents in the lower density cases (see Figure 4.11). The higher latency can be explained

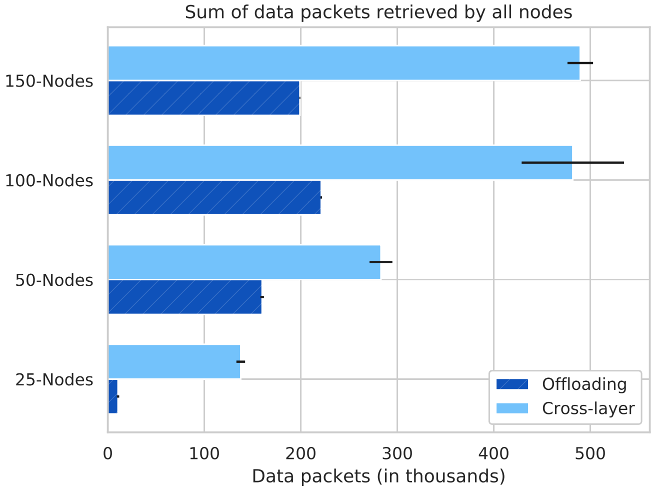

Figure 4.7. Total number of contents downloaded by all nodes in scenario I.

when nodes request a content, thus starting a timer, that is not present in the neighboring nodes' caches. The content is retrieved at a later time, after retransmissions, when the desired data becomes available either at caches or through an alternative path to the producer.

Figure 4.9 shows the number of retransmissions for different node densities. The much higher number of retransmissions of Controlled Flooding is due to the shorter back off timer. As the number of nodes in the simulation increase, more paths become available, increasing the hop count traversed by data packets.

Figure 4.11 shows the total number of packets downloaded by all nodes in the simulation scenario. As can be seen, Cross-layer is able to download up to 83.7% more packets than Controlled Flooding in lower node count scenarios. On the other hand, Controlled Flooding performs better in denser scenarios, where Cross-layer saturates. The overhearing mechanism implemented by Controlled Flooding, along with the shorter back off timer, seem to be more effective to reduce traffic in high-density the MANETs.

