DeToks: Decentralised Social Media using 5G NAT puncturing

Orestis Kanaris
Delft University of Technology
Delft, Netherlands
O.Kanaris@student.tudelft.nl

Johan Pouwelse (MSc Supervisor)
Delft University of Technology
Delft, Netherlands
J.A.Pouwelse@tudelft.nl

***Abstract*—We present a decentralised alternative to the winner-takes-everything dynamics of social media platforms. For 25 years there have been continuous attempts to decentralise file sharing, music streaming, video conferencing, and social media. None of these hundreds of projects to *re-decentralise* the Internet have reached the uptake level of YouTube and TikTok. They are rarely easy to use. We present DeToks, a fully decentralised alternative to Youtube and Tiktok. DeToks is not dependant on any central server or cloud. DeToks is specifically designed to be as decentralised and attack-resilient as Bitcoin and Bittorrent.**

Our core contribution is effortless 5G Network Address Translators (NATs) puncturing. Direct phone-to-phone communication is not available on today's smartphones. DeToks solves this problem.

NATs and carrier-grade NATs block direct communication between smartphones. We procured 30+ SIMs card on European 4G/5G mobile networks and measured the carrier-grade NATs behavior. We determined the NAT types (full cone,restricted,symmetric) and their time-out settings. By leveraging provider-aware (Vodafone,Orange,Telia, etc.) NAT puncturing strategies we create direct UDP-based phone-to-phone connectivity. We utilise parallelism by opening at least 500 Internet datagram sockets on two devices. By relying on provider-aware IPv4 range allocations, provider-aware port prediction heuristics, high bandwidth probing, and the birthday paradox we can successfully bypass even symmetric NATs. Our communication method achieves peer-to-peer 5G connectivity at the cost of merely some initial delay and bandwidth, without any assistance from third party servers or clouds.

Detoks validates our 5G puncturing work. We demonstrate the feasibility of fully decentralized social media platforms on consumer mobile devices.

***Index Terms*—NAT, CGNAT, 5G, Distributed Social Media, NAT puncture**

I. Introduction

We present DeToks, meticulously designed to empower Internet users to take full control of their social media experience. DeToks is a decentralised TikTok alternative. Our proof-of-principle social media app does not require servers, avoids using any cloud, bypasses the need for any legal entity, and abstains from any centrality in general. Relentless improvements in mobile hardware now enable on-device alternatives for the cloud. DeToks offers a fully decentralised swipe-based media experience using BitTorrent and *5G NAT puncturing*.

5G NAT puncturing is a technique to communicate freely on The Internet. Personal devices, specifically smartphones, communicate through home Wi-Fi and mobile networks like 4/5G. Using these networks, the devices usually end up behind a home NAT or a Carrier-Grade NAT (CGNAT). These devices divide scarce IPv4 Internet addresses amongst active users. However, the existence of these NATs makes it hard for the devices to communicate with each other since they lock their discoverability by hiding the devices behind the NAT's private network, forcing the "NATed" device to initiate the connection first. This is not a particularly impossible problem if one of the two peers has a static IP address and is discoverable. It is particularly bad when both peers are behind NATs (even worse when it is the same NAT, a problem common with CGNATs [1]), then both need to initiate the connection first, but none of them is "visible" to the other.

The novel contribution of this work is bypassing the carrier-grade NAT hardware inside 4G and 5G networks. The need for this came when the depletion of IPv4 addresses and lack of cybersecurity "forced" 5G network operators to violate Internet protocols. DeToks shows that with advanced 5G NAT puncturing it is possible to create fully decentralised social media.

II. Problem Description

The challenge is to overcome the restricted communication in 5G networks. These mobile networks are exclusively designed to communicate with the cloud. Firstly, this restricts user autonomy and choice, as individuals are often confined to the services and applications approved by the smartphone manufacturers, limiting their ability to access alternative, potentially more innovative or privacy-respecting options [2]. This closed nature also fosters a dependency on a few dominant tech companies, which can lead to monopolistic practices, reduced competition, and a lack of diversity in the market [3]. Furthermore, the exclusive reliance on cloud communication raises significant privacy concerns, as vast amounts of personal data are continuously sent to and stored in centralized servers, making it susceptible to data breaches, surveillance, and misuse by third parties.

All the problems mentioned above are spawned from the design choice of smartphones not being able to communicate directly with each other due to NATs "randomizing" the ports and then rejecting any incoming requests as shown in figure 1 The power of citizens is slowly diminishing, and companies

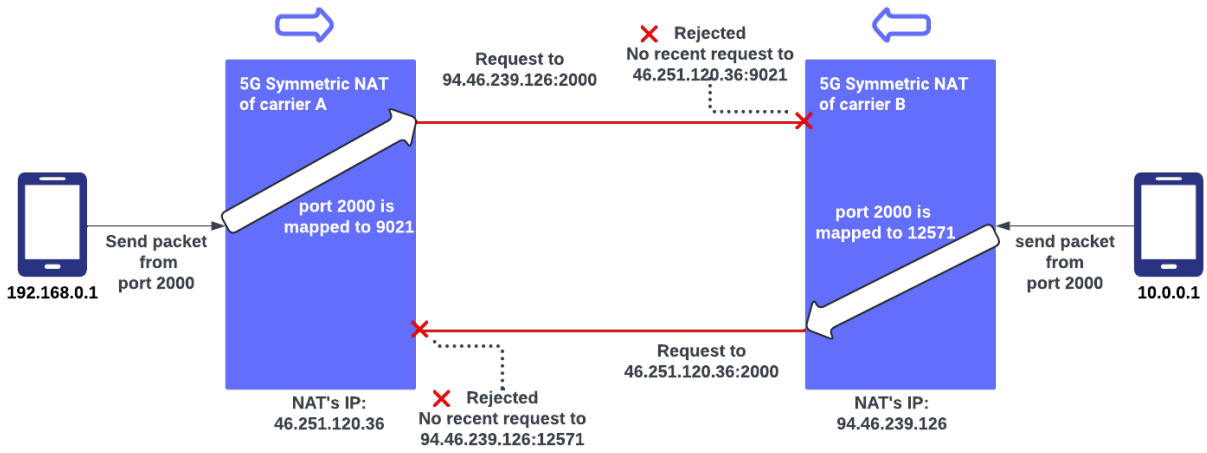


Fig. 1: Two phones behind Symmetric NATs unable to start communication with each other

are gaining more power. Devices such as smartphones, electronic cars, and solar panels are controlled by the cloud of the manufacturer[1], not the citizen that ”owns” them.

The first example of a decentralised 5G overlay network dates from 2017, to the best of our knowledge[2]. Figure 2 illustrates various Android devices participating in a phone-to-phone network using user-space networking on not-rooted devices with their original operating systems. These pure-phone networks are initiated and bootstrapped by smartphones with well-known IPv4 addresses.

