



Department of Mathematics and Computer Science
Coding Theory and Cryptology Group

Secure Sessions for Ad Hoc Multiparty Computation in MPyC

Master's thesis

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■ VPN This way the VPN client can hide the IP addresses of the final destinations of the traffic from hosts between itself and the VPN server. Depending on the use case, the VPN server could either facilitate the client's secure access to other resources on the virtual network, or provide anonymity to the VPN client by hiding its IP address from the hosts its communicating with on the public Internet.	11
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Glossary

***E*³** Extensible Evaluation Environment [27](#)

ACL Access Control List [20](#)

AOT Ahead-Of-Time [38](#), [42](#)

API Application Programming Interface [20](#)

CA Certificate Authority [10](#)

CGNAT Carrier-Grade NAT [15](#)

CIDR Classless Inter-Domain Routing [v](#), [12](#)

DERP Designated Encrypted Relay for Packets [14](#), [20](#)

DNS Domain Name System [9](#)

DTLS Datagram Transport Layer Security [10](#)

ECDH Elliptic Curve Diffie-Hellman [12](#)

FTP File Transfer Protocol [7](#)

HTML HyperText Markup Language [7](#)

HTTP HyperText Transfer Protocol [9](#), [10](#)

HTTPS HyperText Transfer Protocol Secure [10](#)

ICE Interactive Connectivity Establishment [15](#)

IP Internet Protocol [8](#), [11](#), [19](#), [23](#)

IPSec Internet Protocol Security [v](#), [11](#)

ISP Internet Service Provider [7](#), [11](#), [15](#)

JIT Just-In-Time [38](#), [42](#)

JS JavaScript [37](#), [42](#)

LAN Local Area Network [8](#), [19](#)

MAC Media Access Control [23](#)

MPC Secure Multiparty Computation [37](#)

NAT Network Address Translation [13](#)

NAT-PMP NAT Port Mapping Protocol [14](#)

P2P Peer to Peer [19](#), [20](#)

PCP Port Control Protocol [14](#)

PDU Protocol Data Unit [7](#)

PKI Public Key Infrastructure [10](#)

PSK Pre-Shared Key [11](#)

QUIC Quick UDP Internet Connections [9](#), [10](#)

SMTP Simple Mail Transfer Protocol [7](#)

SSH Secure Shell Protocol [7](#), [11](#)

SSI Self-Sovereign Identity [23](#)

SSL Secure Sockets Layer [10](#)

STUN Session Traversal Utilities for NAT [14](#)

TAP Network Tap [19](#)

TCP Transmission Control Protocol [9](#), [10](#)

TLS Transport Layer Security [9](#), [10](#), [11](#), [17](#)

TUN Network Tunnel [19](#)

TURN Traversal Using Relays around NAT [14](#)

UDP User Datagram Protocol [8](#), [10](#), [14](#), [17](#)

UPnP Universal Plug and Play [14](#)

URL Universal Resource Locator [9](#)

VPN Virtual Private Network [v](#), [10](#), [11](#), [12](#), [17](#), [19](#), [20](#)

WASM WebAssembly [38](#), [42](#)

WebRTC Web Real-Time Communication [15](#)

WWW World Wide Web [7](#)

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Chapter 1

Introduction

Part I

The State of Multiparty Communications over the Internet

include a
section on
MPC?

Chapter 2

Internet Communications

This chapter provides important background information on secure Internet communications, the challenges to multiparty communications and the approaches to overcome them.

The Internet is a global network that consists of numerous interconnected computer networks spanning billions of host devices owned by diverse parties from around the world. Key components of the Internet include the Internet Protocol Suite (known as TCP/IP) and the physical infrastructure that connects the individual networks. Sections of the infrastructure are deployed and managed by different tiers of [Internet Service Providers \(ISPs\)](#) who also maintain links between each other. To ensure efficient utilization of the hardware, the Internet relies on packet-switching techniques that divide the data traffic into smaller individually processed **packets**.

Communication protocols are usually organized into abstraction layers based on the scope of their functionality with higher-layer protocols relying on the services provided by the lower-layer protocols. Several reference models define different layering schemes, for example, the OSI model recognizes 7 layers, while TCP/IP itself combines some of the layers and recognizes 4. Figure 2.1 shows how the two models relate to each other and describes the responsibilities of the various layers. Throughout this thesis, we will refer to the 7 layer numbers of the OSI model as they are more widely used in the literature.