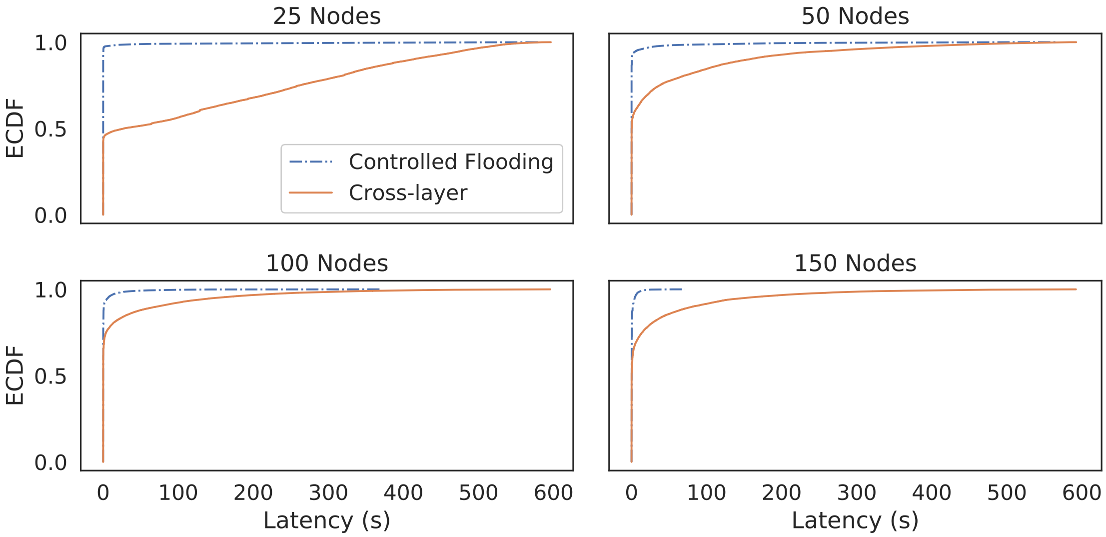

Figure 4.8. Empirical CDF of latency for scenario II

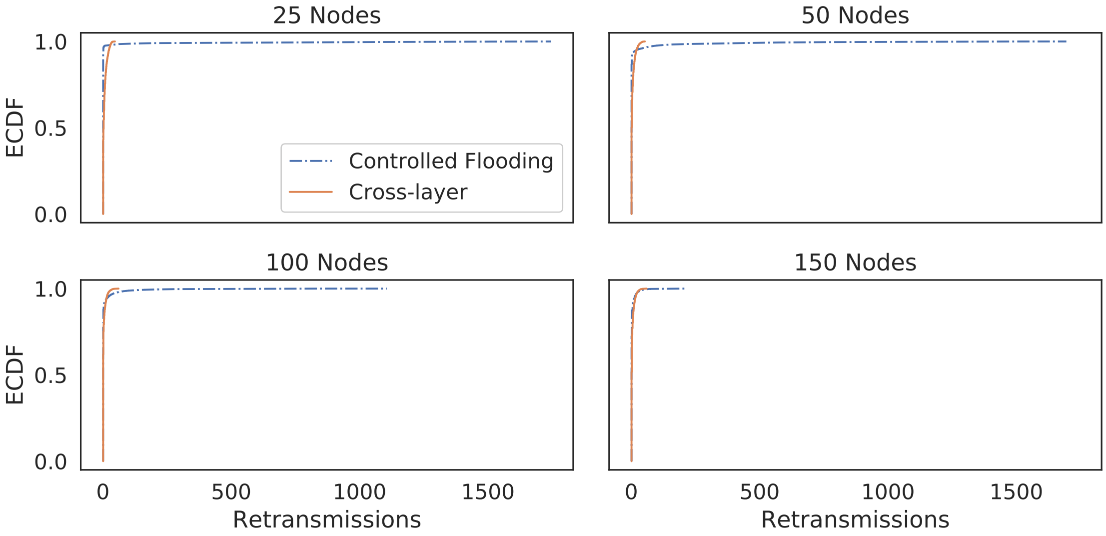

Figure 4.9. Empirical CDF of retransmissions for scenario II

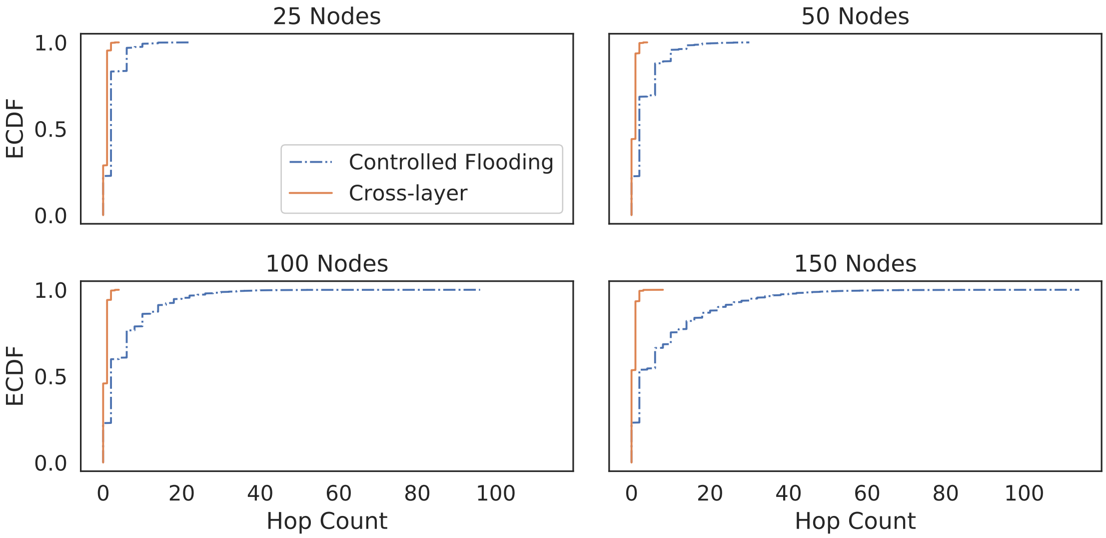

Figure 4.10. Empirical CDF of hop count for scenario II

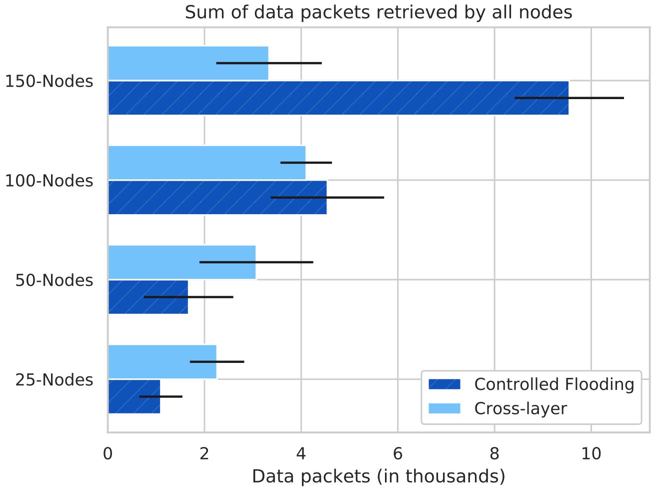

Figure 4.11. Total number of contents downloaded by all nodes in scenario II.

4.5 Conclusion

With the rapid increase in mobile traffic, the need for improved protocols and architectures to support this demand is becoming more important. The current ad hoc protocols built on top of the TCP/IP stack are rather inefficient with regards to packet overhead or latency. More recently, ICN architectures were proposed to solve some of the architectural challenges of IP, including support for mobility. Additionally, ICN supports transparent en-route caching, loop-free topologies, and named content retrieval, which make its application in MANETs very attractive.