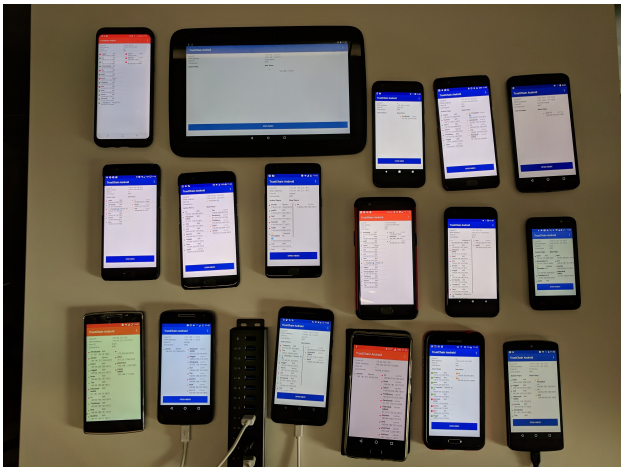


Fig. 2: IPv8 in 2017 running on multiple Android devices

To date, the state-of-the-art way of bypassing NATs and firewalls is still brute-force network flooding. Two studies were conducted more than a decade ago [4], [5], to understand how the infrastructure of cellular providers work and how this affects the cellular network behaviour and performance; their findings are now outdated due to newer generations of cellular networks becoming the new de-facto.

[1]https://berthub.eu/articles/posts/gigantic-unregulated-power
[2]https://github.com/Tribler/tribler/issues/3237

Establishing a connection between devices is essential to enable peer-to-peer distributed social media. Key communication parameters such as NAT type, timeouts and maximum UDP packet size are critical for maintaining the connection and selecting appropriate connectivity strategies. However cellular providers do not publicly disclose these parameters.

Some improvements were proposed, i.e. birthday-paradox-based network flooding [6]. To our knowledge, no one utilizes insights into the LAN hardware used, specifically the ones used by cellular providers, to maximize the connectivity success rate.

III. Architecture and Implementation

Figure 1 shows two smartphones running our DeToks application. We pioneered a new level of decentralisation by crafting the first 5G phone-to-phone network. No prior scientific work offers the same level of decentralisation as DeToks, to the best of our knowledge.

The software used to gather the cellular-specific parameters mentioned in this chapter is available on GitHub [7]. Two phones running the decentralized DeToks app using CytaMobile-Vodafone's 4G in Aglantzia of Nicosia, Cyprus are shown in figure 3.

A. NAT Types

The STUN protocol (RFC3489 [8]) classifies NATs into four types: Full-cone NAT, Restricted-cone NAT, Port-restricted cone NAT, and Symmetric NAT. RFC4787 [1] refines this categorization into ”easy” NATs using Endpoint-Independent Mapping (EIM) and ”hard” NATs using Endpoint-Dependent Mapping (EDM). EIM ensures consistent external address and port mapping for requests from the same internal port.

According to V. Paulsamy et al. [9], the specifications for these NAT types are:

- **Full-Cone NAT:** An EIM NAT that maps all requests from a single internal IP to a corresponding public IP, allowing any internet host to communicate wit the LAN host by targeting this public IP.

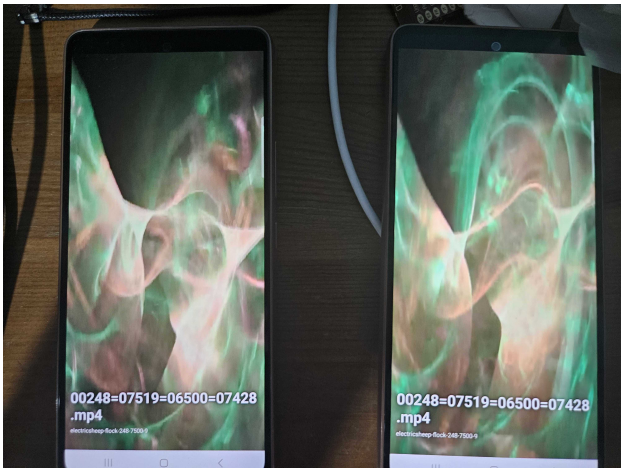


Fig. 3: Two Android phones running decentralized TikTok on cellular data after Nat puncturing

- **Restricted-Cone NAT:** Similar to Full-cone NAT, but restricts communication from the internet to a LAN machine unless initiated by the LAN machine.
- **Port-restricted cone NAT:** A more restrictive EIM NAT than Restricted-cone, limiting external host communication by both IP and port.
- **Symmetric NAT:** An EDM NAT that maps requests from the same internal IP:Port to different public IP:Port pairs depending on the destination, complicating peer-to-peer connections.

Symmetric NAT, functioning like a strict firewall, restricts incoming packets to those from an IP pair that has already sent an outgoing packet. Administrators may prefer Symmetric NAT for its ability to support up to 65535 users per IP while seemingly enhancing security by limiting exposure to selected hosts, a response to the Internet's lack of protection against unsolicited data, including spam and malware [10]. While it does not affect browsing, Symmetric NAT significantly hinders peer-to-peer protocols like BitTorrent. J.J.D. Mol et al. [11] noted that peers behind firewalls struggle with fair sharing, suggesting NAT puncturing or static IPs for better performance.

The method used to determine the NAT type of each cellular provider is based on RFC3489 [8] where the client (in this case, the mobile phone) sends a Binding Request —over UDP— to a STUN server to determine the bindings allocated by the NATs. The STUN server will respond with a message containing the IP address and port from which the request came. The client will then send more Binding Requests to ports and STUN servers. With the responses to these requests, the client can then determine the NAT type that they are behind by analysing how the responses of the STUN servers changed.

The type of NAT used by the cellular providers tested are shown in section IV-B. The information can be used to tailor the connectivity technique on the peer's carrier.

B. Determining NAT Timeouts

To get a clear idea of how the NAT mappings over UDP work, the first outgoing also acts as a connection initiation packet. When this first packet is sent, the NAT from which the packet was sent starts a timer as soon as the packet leaves. That timer waits for a response from the receiving client, meaning that the packet was received/accepted, and regular communication will follow. This timer will be referred to as `connection initiation timeout` throughout this section. Knowing this parameter is very useful for the case of a fully collaborative distributed network since the connection initiation timeout is the time that the peers have to collaborate and connect the new joiner based on the NAT mapping that the new joiner advertised.

The second type of timeout we will call `session timeout`, signifying how long the mapping will remain active while there are no outgoing or incoming packet flows. Knowing how long the session can stay active while idle is used to determine how often "connection maintenance" packets need to be sent to keep the connection alive. Once a connection is established, it is preferred to be maintained since maintaining a connection is much "cheaper" than re-establishing one.

The two are considered separately because the connection initiation timeout is usually different, often smaller than the session timeout.

Starting with determining the connection initiation timeout, initially a lower and an upper bound on the time the mapping will remain active while waiting for a response is estimated. This is achieved by sending a packet to the server; the server waits a fixed amount of time before responding. After receiving each packet, the server's wait time increases by a fixed amount. If no response is received, indicating that the NAT mapping has expired, the time the server waited to send the response represents the upper bound of the timeout. Therefore, the wait time of the last successfully received packet is the lower bound.

When the bounds are established, a binary search is performed on those bounds to find the precise —down to the second— timeout of the NAT.

The process for determining the session timeout is very similar to the one for connection initiation timeout; Initially, a lower and upper bound on the idleness time of a connection is estimated. To achieve this, the client sends a packet to the server, and the server responds with the port number from which the client sent it. Then, the client waits a fixed amount of time until it sends the next packet. The wait time is incremented by a fixed amount for each subsequent transmission. The client compares the port in the server's response, i.e., the port from which the client's NAT sent the message. If the port in the latest response is not the same as in the previous one, then the mapping timed out, creating a new one. The time the client waited to send the last request becomes the upper bound, and the time they waited for the penultimate request becomes the lower bound of the session

timeout.