The packets that are transmitted over the network contain information from multiple protocols organized in [Protocol Data Units \(PDUs\)](#) with the lower-layer PDUs **encapsulating** the higher-layer PDUs as a (usually opaque) **payload**. Additionally, the PDU of a protocol contains control information for the protocol itself in the form of a **header** or **footer**.

Services that are implemented as Application layer (L7) protocols on top of TCP/IP include the [World Wide Web \(WWW\)](#), file transfer ([FTP](#)), email ([SMTP](#)), instant messaging, remote access ([SSH \[LY06\]](#)) and others. The Web is a collection of interconnected documents that use Web technologies such as [HTML](#) and JavaScript. It is typically accessed via a user-agent software such as a **Web Browser**.

The following sub-sections will briefly cover the main protocols of the Internet Protocol Suite, the issues for multiparty communications and some of the low-level mitigation techniques.

Is there a more fitting section name than "The Internet"

add a paragraph that describes what the rest of the section will contain

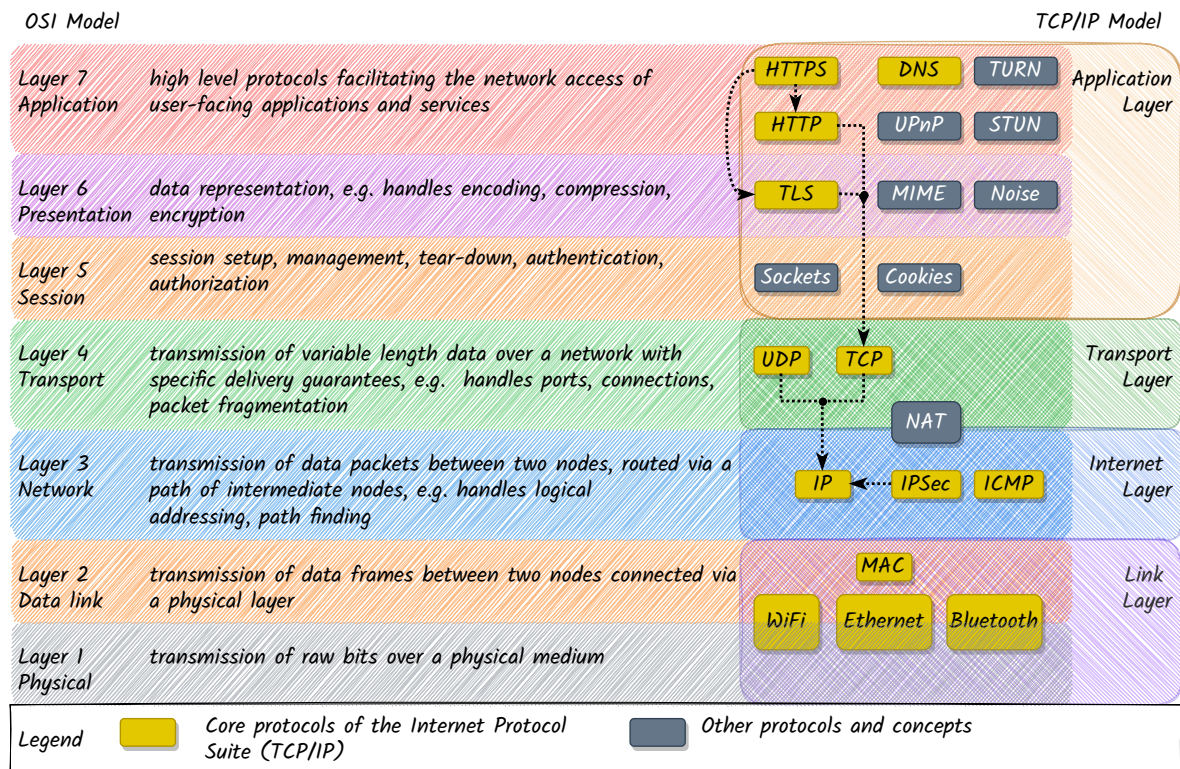


Figure 2.1: OSI model mapping of the Internet Protocol Suite

2.1 Communication Protocols

2.1.1 Network Layer (L3)

The **IP** [81] is a Network layer (L3) protocol of the Internet Protocol Suite that is responsible for transferring datagrams between devices across the boundaries of their **Local Area Networks (LANs)** by possibly routing them via multiple intermediate devices (e.g. routers). A datagram is a self-contained unit of data, typically associated with connectionless protocols that provide no guarantees for delivery or ordering (e.g. IP, UDP). IP datagrams have a header that contains fields such as the **IP addresses** of its source and destination, and a payload that encapsulates the data from the Transport Layer (L4) protocols. A **router** is a device that is part of multiple networks and relays datagrams between them based on a routing table that maps IP address ranges to networks.