This paper proposes a cross-layer assisted forwarding strategy in ICN MANET that facilitates D2D communication to fetch popular contents from nearby nodes, offloading traffic from the cellular infrastructure. Our proposed scheme considers the distance from the node to the originator, the SINR, and the energy level at the node to make forwarding decisions. We evaluated our approach using network simulatons with up to 150 nodes in an urban scenario, comparing it with two existing approaches. First, where the cellular network is present, our simulation results showed a 12.98x improvement in the total number of packets retrieved from the network, while maintaining latency at low levels. Second, when the cellular base station is replaced with a WiFi access point (shorter communication range), our approach achieves a 1.83x improvement over the baseline in low-density scenarios, but saturates in higher-density scenarios.

These results suggest a promising path towards a hybrid cellular and D2D network, reducing complexity and cost for the network operator.

4.6 Future Work

We have identified important tasks for future investigation. First, despite the fact that nodes in scenario I are able to download more contents from the network than our baseline comparison, we need to improve the amount of data that comes from neighboring nodes. On the second scenario, the overhearing mechanism showed to be effective to control traffic in higher density scenarios. We plan to implement that feature in our scheme in the near future. Future experiments with different back off times, different cache sizes, and the overhearing mechanism should help answer these questions.

CHAPTER 5

FUTURE WORK
EXTENDING THE REACH OF THE NETWORK USING D2D COMMUNICATION AND MARKETPLACES

In Chapters 3 and 4 we developed and implemented a scheme to offload cellular base stations and to improve D2D communication using cross-layer information. Our assumption however, is that users are willing to participate in the system by sharing a portion of their mobile devices' storage for communicating with peers. Additionally, the extra communication (either trying to download content from the MANET or just relaying packets) can accelerate the battery depletion, which can be undesired at times. Moreover, in low-density or rural areas, there might not be enough peers in the communication range. Therefore, extra MANET nodes need to be deployed to serve as relay points, bridging the gap in the communication channel where one or more nodes are out of range. Another issue is that deploying relay nodes with COTS radios range from 100 to 1,000 USD each. Furthermore, users might not be willing to participate in the system without financial incentives.

In this chapter we propose a platform that financially rewards users based on the content that is served or relayed by their devices to increase the adoption of cooperative communication.

5.1 Introduction

The majority of efforts in cellular networks are focused on reducing the cost for the network operator, while increasing the data rate for end-users. We have seen in previous chapters that this approach has caveats in densely populated urban areas. Another shortcoming of the current approach arises in disaster scenarios, where the infrastructure is partially impaired if not available at all. Recent events in the aftermath of Hurricanes Maria,[1] in Puerto Rico, and Harvey,[2] in Houston, have demonstrated the fragility of the infrastructure in a shocking manner.

Having a more robust peer-to-peer (P2P) communication infrastructure can alleviate the impact of the impaired cellular infrastructure in disaster scenarios. More importantly, it can serve as a communication channel for rescue efforts. Another advantage is that a low-cost P2P infrastructure can be used to expand the reach of the network to low density and rural areas that are not currently served by the Internet, potentially adding hundreds of millions to billions of new users to the network, as the latest ITU ICT report [37] shows that only 53.6% of the world's households have access to the Internet.

With a decentralized infrastructure that moves away from the lengthy contract with telecom carries is aligned with the increasingly popular concept of a decentralized Internet, where users own their data instead of corporations. For instance, Tim Berners-Lee, the inventor of the Wolrd Wide Web (WWW), leads the Solid project at MIT [3]. The idea is that each user will have one or more pods (a data storage device) and that applications will fetch data from the pods instead of the users' personal data being stored on their servers. IPFS [20] and Secure Scuttlebutt [10] are another two examples of such architectures. Other proposals are also available at the Decentralized Web Summit website.[4] However, these projects do not address the economic interactions necessary to deploy and maintain the underlying infrastructure.

Our proposed work focuses on creating a marketplace that financially rewards users for participating in a decentralized platform, either by deploying relay nodes or by serving

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[1] `https://www.weather.gov/sju/maria2017`

[2] `https://www.weather.gov/hgx/hurricaneharvey`

[3] `https://solid.mit.edu/`

[4] `https://www.decentralizedweb.net/science-fair/`

content to other peers. In our proposed decentralized platform, each node in the network runs an instance of the marketplace that is used to earn and spend monetary credits. The goal is to create the necessary monetary incentives to deploy relay nodes using COTS radios to extend the reach of the Internet to low-density, rural areas, and other under served communities, bringing modern applications and other benefits of the Internet to these communities.

The remainder of this chapter is organized as follows: Section 5.2 presents the related work, while Section 5.3 describes our proposed platform. Section 5.4 concludes the chapter.

5.2 Background

Bringing the Internet, its practicalities, and its innovations to sparsely populated areas has attracted attention in the past. For instance, Google's project Loon[5], aimed at connecting remote areas of the world to the Internet via hot air balloons. However, the project is costly, the balloons can only stay afloat for up to 100 days at a time. There have been multiple reports of balloons crashing on infrastructure.