When the bounds are determined, a binary search is run within those bounds to determine the expiration time down to the second precisely.

The results of multiple runs using different cellular providers can be seen in section IV-C.

C. Maximum Transmission Unit

The maximum transmission unit (MTU) denotes the maximum size of a single data unit that can be sent in a network layer transaction. MTU is related to the maximum frame size at the data link layer (such as an Ethernet frame).

A larger MTU is linked with reduced overhead, allowing more data to be transmitted in each packet. Conversely, smaller MTU values can help decrease network delay by facilitating quicker processing and transmission of smaller packets. Determining the appropriate MTU often hinges on the capabilities of the underlying network. It may require manual or automatic adjustment to ensure that outgoing packets don't exceed these capabilities.

A jumbo frame is an Ethernet frame with a payload greater than the standard maximum transmission unit (MTU) of 1,500 bytes.

Determining the MTU of a cellular provider requires running multiple ICMP pings [3] with binary-search-like varying payload sizes until the exact payload size is determined, where one more byte will cause the packet to be slit into two. Section IV-D presents the MTU of the different providers tested and whether they support Jumbo frames.

D. Reverse-engineering the NATs

To understand the inner workings of the NATs, it was first assumed that no provider uses the same NAT (in terms of configuration) since it was observed from different experiments, i.e. NAT timeouts, that even though there are some standards on how a NAT should be configured such as RFC 2663 [12] and RFC4787 [1] which are not necessarily followed; thus an Android mobile client and a Kotlin server were developed [13] to gather data on each provider that a SIM card could be easily acquired from by visiting the country, buying SIM cards and collecting data about their NAT's mapping strategy on their local network. The mobile client sends packets containing a UUID[4] to the server from random mobile ports to random server ports. The UUID, a timestamp, and the source and destination ports are saved in a CSV file for each packet sent. The server, which lies behind an unrestricted network having a static IP address, does the same; once a packet is received, it stores the UUID (which is in the body of the packet), the port that the mobile sent it from (NAT mapping), and the port that the server received it from together with a timestamp on when the packet was received. The two CSVs are then inner-joined on the UUID column, resulting in two crucial columns: the port the mobile believes it sent the packet from and the port the packet came from, i.e. the exact NAT mapping.

To figure out the algorithm behind each mapping, i.e. what drives the decision-making on which port maps to which and when, a manual Exploratory Data Analysis (EDA) [14] is performed [15] to uncover the hidden inner workings of each NAT. The questions that the EDA aims to answer are:

1) Is the first port mapping completely random?
2) Is the mapping following a pattern?
3) Does the pattern, if it exists, depend on the port choices, sender or receiver? Is it time-based?
4) For how long is the pattern being followed, and if it changes at some point, why?

To answer these, different tests are performed while trying to make sense by visualizing the data or analysing time or population-based windows. The results of this EDA are explained in section IV-A.

IV. NAT Analysis

A. Inner workings of NATs

This chapter explores the internal mechanisms of cellular data NATs used by various European carriers, focusing on the five leading Dutch providers: KPN, Vodafone, LycaMobile, Lebara, and Odido (formerly T-Mobile Netherlands). Through reverse engineering, it reveals the distinct mapping algorithms, timeouts, and MTUs each provider employs. Understanding these behaviours enables the establishment of successful peer-to-peer connections on 5G networks without intermediary assistance. The methodologies for analyzing NAT mappings are documented and available on GitHub [15] and summarized in Table I.

The chapter consists of a discussion of NAT types, timeout settings and MTUs for all tested carriers, followed by an analysis of the mapping algorithms of the primary Dutch providers.

The Nat mapping algorithms of all carriers tested are shown in table I. The results of this study align with the findings of Z. Wang et al. [4] while also showing that the NAT algorithms evolved in many cases since the publication of that study.

B. Nat Types

Knowing the NAT type of the carrier one is using, and the one of the peer they want to connect to allows one to adapt their connectivity strategy to increase the chance of connecting. Different strategies should be adopted based on the types, i.e. a Symmetric NAT requires a Birthday Attack to connect. In contrast, one can easily connect with a peer behind a Full-Cone NAT using a STUN server or some peer acting as a middleman relaying information to the rest of the network. The types of the NATs of various carriers are presented in the sixth column of table I.

C. Timeout of NATs

Analyzing the NAT timeouts showed two crucial things. First, roaming highly influences the timeout, as seen from the results of the Norwegian cellular carriers and Belgium's

[3] https://www.cloudflare.com/learning/ddos/glossary/internet-control-message-protocol-icmp/

[4] https://docs.oracle.com/javase/8/docs/api/java/util/UUID.html

Country	Name	Algorithm	Infrastructure Owner	ID Required	NAT Type	MTU	Allows Jumbo Frames
NL	KPN	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports with numbers incrementing linearly When B_i has no available ports, user is assigned to B_j, etc.	✓	✓	Symmetric	1445	×
NL	Lebara	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports with numbers incrementing linearly When B_i has no available ports, user is assigned to B_j, etc.	KPN	×	Restrict	65507	✓
NL	Lyca	Random Sampling from the block [2048, 65535]	KPN	×	Full Cone	1473	×
NL	Vodafone	Beta Distribution: $Y \sim \mathrm{B}(\alpha, \beta, loc, scale) = \mathrm{B}(2.242, 5.008, 4630, 13937)$	✓	×	Restrict	1437	×
NL	Odido	Semi-Random Sampling from the block $[2048, 65535]$ Sampling strategy is analysed in \ref{sec:odido}	✓	×	Symmetric	3972	✓
FR	Orange	Random Sampling from the block $[1, 65500]$	✓	✓	-	-	-
FR	SFR	Random Sampling from the block $[1025, 65535]$	✓	✓	-	-	-
BG	Orange	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports in the block randomly User will stay assigned to B_i for an extended period and reuse the same ports	✓	✓	Symmetric	1472	×
BG	LycaMobile	Random Sampling from $[2048, 65535]$	TeleNet	✓	Restrict	42987	✓
NO	Telia	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports in the block randomly User will stay assigned to B_i for an extended period and reuse the same ports	✓	✓	Restrict	65507	✓
NO	MyCall	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports in the block randomly User will stay assigned to B_i for an extended period and reuse the same ports	Telia	✓	Full Cone	65507	✓
CY	Epic	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports with numbers incrementing linearly When B_i has no available ports, user is assigned to B_j, etc.	✓	×	Symmetric	4433	✓
CY	Cyta	Random Sampling from the block [5000, 65535]	✓	×	Restrict	1472	×
CY	Primetel	Random Sampling from the block $[1024, 15500]$	Cyta	×	Symmetric	4433	✓
CY	Cablenet	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports in the block randomly User will stay assigned to B_i for an extended period and reuse the same ports	✓	×	Restrict	65507	✓
IT	TIM	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports in the block randomly User will stay assigned to B_i for an extended period and reuse the same ports	✓	✓	Full Cone	65507	✓
IT	WindTre	Let B_i represent a block of 256 port numbers $[B_i = \{256 \times i, 256 \times i + 1, \ldots, 256 \times i + 255\}] \forall i \in [0, 255]$ The user is assigned to a block B_i, Users consume ports with numbers incrementing linearly When B_i has no available ports, user is assigned to B_j, etc.	✓	✓	Symmetric	8873	✓

TABLE I: The algorithm each carrier's NAT uses, their configurations, and the ease of obtaining a SIM card.