2.1.2 Transport Layer (L4)

User Datagram Protocol (UDP) is a very thin Transport layer (L4) protocol that only provides port multiplexing and checksumming on top of IP. - Port multiplexing - uses 16-bit numbers to allow multiple processes behind the same IP address to establish their own communication channels - Checksumming - used to detect errors in the datagram header and payload

As with IP, UDP packets are referred to as datagrams because they are not delivered reliably and if such features are required, they must be implemented by the consumer of the protocol.

packet is the physical envelope of the IP datagram

show a diagram of the internet with multiple local networks

Transmission Control Protocol (TCP) is another Transport layer (L4) protocol. Like UDP, it provides port multiplexing and checksumming, but it offers stronger delivery guarantees. Some of the features it offers are listed below:

- Connection management - TCP establishes reliable connections between the communicating hosts and can gracefully terminate them when required
- Segmentation - TCP splits variable-length data streams into segments that fit inside IP datagrams and transmits them individually
- ordering - segments have sequence numbers to ensure that they are reassembled in the correct order at the receiving host
- Error detection and correction - TCP retransmits a segment if its checksum fails

Both TCP and UDP are useful in different scenarios. UDP is faster and is used for applications that can tolerate packet loss, e.g. video streaming, VoIP, or in cases where it is preferable for an application to implement its own reliable delivery. TCP has a higher overhead than UDP but its reliable delivery is a good default for most applications on the Internet.

Quick UDP Internet Connections (QUIC) is a more recent Transport layer (L4) protocol that is built on top of UDP and offers similar features to TCP, but with lower latency in some scenarios. It provides an additional level of multiplexing within a process, which allows multiple streams of data to be sent over the same connection asynchronously. To better optimize the establishment of secure connections, QUIC is tightly coupled with **TLS** version 1.3. One of the main uses of QUIC is inside **HTTP** version 3.

2.1.3 Application Layer (L7)

HyperText Transfer Protocol (HTTP) is an Application layer (L7) protocol that enables stateless request/response interactions on the Web between web servers and clients (e.g. browsers). Similar to other L7 protocols, it uses **Universal Resource Locators (URLs)** for locating resources.

URL format: `scheme://host:port/path?query=value#fragment`

URL example: `http://www.example.com:80/path/to/file.html`.

HTTP up to version 2 uses TCP as a transport protocol and since version 3 uses **QUIC**. HTTP provides several features such as:

- Request Methods - used by the client to specify the action to perform on the resource behind the given URL, e.g. GET, POST, PUT, DELETE, etc.
- Headers - used to provide additional information about a request or response, e.g. Content-Type, Authorization, Cache-Control
- Status codes - used to indicate the result of a request, e.g. if it was successful (200), or if the resource is missing (404)
- Cookies - used to include stateful information about the user kept on the client-side
- Caching - used to specify that the result of a request can be cached for a certain time to avoid repeating the request's action.

The **Domain Name System (DNS)** operates at the Application Layer (L7) and allows the conversion of human-readable domains to IP addresses, e.g. `google.com` to `142.250.179.142`.

2.2 Secure Communication Protocols

The communication protocols from the previous section do not encrypt the payloads of their packets, which allows intruders and routers between the communicating hosts to see the data. This section provides an overview of protocols that provide security to those communication protocols.

2.2.1 Transport Layer (L4) to Application Layer (L7)

[Transport Layer Security \(TLS\)](#) [Res18] and its precursor [Secure Sockets Layer \(SSL\)](#) are protocols that provide secure communications to Application layer (L7) protocols on top of a reliable Transport layer (L4) protocol like [TCP](#). [Datagram Transport Layer Security \(DTLS\)](#) is a related protocol that works with connectionless transport protocols like [UDP](#). TLS is usually placed somewhere between the Presentation layer (L6) and the Transport layer (L4) because Application layer (L7) protocols use it as a transport protocol while having to manage the TLS connections.