In DakNet [60], the authors propose a mechanical backhaul to connect remote villages in rural India. The main idea is to use inexpensive storage devices to carry traffic on buses that regularly visit these villages, acting as the link to the Internet. There are several application for this type of asynchronous communication, such as e-mail, where both ends need not to be connected at the same time. We believe that we can expand the reach of the Internet to such villages by using inexpensive radios, providing constant connectivity.

In [48], Marentes et al. proposed a pricing mechanism that advocates for accessible rates for low income rural areas, addressing the issue of low return on investment for network operators in such scenarios. In [99], Zhuo et al. have shown that, with the proper

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[5] `https://x.company/projects/loon/`

financial incentives, users are willing to tolerate a slightly higher delay to retrieve content. Moreover, users can collaborate by storing and carrying data (data mulling). Each user sends bids with the delay they tolerate and the expected incentive. The operator makes decisions based on the users' access to data and mobility patterns. The incentives in this case, are given by the network operator as a form of discounts for services. The authors in [97] use a similar payment scheme, but focus on delivering data to a geographical region of interest where cached content is present, named floating circle. When a node requests content, it negotiates with the operator for which floating circle to send the request to, freeing resources in the backhaul network. Our proposed work also rewards users based on the content that is served or relayed by their devices, which is directly related to the number of cache hits and content size.

More recently, IPFS [20] was proposed as a global distributed file system using distributed hash tables (DHT) with a version control mechanism. The main idea of IPFS is a platform for applications and file sharing with versioning data. In Secure Scuttlebutt [10], the authors propose a gossip protocol that supports decentralized applications and it works well offline. Secure Scuttlebutt is a decentralized social network. It uses cryptography to secure personal data and distribute information via physical meetings or through a Pub entity (a rendezvous point). However, these projects do not use a named-content as the primary entity in their protocols, nor propose financial incentives to encourage users to join the platform.

In [27], Dehghan et al. devised a caching optimization scheme for networks with in-network caching. The authors seek to minimize content retrieval delay considering an inter-related routing and caching problem. Their greedy algorithm reduces complexity and significantly reduces content retrieval delay compared to optimized LRU caching, which can be advantageous in our decentralized platform.

Our proposed work seeks to maximize the financial incentives for users, based on content that is served or relayed by their devices using relative inexpensive MANET radios. Section 5.3 explains the architecture and communication patter of our proposed platform.

5.3 A Decentralized, Infrastructure-less, Disruption-Tolerant Platform for Low Cost Mobile Communication

Building on the work from the previous chapters, we propose DID, a decentralized, infrastructure-less, disruption tolerant platform for low cost mobile communication. DID aims at using *D2D communication* and *ICN* to enable the exchange of information between peers in an opportunistic and inexpensive way, addressing the lack of connectivity to the Internet that affects more than 3.2 billion people worldwide [37].

DID is decentralized in the sense that there is no single entity that owns the infrastructure, instead, it is owned by many small parties that deploy relay nodes and use their devices for communication. It is infrastructure-less since it does not require the cellular provider infrastructure (eNodeB, MME, SGW, and PGW). It is opportunistic as it takes advantages of short-lived paths to forward data. It is disruption-tolerant since it uses inherent caching and named-data to communicate, thus, if a communication link is disconnected, nodes can easily retrieve the content from the closest node once the link is re-established. Finally, DID is low-cost because it uses a, one-time purchase, inexpensive radio for relaying packets and does not require a lengthy contract with cellular operators.

An instance of our platform would run on every participating device that communicates with each other to create a large mesh network. DID can be used in urban areas to offload congested base stations or in sparsely populated areas to bring Internet connectivity at low cost and without lengthy contracts, but still creates the financial incentives for users to deploy relay nodes.

Users are able to run current Internet applications, such as web browsing, messaging, and social media. Real-time time applications however, are more dependent on the constant