LycaMobile. Second, the timeouts are multiples of a minute, a behaviour that is to be expected. Still, it also shows that designers did not optimize the timeouts to the full extent since it is highly unlikely that the optimal timeout is nicely rounded to the minute.

Table II can be interpreted as `LB` being a lower bound and `UB` being an upper bound. Bounds are used since, due to network delays, it is hard to know which of the two is the actual timeout. On the left side is the timeout for how long the mapping will remain active when the recipient does not receive an initial response. On the right side is the communication timeout, i.e., communication is established (initial response is received) but is currently idle. The timeouts of each cellular provider don't differ significantly except for the two extremes, which are Lyca of Belgium being unable to establish a connection while roaming and CytaMobile of Cyprus having an enormous session timeout of half an hour.

D. Maximum Transmission Unit

Understanding a carrier network's Maximum Transmission Unit (MTU) provides several benefits. It allows for optimizing network performance by identifying the largest packet size that can be transmitted without fragmentation, thereby minimizing overhead and latency. Additionally, knowing the MTU facilitates efficient bandwidth utilization, as smaller packets can increase overhead and reduce throughput.

Jumbo frames improve network efficiency by accommodating larger packet sizes than the standard MTU, reducing transmission overhead. However, compatibility with all devices and networks must be ensured to fully utilise jumbo frames.

The MTU values for various carriers and their support for jumbo frames are presented in the last two columns of Table I. Overall, there is no consistent MTU standard across cellular providers, especially regarding jumbo frame support, with variations near the 1500-byte threshold for those not supporting jumbo frames.

E. Analysis of Dutch Carriers

1) Lebara Netherlands: Analysis of Lebara's NAT behaviour showed that sender ports often followed a sequential pattern, starting with a random port and incrementing to adjacent ones until a new random port was selected. These initial random ports were frequently reused within the same session, making them significant, though inconsistent across runs.

As shown in figure 4a, which shows the port mappings of an $\approx$ 2 hour run, port mappings often began around the 3625 region, cycled through sequential increments, moved to other random blocks, and returned to the original region at consistent intervals. During low traffic periods, initial ports were typically multiples of 256, followed by 255 consecutive ports, as illustrated in figure 4b. This is consistent with prior findings [4], with the added insight that Lebara's NAT behaviour is both usage-based and time-based. Users stay in a port block until it times out or all ports are used.

It appears that ports are organized in blocks of 256 and assigned to users based on availability. Assignment strategies may depend on active users or available ports, as indicated by different behaviours observed during low and high traffic periods. Clarifying these allocation strategies requires further study, as proposed in section VII-A.

After concluding the analysis, it was noticed that the Lebara SIM card used was deprovisioned without notice, and subsequent attempts to reconnect or reactivate it were unsuccessful, indicating a potential carrier response to the testing activities.

2) KPN: KPN, like Lebara, groups ports into blocks of 256 consecutive numbers. The main difference is that KPN, with more infrastructure as a primary network operator, allows more extensive consumption of these port blocks compared to Lebara, as shown in Figure 5. This difference likely results from fewer users per IP address on KPN.

During testing, the phone completely consumed a block of 256 ports 32.3% of the time. Additionally, 36.9% of the time, the phone was assigned to a group starting with a port number divisible by 256. This pattern suggests that targeting ports divisible by 256 potentially increases the likelihood of successful connections, as all mappings remain active concurrently if attempted without interruption.

3) LycaMobile Netherlands: LycaMobile, using the KPN network, adopts a random address mapping strategy. Analysis of approximately 288,000 mappings revealed port usage within the range of 2048 to 65535, resulting in around 51,000 unique mappings. Port reuse lacked a consistent pattern, with intervals varying from 85 to 5980 seconds, suggesting a First Come, First Serve allocation approach.

The observed port reuse after 85 seconds, shorter than the typical timeout, implies that ports may timeout earlier due to high demand or excess usage. LycaMobile appears to use a shared port pool for the $[2048, 65535]$ range, with no evidence of systematic sorting, as consecutive port usage was infrequent.

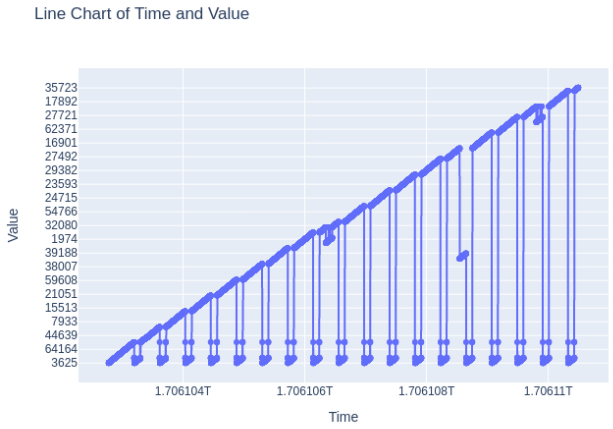
4) Vodafone Netherlands: Over 900,000 mappings were analyzed for Vodafone, revealing that it does not follow the KPN and Lebara model of dividing ports into 256 blocks, nor does it use LycaMobile's random port assignment strategy. Initial observations suggested a normal distribution in the frequency of port mappings; however, a Shapiro-Wilk test [16] disproved this, indicating that a beta distribution provides a better fit, as shown in Figure 6.

The beta distribution, a continuous probability distribution defined on $[0, 1]$, is characterized by shape parameters α and β, influencing the distribution towards higher or lower values, respectively [17]. The location and scale parameters were also relevant, shifting and spreading the distribution along the x-axis. The empirical beta distribution for Vodafone is: $Y \sim \mathrm{B}(\alpha, \beta, loc, scale) = \mathrm{B}(2.242, 5.008, 4630, 13937)$

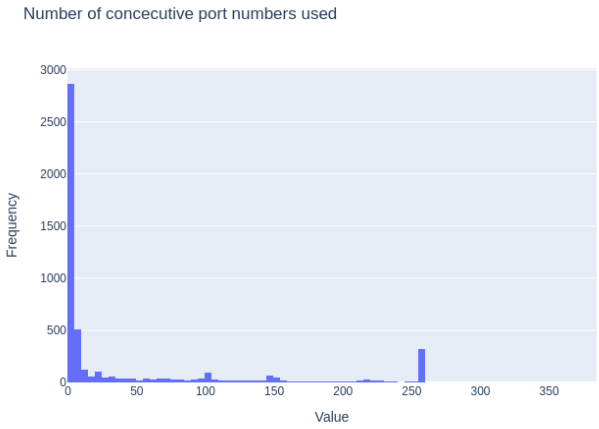
5) Odido: Odido's NAT randomly selects ports, with analysis showing that only 9,920 unique ports were used out of 493,982 mappings scattered across the port space rather than using consecutive ports like Vodafone. Figure 7 illustrates the distribution of Odido's mappings.