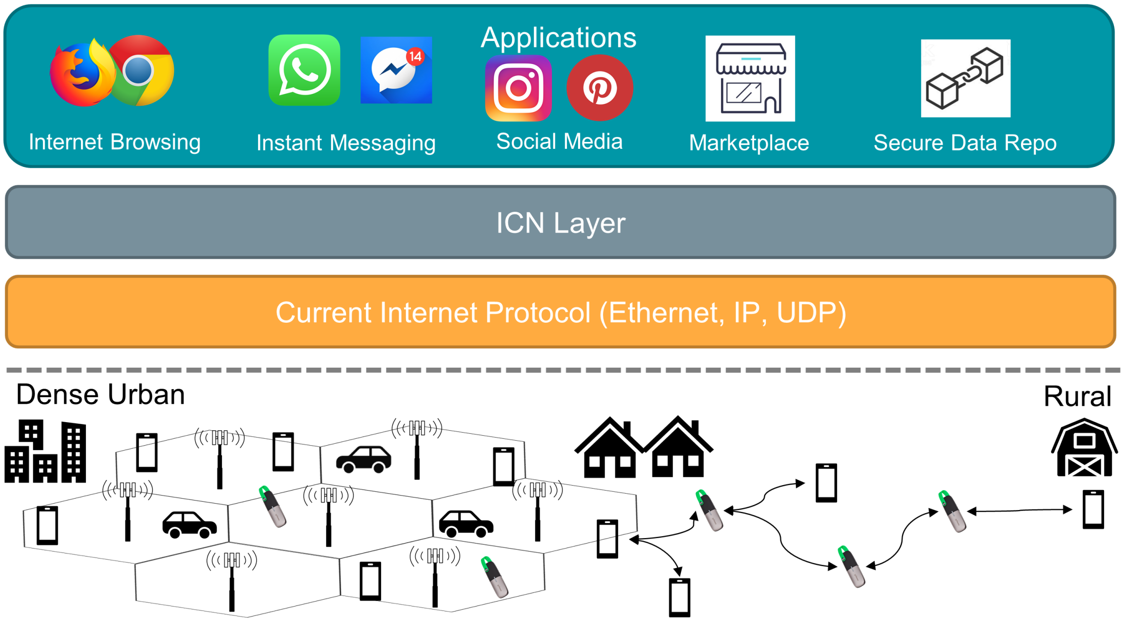

Figure 5.1. The DID Architecture, showing a variety of applications on top of an ICN layer, which can work on top of existing Internet protocols. DID can be used in dense urban scenarios to offload traffic from the infrastructure, or in sparse populated areas to extend the reach of the Internet to areas currently underserved.

existence of a path to the Internet and their use would depend on a more stable setup. DID provides a platform for a decentralized secure data repository, such as Secure Scuttlebutt. More importantly, every instance would also run a marketplace that negotiates prices and would be responsible for distributing payments to the participating entities.

Figure 5.1 depicts the overview of our proposed platform. The applications run on top of an ICN layer that offers named-content forwarding, which facilitates content retrieval since any node with a cached copy can reply to the request. Additionally, to accommodate the sparsely populated areas and potentially short-lived connections, DID is delay tolerant using opportunistic communication and retransmissions.

Perhaps one of the most important components of our work is the marketplace, enabling financial transactions and providing the incentives for users to join the platform. When a user (say Alice) wants to download a content, it advertises to nearby nodes the intent to retrieve the content along with an associated price (optional) and the accepted latency (op-

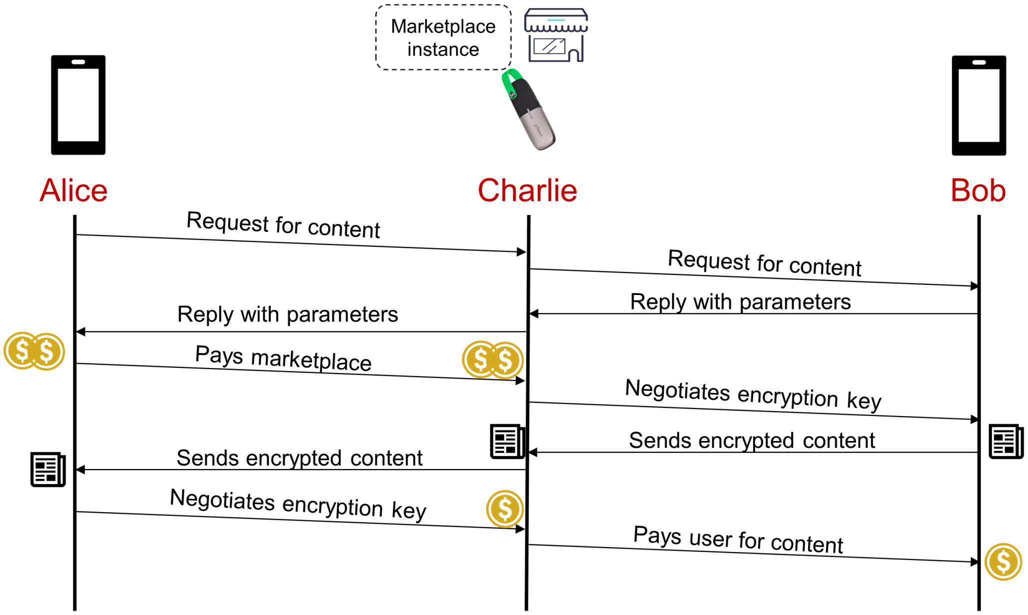

Figure 5.2. The basic interaction model of the DID Marketplace, showing the distribution of money and content between three users.

tional). If a nearby node (say Bob) has the content cached, it will reply to the request for content and the negotiation starts with the marketplace (say Charlie). Alice pays Charlie (the marketplace) for the content. Charlie then negotiates with Bob an encryption key and sends Bob a signal to send the encrypted content to Alice. Once the transmission is completed, Alice negotiates with Charlie the encryption key to decrypt the content, while Charlie negotiates with Bob for clearing the payment, keeping a share for intermediating the exchange of messages. These transactions are depicted in Figure 5.2. It is worth noting that nodes constantly monitor surrounding nodes via periodically *HELLO* beacons, a similar mechanism implemented by OLSR [38].

The previous transactions only work if there are three or more communicating nodes. When there are only two nodes, we can no longer guarantee the fairness of the financial transactions; therefore nodes can still exchange data, but can no longer engage in monetary exchange.

5.4 Conclusion

With more than three billion people without access to the Internet, several efforts have been proposed to increase the penetration of the Internet in sparse populated and other underserved areas. These projects vary from hot air balloons to drones[6] to mechanic backhaul (the exchange of data via vehicles to remote areas). In this chapter, we laid out our proposed design for a Decentralized, Infrastructure-less, Disruption-Tolerant platform (DID) that allows users to communicate without the (or with reduced) need for the infrastructure. DID allows users to use web applications where the Internet currently does not reach. It utilizes a content-centric architecture to facilitate the dissemination of information between nodes, including named-content forwarding, a loop-free topology, and in-network caching. Additionally, our model incentivizes the adoption of our platform by financially rewarding users to share content. We do so by allowing participants in the platform to deploy relay nodes using COTS radios and marketplace instances, facilitating the communication between the participating entities and the exchange of money. With DID, we expect to fill the gap in investment to deploy infrastructure and make the Internet more inclusive to the population that it does not currently serve.

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[6] `https://engineering.fb.com/connectivity/high-altitude-connectivity-the-next-chapter/`

CHAPTER 6

SUMMARY

The Internet has seen a tremendous success since its conception, reaching billions of users worldwide. Much of this success is attributed to the TCP/IP protocol and its narrow-waist that unleashed innovations in all layers of the protocol stack. However, more modern technologies and applications are more noticeable in dense urban scenarios where the ROI is lower. Sparsely populated areas have yet to see some of these trends and breakthrough technologies.

In the first part of this work we propose a scheme that combines open access networks and new Internet architecture concepts to develop a marketplace of network services where users and providers can establish dynamic, fine-grained contracts on a per-connection basis. In this design, users can seamlessly switch between providers and choose the best quality and price parameters that fit their profile. To evaluate our scheme, we developed an agent-based simulator that analyses the behavior of multiple interacting entities (e.g., end-users, ISP, transit providers, and marketplaces). Our simulator outputs the financial outcomes based on different competition scenarios.

We simulated the two most common cases in the US, which are monopoly and duopoly, along with an open access network implemented by the public sector. Our results suggest that competition in the access market drives prices down for consumers, but harms providers' profits. This scenario limits the ability of providers to upgrade the infrastructure, creating a gap between dense and sparely populated areas. Nevertheless, open access networks reduce the risk for Internet providers that need to focus only on services, creating competition in the access market with higher profits. Moreover, since users can easily switch between providers, it creates more incentives for innovation.

In Chapters 3 and 4 we tackle a similar issue in the wireless scenario, where sparsely populated areas lag behind on innovations, while densely populated areas are getting crowded with more base stations. In Chapter 3, we propose a D2D communication scheme that uses ICN to offload traffic from cellular base stations and can also be used to extend the reach of the Internet to areas that are not currently connected. Our scheme takes advantage of the fact that content follows a Zipfian distribution and tries to download content from neighboring nodes first. Only when the content is not found in the vicinity that the node sends the request to the cellular network. Moreover, by using ICN in MANETs, our scheme can take advantage of named-content, in-network caching, and inherent multipath forwarding to circumvent some of the issues of a TCP/IP based MANET. Our simulation results showed that 51.7% of contents can be downloaded from nearby nodes. When latency is not an issue and the application can retransmit multiple times, this metric can be increased to 68.31% when retransmitting the Interest to the MANET four times. These results suggest a promising path towards reducing the dependency on base stations, also reducing complexity and cost for the network operator.

In Chapter 4, we develop a cross-layer assisted forwarding strategy that considers information from the surrounding environment to make forwarding decisions, improving communication in the MANET. In our scheme, nodes use a weighting function that takes as input the distance from the originator, the node's current battery level, and the SINR to slightly delay packets to reduce collisions in the physical layer. Our simulation results showed an 12.98X improvement in the total number of packets retrieved from the MANET when the cellular network is present, while maintaining latency at low levels. When the cellular network is not present, our scheme was able to achieve a 1.83X improvement over the baseline scenario. While there is more room for optimization, our results show that offloading traffic from cellular networks using nearby peers and ICN at low latency can greatly benefit users and network operators.

We combine the work of the previous chapters to propose a decentralized, infrastructure-less, disruption-tolerant platform in Chapter 5. Our platform uses D2D communication with ICN to enable content sharing between users via marketplaces that enable financial transactions to reward users and provide incentives to expand the Internet to underserved communities. This combination fills the gap where the Internet is not present, providing low-cost connection to potentially billions of new customers.