	Connection Initiation Timeout				Session Timeout			
Provider	***LB(s)***	***UB(s)***	***Server Port***	***Roaming***	***LB(s)***	***UB(s)***	***Server Port***	***Roaming***
Lebara NL	120	121	2000	-	240	241	2000	-
Lyca NL	120	121	2000	-	120	121	2000	-
Odido NL	120	121	2000	-	119	120	2000	-
Vodaphone NL	302	303	2000	-	299	300	2000	-
KPN NL	120	121	2000	-	239	240	2000	-
Orange BG	58	59	2000	Odido	60	61	2000	Odido
Orange BG	59	60	2000	Lyca NL	57	58	2000	Lyca NL
Lyca BG	F	F	2000	Lyca NL	F	F	2000	Lyca NL
Telia NO	120	121	2000	-	-	-	-	-
Telia NO	5	6	2000	Lyca NL	300	301	2000	Lyca NL
MyCall NO	120	121	2001	-	-	-	-	-
MyCall NO	19	20	2001	Lyca NL	299	300	2001	Lyca NL
CytaMobile CY	59	60	2000	-	1800	1801	2000	-
Epic CY	239	240	2001	-	240	241	2001	-
PrimeTel CY	200	201	2000	-	240	241	2000	-
CableNet CY	20	21	2001	-	30	31	2001	-
TIM IT	299	300	2000	-	420	421	2000	-
WindTre IT	30	31	2001	-	30	31	2001	-

TABLE II: Timeouts of various carriers in seconds. On the left are timeouts for waiting for communication to be established, and on the right is a timeout of the idle communication channel.



(a) 128 minutes Lebara of Lebara port mappings



(b) Frequency of consecutive port numbers used by Lebara

Fig. 4: Lebara analysis

To optimize NAT penetration for Odido, a proposed algorithm merges consecutive bins with frequencies above 30 to avoid over-specifying, accommodating time-dependent results. An exploitation-exploration strategy is then applied, with 40% of port selections based on established frequency ranges and 60% from random ports within $[2048, 65535]$[5]. Selecting bins based on frequency showed inferior performance due to increased delays and potential overfitting, leading to random bin selection.

Various European carriers were analysed during this project. Their in-depth analysis is presented in appendices A-H.

V. NAT PUNCTURING

A. Simple Birthday Attack

The rule for communicating in a NATed network is that the person behind the NAT must initiate communication first. The assumption is that the Internet works mainly in a Client-Server fashion where the Server is discoverable (has a *Public Static IP address*). This assumption breaks in the case of peer-to-peer communication between two clients behind a NAT since none are discoverable, and no one can initiate the communication.

A solution to this is, as explained in [6], [18], both peers should send packets to random ports until a "match" is achieved. A match is when peer A sends a packet from port X to peer B's port Y, and peer B sends a packet from port

[5]Details of the bins and algorithm implementation are available in section V-B

$\mathbf{Attempt} :=$ At most **243587** packets sent
$\mathbf{H_0} = \mathbf{P_{random}} \leq \mathbf{P_{CellularProviderAware}}$
$\mathbf{H_1} = \mathbf{P_{random}} < \mathbf{P_{CellularProviderAware}}$
$\alpha = 5\%$

NETHERLANDS	**Odido**	**Lebara**	**LycaMobile**	**VodaFone**	**KPN**
Odido	Penetrations: $\frac{0}{10} \Rightarrow \frac{4}{10}$ $p = 0.0433$ H_1 is accepted	-	-	-	-
Lebara	Penetrations: $\frac{0}{10} \Rightarrow \frac{6}{10}$ $p = 0.0054$ H_1 is accepted	Penetrations: $\frac{1}{10} \Rightarrow \frac{1}{10}$ $p = 0.7632$ H_1 is rejected	-	-	-
LycaMobile	Penetrations: $\frac{1}{10} \Rightarrow \frac{1}{10}$ $p = 0.7632$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	-	-
VodaFone	Penetrations: $\frac{2}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{1}{10} \Rightarrow \frac{6}{10}$ $p = 0.0286$ H_1 is accepted	Penetrations: $\frac{1}{10} \Rightarrow \frac{2}{10}$ $p = 0.5$ H_1 is rejected	Penetrations: $\frac{4}{10} \Rightarrow \frac{3}{10}$ $p = 0.8251$ H_1 is rejected	-
KPN	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{4}{10}$ p=0.0433 H_1 is accepted	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected

CYPRUS	**Cyta**	**Epic**	**PrimeTel**	**CableNet**	**-**
Cyta	Penetrations: $\frac{1}{10} \Rightarrow \frac{9}{10}$ $p = 0.0005$ H_1 is accepted	-	-	-	-
Epic	Penetrations: $\frac{0}{10} \Rightarrow \frac{2}{10}$ $p = 0.2619$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	-	-	-
PrimeTel	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	-	-
CableNet	Penetrations: $\frac{0}{10} \Rightarrow \frac{3}{10}$ $p = 0.1053$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{2}{10}$ $p = 0.2368$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	Penetrations: $\frac{0}{10} \Rightarrow \frac{0}{10}$ $p = 1.0$ H_1 is rejected	-

TABLE III: Results of the hypothesis testing on Random Birthday Attack versus Cellular Provider Aware NAT Puncturing for ten attempts on each carrier combination and technique.

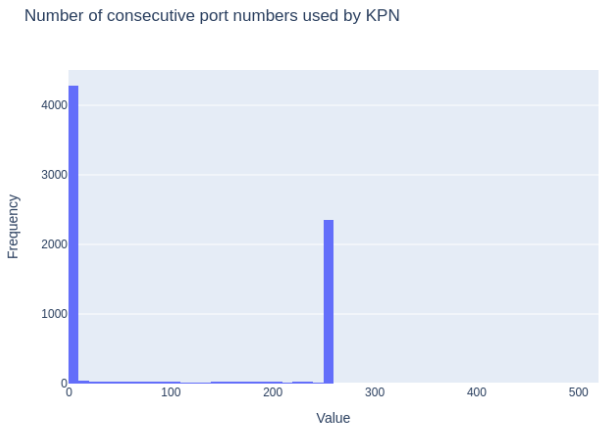


Fig. 5: Frequency of consecutive port numbers used by KPN

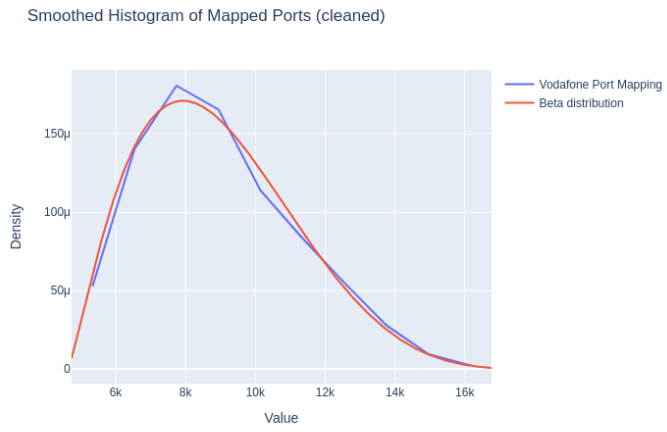


Fig. 6: Beta Distribution fitting on Vodafone's mappings

Y to peer A's port X in a timeframe smaller than their NAT's timeout. One can understand that the probability of this match is $\frac{1}{65535^2}$ without factoring in the timeframe that this should occur, which is almost impossible to achieve given restrictions imposed by the providers and NATs having limited memory, let alone it will take a lot of time.