This dissertation addresses issues in wired and wireless access networks. We believe that this work represents an important step towards solving some of the shortcomings that prevent innovations in these networks to reach a more broad public.

APPENDIX

ADDITIONAL SIMULATION RESULTS FOR INTERNET ACCESS

In Chapter 2, we evaluated three scenarios for the Internet access market. They are the following: Monopoly, Competition, and Competition with an Open-Access provider. While these scenarios represent the most common cases in the US, there are other possible combinations with a different number of providers. Figure A.1 shows the preliminary results for all possible combinations for our simulator. The different combinations for the transit market are organized in columns, while the different combinations for the access market are organized in rows. There can be on or multiple providers at a time, as well as these providers can be profit-oriented or non-profit-oriented. It is worth noting that these additional scenarios were run with one random seed. Thus, we will only draw high level conclusions.

Figure A.1 shows the preliminary simulation results for the consumer market share for each scenario. It is clear from the figure that when the ISP provider operates as a monopoly (first row), only a small percentage of consumers join the market, while the provider profits and the quality parameter degrades. The monopoly scenarios from Chapter 2 represent the scenario in the first row, third column. Secondly, when the ISP provider operates as a non-profit provider, the share of consumers that joins the market is greater than the other scenarios (competition and monopoly). This type of provider can be accomplished by a municipal broadband network, for example.

Perhaps the more exciting scenarios are when different providers compete for customers (third row). The willingness from providers to capture more market share and profits greatly benefits consumers, that ended up with better services, resulting in more consumers

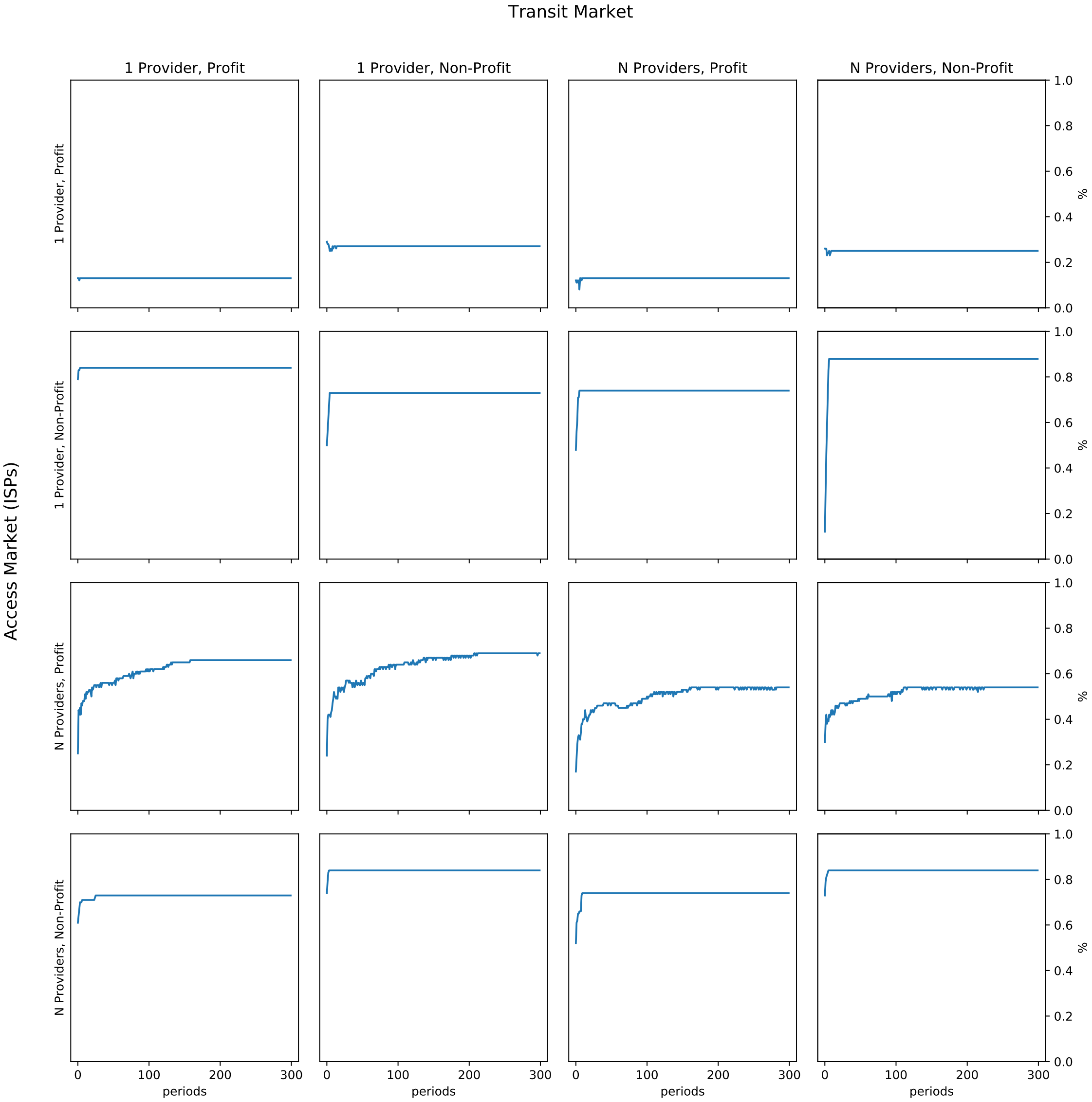

Figure A.1. Evolution of consumer market share, showing the percentage of consumers that join the market for a specific scenario.