This can be improved using a Birthday Attack, which is an attack built on the Birthday Paradox [19], a counterintuitive probability theory concept that states that in a group of just 23 people, there's a better than 50% chance that two people share the same birthday. This might seem surprising, as intuition might lead one to think that with 365 days in a year, it would

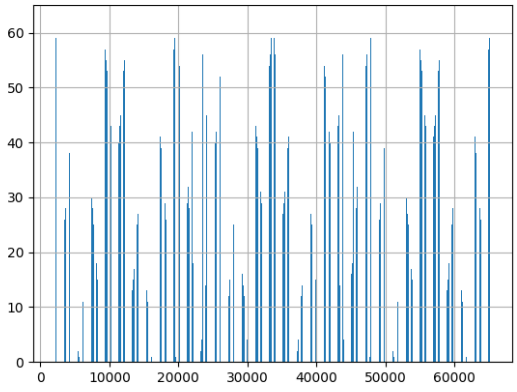


Fig. 7: Thousand bins histogram of the output of Odido's mapping strategy

Algorithm 1 Simple Birthday Attack

Require: On packet received, send an ACK
Require: On packet received, $ackRcvd \leftarrow True$
Require: On packet received, store senders port
  $ackRcvd \leftarrow False$
  $msgsSent \leftarrow 0$
  $packet \leftarrow createPacket(UUID)$
  while $msgsSent < 243587$ and no $ackRcvd$ **do**
    $port \leftarrow getRandomPort()$
    $sendPacket(port, packet)$
  end while
  if $ackRcvd$ **then**
    return port
  else
    Birthday Attack was unsuccessful
  end if

require many more people to have such a high probability of a shared birthday. The paradox arises because we're not just looking for a specific birthday match but any pair of people with matching birthdays. The probability of two people not sharing a birthday decreases as more people are added to the group, and the likelihood of at least one pair sharing a birthday increases significantly.

The birthday paradox can be used to reduce the number of combinations of $sender\_port, receiver\_port$ while maintaining a satisfactory match probability. From the Birthday Paradox calculator [20] and assuming NAT devices with enough memory to keep all mappings active, one can get a 50% success rate of a match after sending 77162 packets. For a 99.9% success rate, 243587 packets are needed. Due to the nature of NATs (timeouts and a limited number of mapping maintained), these probabilities are unlikely to occur. Still, it gives a good idea of how the solution becomes more accessible.

Using the numbers above, an Android application [7] was developed to attempt to connect two mobile peers using 4/5G (which is by default using a NAT) using algorithm 1.

The evaluation results of 10 runs per provider in the Netherlands and Cyprus are shown in table III, where the first row of each cell (on the left side of the arrow) shows the success rate of penetrations using a randomized birthday attack. The evaluation of the simple birthday attack did not show encouraging results. The first conclusion that can be derived is that whether the attack will lead to a connection is very dependent on the cellular provider pair.

These aside, a small part of the trials resulted in at least one successful connection, although many provider combinations never succeeded. Even though some carrier combinations eventually connected, it is not satisfactory since a few successful attempts make this technique costly in terms of cellular data used and time inefficient since coordinating two users to start attacking at the same time is already challenging and error-prone on its own, doing it multiple times to achieve a single connection will deem the application hard to use for the general public.

B. Cellular Provider Aware NAT Puncturing

After multiple hypotheses on how to improve the connectivity based on time of connection, area, etc., the most prominent idea that we came up with is to understand the inner workings of each NAT, i.e., discover how the mapping works, whether there are any consistent patterns followed, etc. and then use that to predict what the following ports that each NAT will map the requests to. So instead of trying to connect to random ports of the peer, make a prediction —partially based on the NAT's inner workings, partially random, to enable exploration and exploitation— of what port the peer's NAT will open. The peer will do the same, thus *potentially* increasing the probability of connecting. Attempts will be based on the Birthday Paradox 99.9% likelihood of success, i.e. an attempt is defined as at most 243587 packets.

Using the findings of the EDA proposed in section III-D, a new connectivity library was developed [21]. The implementation is very similar to algorithm 1 used for the simple birthday attack, with two significant differences. Instead of choosing a random port to send to, it selects the port based on the peer's port-choosing algorithm shown in table I. The algorithm for NAT puncturing applies exploration and exploitation, meaning that sometimes it chooses the port based on the NAT's inner workings and sometimes picks a random port. The specific percentages can be seen in the `PortChooser` file of the connectivity library[6]. This means that the peer's provider needs to be known to have a higher probability of connecting. The second difference is that the phone opens five hundred random ports and listens to them simultaneously, potentially increasing the likelihood of choosing an open port.

This library can connect to multiple peers simultaneously by sending `CONNECTION-INIT` packets from var-

[6]https://github.com/OrestisKan/kotlin-birthday-connect/blob/master/src/main/kotlin/PortChooser.kt

ious open ports and awaiting responses. Connectivity attempts are made asynchronously, allowing the main app to remain responsive during connection establishment attempts. The peer's ID, IP address, and port are returned asynchronously upon successful connection. The library also sends `CONNECTION-MAINTENANCE` packets periodically to keep connections active based on the peer's timeout settings. A demo app[7] was developed to evaluate the library's success rate against a simple random birthday attack.

Evaluation results, shown in Table III, indicate that provider-aware NAT puncturing led to successful connections in four additional combinations compared to the random method in the Netherlands: Odido-Odido, Odido-Lebara, Lebara-Lebara, and VodaFone-KPN. For Cyprus Cyta-Cyta, Cyta-Epic, CableNet-Epic and CableNet-Cyta showed improvements with the carrier-aware connectivity method but not statistically significant except for Cyta-Cyta, which had the highest connectivity rate out of all (9 out of 10 attempts were successful). Notably, Cypriot carriers had almost no successful connection with the random birthday attack, while there were many more with the carrier-aware attack. Also, Odido-Vodafone showed no successful connections, and VodaFone-VodaFone had one less success than the random attack. Despite these mixed results, hypothesis testing was conducted for each provider combination to assess the statistical significance of the observed improvements.

Hypothesis testing was conducted using Fisher's exact test due to the limited sample size of connectivity attempts (an attempt is defined as at most 243587 packets sent) [22]. The null hypothesis (H_0) holds that the proportion of successful NAT punctures using cellular-aware NAT puncturing is not greater than with the random birthday attack: $H_0 = P_{random} \leq P_{CellularProviderAware}$. The alternative hypothesis (H_1) suggests that cellular-aware NAT puncturing has a higher success rate: $H_1 = P_{random} < P_{CellularProviderAware}$. A significance level of 0.05 was used. If the p-value from Fisher's test is below this threshold, H_0 is rejected. Table III presents the p-value results, with green-highlighted cells indicating where H_1 is accepted, demonstrating that cellular-aware NAT puncturing performed statistically better than the random birthday attack method.

The results of cellular provider-aware NAT puncturing, although a few times showed that it improved the connectivity rate statistically significantly, did not make it worse. Since the inverse, Fisher's exact test (H_1 being that random birthday attack has a higher proportion of successful results) would not be accepted in any provider combination of the ones tested.