joining the market. In fact, we can achieve similar levels from when the providers operate as non-profit. The simulation scenarios from Chapter 2 are in the second row and second column (competition with an open-access provider) and second two and third column (competition).

While the providers in our simulations create offers at random points in the price x quality space and then adjust the offers accordingly, another variation is for providers to start offering services at certain tiers. The advantage creating offers in tiers is that providers may capture more customers with those offers. One drawback of this approach, however, is that margins might be slim initially.

Figures A.2 and A.3 show the price, quality, and profit evolution for the transit and access market when providers offer services in three tiers. The price tiers are $[P, Q] = [0.3, 0.2], [0.6, 0.5], [0.9, 0.8]$. As expected, profits are slimmer than the previous scenario without tiers where providers can create offers farther from the frontier. On the flip-side, Figure A.4 shows that more consumers join the market in this case, 83$\%$ versus 62$\%$ from Chapter 2. The reason for this increase is that more offers are located near the frontier, satisfying a larger amount of customers.

These preliminary simulations shed light on the different Internet provider setups and their outcomes for customers. They are also helpful in advocating for open-access providers and better connection quality for their customers.

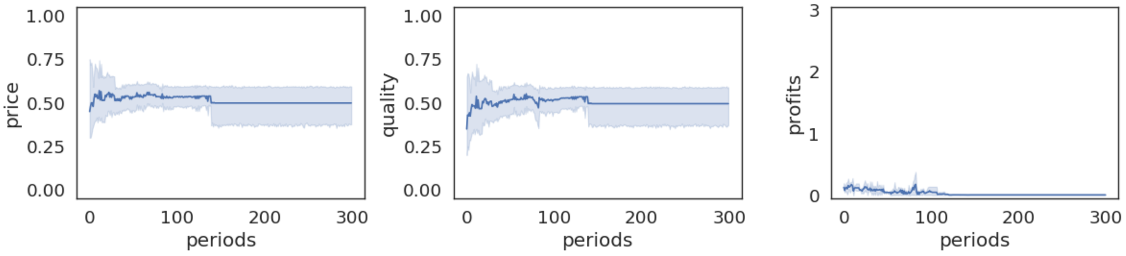

Figure A.2. Mean and 95% confidence interval of price, quality, and profits for the transit provider. In this scenario, the transit providers create offers in tiers.

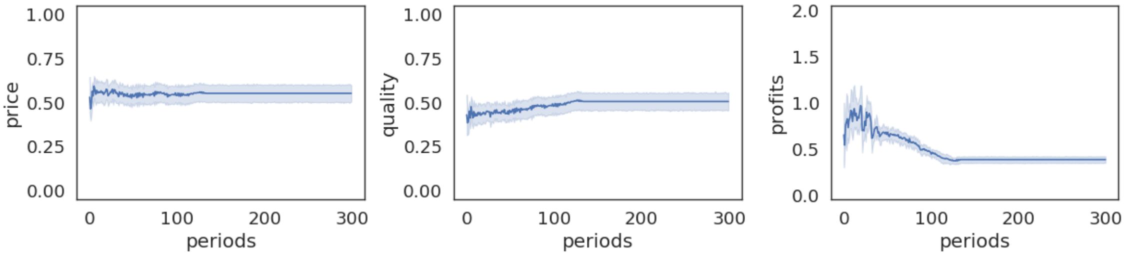

Figure A.3. Mean and 95% confidence interval of price, quality, and profits for the ISP providers. The ISP providers in this scenario create offers in tiers.

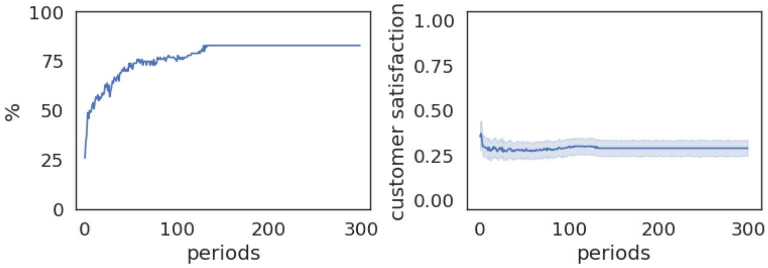

Figure A.4. Mean and 95% confidence interval of share of customers served by the ISP provider and customer satisfaction.

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