C. Roaming

Roaming is significantly hindering the success of a connection attempt between two peers. No definite reason is derived on why roaming hinders connectivity since many parameters of the NATs change when roaming. Some observations of behavioural and parameter changes are:

[7] https://github.com/OrestisKan/bday-demo-app

1) **Telia and MyCall Norway:** Telia and MyCall of Norway both had a 120-second timeout for connection initiation —measured in the Oslo airport. When measured in Delft, Netherlands (both tunnelling through LycaMobile), the timeout fell to 5 seconds and 19 seconds, respectively, showing that roaming changes the timeout configuration.
2) **LycaMobile Belgium:** LycaMobile Belgium's connection initiation timeout could not be measured in Delft, Netherlands, as no response reached the phone after multiple attempts. This suggests that the timeout is extremely short, making it highly susceptible to even minimal network delays. Such a brief timeout would likely result in a poor user experience, indicating this may not be standard behaviour. The findings suggest that they also alter their timeout settings when roaming.
3) **Vodaphone Netherlands:** A birthday attack conducted between two phones on the Vodafone NL network resulted in a 40% success rate (success defined as at least one packet received out of 243587 sent). In contrast, when re-measured from Cyprus (with both phones roaming via CytaMobile-Vodafone), using identical conditions and during low traffic hours, there were no successful connections over approximately 4 hours of of sending packets. This significant decrease in success rate indicates that roaming introduces underlying differences despite the appearance of similar network conditions. Notably, the timeout and NAT types remained consistent during roaming tests.

The initial goal of creating a matrix to show connection times across European cellular providers was aborted due to a near-zero success rate for birthday attacks when roaming. Despite using validated software and various roaming configurations, no successful connections were made when at least one phone was roaming.

Experiments conducted over a week showed that roaming features significantly hinder connectivity. Although it remains unclear if cross-provider connections are impossible, they are unachievable within a reasonable timeframe using the current approach. Thus, the creation of the connection time matrix is postponed.

1) Roaming makes birthday attack-based connectivity almost impossible: This section compares the connection time required between two roaming peers versus two peers on the local Telia network in Norway. For the roaming scenario, we assume a best-case situation where the roaming user is the sole user of the roaming tower, with both peers in Cyprus using a Samsung Galaxy A53 5G (SM-A536B/DS).

Three key variables are considered:

- $p \approx 2.98$ **ms**: processing time
- $l \approx 79.20$ **ms**: average latency from Limassol to Oslo [23]
- $P = 64511$: available ports

In this scenario, each phone's NAT (NAT A and NAT B) creates mappings, X_A and X_B, with a 5-second connection

initiation timeout. The algorithm aims to cause a collision while these mappings are active by sending packets to random ports. The probability of a collision is approximately 0.00000000024. The window of puncturing opportunity is the time-to-live of a port that has yet to receive a response to its connection requests; in this case, the time-to-live is 5 seconds minus latency. Each phone can send a packet every p milliseconds. Hence, it can attempt about 1678 ports per window, resulting in a collision probability of 0.0000004032 per window. In the worst case, about 2480159 windows are needed. Since a new window is created every l milliseconds, it equates to approximately 54.6 hours.

For the local Telia Norway network, the parameters change to:

- $p \approx 2.98$ **ms**: processing time
- $l \approx 23$ **ms**: average local latency [24]
- $P = 64511$: available ports

With a time-to-live of around 120 seconds, each phone can attempt about 40269 ports per window, resulting in a collision probability of 0.00000967616. Thus, approximately 103347 windows are needed, equating to about 39.6 minutes.

These calculations demonstrate that establishing a connection while roaming takes at least 82 times longer than on the local network.

VI. Acknowledgements

The 5G puncturing knowledge presented here shows the feasibility of a generic provider-aware NAT solution in the future [8]. Our ideas are inspired by the IPv8 networking technology pioneered by Dr. Stokkink[9]. The IPv8 networking stack uses UDP puncturing of LAN devices as the exclusive mechanism for network discovery. This 2018 work inspired us to attempt 5G puncturing. The basic open-source skeleton of DeToks was provided by user *InvictusTMC* on GitHub.

VII. Discussion and Future Work

This exploratory study on the inner behaviour of NATs showed various exciting properties. First of all, no NAT implementation is the same. Birthday attacks are inherently unpredictable; even with complete knowledge of a carrier's NAT mapping function, randomness and outside influences affect the attack's success. For example, attempting a birthday attack during peak network usage hours will probably lead to a lower success rate than during peak hours. This is due to the carriers experiencing congestion on their network and employing some fairness protocols to allow all users to be connected, thus limiting a user that requires high network usage (one that performs a birthday attack, which constantly opens up sockets in a "robotic" way).

Another limiting factor is roaming. As explained in section V-C, roaming significantly hindered this research since the connectivity through birthday attacks while roaming is almost impossible for reasons that have not yet been fully identified.

The main takeaway from this research is that connectivity through birthday attacks in a fully distributed setting is possible in principle. Still, it is hard to accurately quantify the success rate and its reliability. So many factors may jeopardize it, such as NAT type of carrier, combination of carriers, time of the day, congestion of the network and roaming.

A. Future Work

This study marks a significant step towards understanding and enhancing connectivity in distributed artificial intelligence (AI) deployments over 5G networks. However, several areas for further research and development can build on the findings presented.

1) Optimization of NAT Puncturing Techniques: Although the provider-aware NAT puncturing strategy showed promising results, there is room for optimization. Future work could explore more advanced algorithms that adaptively adjust puncturing strategies based on real-time network conditions or leverage machine learning to predict the most effective puncturing patterns based on historical data. Additionally, integrating these techniques into existing networking protocols could streamline implementation and improve scalability.

2) Addressing Roaming and Mobility Challenges: The research highlighted significant challenges in maintaining connectivity during roaming, which remains an open problem. Future research could focus on developing robust mechanisms to overcome roaming's limitations.

3) Development of Decentralized AI Applications: The proof-of-concept decentralized social media application demonstrated the feasibility of the proposed architecture. Future work could expand this by developing and testing more complex decentralized AI applications across different domains, such as search engines or any area where there is a monopoly or oligopoly by some companies.

4) Security and Privacy Considerations: As decentralized AI systems gain traction, security and privacy concerns become increasingly important. Future research should explore the security implications of decentralized networks, focusing on potential vulnerabilities introduced by NAT puncturing and strategies to mitigate these risks.

5) Evaluation of Long-Term Performance and Scalability:: The study provided an initial assessment of the system's performance, but further long-term evaluations are necessary. Future research could investigate the system's scalability, especially under heavy network traffic or during peak usage times, and assess its robustness in real-world deployment scenarios. This could involve stress-testing the system in large-scale simulations or live environments to understand its limitations and potential failure points.

By addressing these areas, we can continue to enhance the viability and resilience of distributed systems on 5G networks, paving the way for broader adoption and innovation in this field.

VIII. Conclusion

This thesis investigated the complex NAT configurations employed by various European cellular providers to sup-

[8]This project was partly funded by NWO grant BLOCK.2019.004

[9]https://datatracker.ietf.org/doc/html/draft-pouwelse-trustchain-01

port decentralized social media applications over 5G networks. Through reverse engineering, it was revealed that each provider utilizes distinct strategies for port management, ranging from random allocation to the use of structured port blocks. This configuration diversity poses challenges for true peer-to-peer connectivity, which requires navigating these varied NAT behaviours without relying on centralized servers.

The introduction of a provider-aware NAT puncturing strategy marked a significant advancement over traditional random methods. Empirical results demonstrated improved connection success rates, and hypothesis testing via Fisher's exact test confirmed statistically significant enhancements in specific cases, as highlighted in the results table. These outcomes affirm that tailoring NAT penetration techniques to the particular configurations of different carriers can substantially enhance connectivity performance in distributed 5G applications.

These findings highlighted the critical role of understanding and adapting to NAT behaviour in achieving robust and reliable decentralized communication. The feasibility of true decentralized mobile applications is demonstrated by integrating the decentralized connectivity library with DeToks, the Tribler lab's decentralized TikTok.

References

[1] C. F. Jennings and F. Audet, "Network Address Translation (NAT) Behavioral Requirements for Unicast UDP," RFC 4787, Jan. 2007. [Online]. Available: https://www.rfc-editor.org/info/rfc4787

[2] "Lane v. facebook, inc." Court of Appeals, 9th Circuit, USA, p. 811, 2012, no. 10-16380.

[3] "Apple inc. v. pepper," Supreme Court, USA, p. 1514, 2019, no. 17-204.

[4] Z. Wang, Z. Qian, Q. Xu, Z. Mao, and M. Zhang, "An untold story of middleboxes in cellular networks," *Proceedings of the ACM SIGCOMM 2011 conference*, Aug 2011.

[5] A. Nikravesh, D. R. Choffnes, E. Katz-Bassett, Z. M. Mao, and M. Welsh, "Mobile network performance from user devices: A longitudinal, multidimensional analysis," in *Passive and Active Measurement: 15th International Conference, PAM 2014, Los Angeles, CA, USA, March 10-11, 2014, Proceedings 15*. Springer, 2014, pp. 12–22.

[6] D. Anderson, "How nat traversal works - nat notes for nerds," Apr 2022. [Online]. Available: https://blog.apnic.net/2022/04/26/how-nat-traversal-works-nat-notes-for-nerds/

[7] O. Kanaris, "NAT measurements gathering with Naive Birthday Attack for connecting smartphones," Dec. 2023.

[8] J. Rosenberg, C. Huitema, R. Mahy, and J. Weinberger, "STUN - Simple Traversal of User Datagram Protocol (UDP) Through Network Address Translators (NATs)," RFC 3489, Mar. 2003. [Online]. Available: https://www.rfc-editor.org/info/rfc3489

[9] V. Paulsamy and S. Chatterjee, "Network convergence and the nat/firewall problems," 2003.

[10] M. Zolotykh, "Comprehensive classification of internet background noise," 2020.

[11] J. Mol, J. Pouwelse, D. Epema, and H. Sips, "Free-riding, fairness, and firewalls in p2p file-sharing," 2008.

[12] M. Holdrege and P. Srisuresh, "IP Network Address Translator (NAT) Terminology and Considerations," RFC 2663, Aug. 1999. [Online]. Available: https://www.rfc-editor.org/info/rfc2663

[13] O. Kanaris, "NAT Mapping data Gathering and analysing tool," Feb. 2023.

[14] IBM, Oct 2021. [Online]. Available: https://www.ibm.com/topics/exploratory-data-analysis

[15] O. Kanaris, "Cellular Network NAT Reverse Engineering and Exploration," Apr. 2024. [Online]. Available: https://https://github.com/OrestisKan/telecom-analysis

[16] [Online]. Available: https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.shapiro.html

[17] J. B. McDonald and Y. J. Xu, "A generalization of the beta distribution with applications," *Journal of Econometrics*, vol. 66, no. 1, pp. 133–152, 1995. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0304407694016124

[18] O. Kanaris and J. Pouwelse, "Mass adoption of nats: Survey and experiments on carrier-grade nats," 2023.

[19] K. Suzuki, D. Tonien, K. Kurosawa, and K. Toyota, "Birthday paradox for multi-collisions," in *Information Security and Cryptology – ICISC 2006*, M. S. Rhee and B. Lee, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 29–40.

[20] Fast-Reflexes, "Fast-reflexes/birthdayproblem-python: Implementation of a solver of the generalized birthday problem in python." [Online]. Available: https://github.com/fast-reflexes/BirthdayProblem-Python

[21] O. Kanaris, "Birthday-Attack-based smartphone connectivity kotlin library," May 2023.

[22] A. Edwards, "Chapter 67 - r.a. fischer, statistical methods for research workers, first edition (1925)," in *Landmark Writings in Western Mathematics 1640-1940*, I. Grattan-Guinness, R. Cooke, L. Corry, P. Crépel, and N. Guicciardini, Eds. Amsterdam: Elsevier Science, 2005, pp. 856–870. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780444508713501480

[23] Jun 2024. [Online]. Available: https://wondernetwork.com/pings/Limassol

[24] S. Ltd., "Telia norge as speed test," Jun 2024. [Online]. Available: https://www.broadbandspeedchecker.co.uk/isp-directory/Norway/telia-norge-as.html

Appendix

A. Orange Belgium

Analysis of 264479 mappings from North Brussels revealed that Orange Belgium uses only 767 unique ports across three blocks: $[5632, 5887]$, $[9984, 10239]$, and $[25088, 25343]$, with no linear selection or frequent pairs. Ports are grouped into 256-port blocks, assigned based on availability, and used non-linearly. An exploration-exploitation strategy, similar to Dutch Lebara and KPN, is recommended for NAT penetration.

B. LycaMobile Belgium

Analysis of 316151 mappings from North Brussels shows that LycaMobile Belgium, like its Dutch counterpart, exhibits no linear port increment, specific regional preferences, or consistent port reuse, utilizing almost the entire port space. Thus, LycaMobile's NAT likely maps each port to a randomly available one.

C. Orange France

Orange France uses a wide range of ports, from 1 to 65500, with 65407 unique ports mapped to and minimal reuse, suggesting random NAT mapping. Unlike other providers, Orange France mapped to reserved ports (1-1023).

D. SFR France

SFR France shows minimal port reuse and no linear increments, covering ports from 1025 to 65535, with 64509 unique ports used. The dataset of 257,913 entries indicates random NAT mapping.

E. Telia & MyCall Norway

Telia used 256 unique ports, while MyCall used 812, with Telia selecting ports from $[14592, 14847]$ and MyCall from $[7048, 7419]$ and $[42188, 42623]$. Ports are grouped into 256-port blocks and used non-linearly. An exploration-exploitation strategy similar to that used for Dutch Lebara, KPN, and Belgian Orange is recommended.

F. Cyta & PrimeTel Cyprus

Analysis of 824220 mappings for Cyta and 655849 mappings for PrimeTel from Aglantzia, Nicosia, showed no linear port increment, regional preference, or consistent port reuse. This indicates that both NATs randomly map each port to an available one across the entire port space.

G. Epic & CableNet Cyprus

Analysis of 681274 mappings for Epic and 608419 mapping for CableNet from Aglantzia, Nicosia, indicates that both group ports into 256-port blocks, with users assigned based on availability. Ports are allocated sequentially until the block is exhausted in the case of Epic and randomly in the case of CableNet; then, the user is assigned to a new block. The NAT penetration strategy is similar to Dutch Lebara, KPN, Belgium's Orange, and Norway's Telia and MyCall.

H. TIM & WindTre Italy

TIM used 1008 unique ports, while WindTre used 17000; both ports were grouped into 256-port blocks. WindTre allocated ports in the groups linearly, while TIM allocated them randomly. TI only used five consecutive groups of ports and used them whole, while WindTre allocated users in random groups scattered in the whole port space, and users were allocated in a group for significantly less time in each group of ports using WindTre compared to TIM