TLS relies on digital certificates and [Public Key Infrastructure \(PKI\)](#) to establish trust between the communicating parties and to prevent man-in-the-middle attacks. A certificate includes information such as:

- Subject - an identifiable name for the certificate's owner. Depending on the use case it can be a domain name, an IP address, an email address or others.
- Subject's public key - an asymmetric public key that is used by other parties to verify that they are communicating with the subject who is expected to be in control of the corresponding private key. The public key can also be used to encrypt messages that only the subject can decrypt.
- Issuer - an entity that is responsible for validating the identity of the subject. It is usually a [Certificate Authority \(CA\)](#) that is trusted by the consumer of the certificate, but in the case of a self-signed certificate, it can be the subject itself
- Issuer's signature - a signature of the certificate's contents using the issuer's private key

Trusted CAs that serve as the root of trust are usually included in the operating system or a Web browser. This allows applications to verify the certificates of the servers they communicate with. Web browsers use [HyperText Transfer Protocol Secure \(HTTPS\)](#) [Res00] - a variant of [HTTP](#) that uses TLS to secure the underlying [TCP](#) or [QUIC](#) connections of Web applications. The one-way approach where only the server has to authenticate itself to the clients is usually sufficient for most web interactions. TLS can also be used for mutual authentication, where both of the communicating parties have to present a valid certificate to each other, but this requires additional infrastructure to manage the client-side certificates. This mode of operations is sometimes used in Zero Trust networking, in microservice architectures and TLS-based [VPN](#) applications.

Due to asymmetric cryptography being computationally expensive, TLS uses a hybrid approach. The communicating parties use the asymmetric key/s and Diffie–Hellman key exchange to agree on a set of symmetric session keys for authentication and encryption/decryption of their data.

TLS is rather complex because it needs to support many possible use cases while remaining backward compatible. It allows the negotiation of security parameters like cipher suits.

TLS operates at the Transport layer (L4) and above so it encrypts the application traffic, but not the IP datagrams. While an [ISP](#) or an intruder with access to the network cannot decrypt the traffic to see what is being communicated, it could see which IP addresses are communicating with each other.

[Secure Shell Protocol \(SSH\)](#) is an Application layer (L7) protocol that allows a client to securely log in and execute commands on a remote server. It does not rely on TLS but uses similar cryptographic primitives. Both the client and the server must authenticate to each other using public-key cryptography or a password. The cryptographic material must be distributed via a side channel either manually or via automation tools.

2.2.2 Network Layer (L3)

Network layer (L3) security protocols provide host-to-host security in Internet Protocol communications. Their implementations are usually configured in the operating systems of the hosts and are invisible to the higher-layer protocols that depend on the Internet Protocol.

IPSec

[Internet Protocol Security \(IPSec\)](#) is a Network layer (L3) protocol suite that provides host-to-host secure communications between [IP](#) hosts. It has two modes of operation:

- Transport mode - encrypts the payload of an IP datagram, but not the header. This mode secures the traffic between two network hosts, but similarly to [TLS](#), the routers between the hosts can still see the IP addresses of the hosts and the ports they are communicating on
- Tunneling mode - encrypts the entire IP datagram and encapsulates it in a new IP datagram with an unencrypted header. This mode is used for secure comm allows a host to decrypt the encapsulated both the traffic connection between a client and a server that can decrypt the encapsulated IP datagram and forward it to its destination.is often used to securely connect a client to a server that can decrypt the encapsulated IP datagrams and forward them to their destination. The client

IPSec always requires mutual authentication, unlike [TLS](#), where it is optional. Authentication can be achieved either via digital certificates, [Pre-Shared Keys \(PSKs\)](#) or others.

OpenVPN Protocol

-
-
-
-

WireGuard

WireGuard [[Don17](#)] is a more recent protocol with a design informed by lessons learned from IPSec and OpenVPN and a key management approach inspired by [SSH](#). It is a lower-level protocol that focuses on configuration simplicity while network topology, peer discovery and key distribution are left as a responsibility of higher-level systems that use it as a building block. Wireguard is implemented as a Layer 3 overlay over UDP tunnels. WireGuard has

VPN This way the VPN client can hide the IP addresses of the final destinations of the traffic from hosts between itself and the VPN server. Depending on the use case, the VPN server could either facilitate the client's secure access to other resources on

both user-space implementations that use a TUN driver and also has direct support built into the Linux Kernel since version 5.6 (May 2020). The kernel implementation allows for better performance because it does not need to copy packets between the kernel and user-space memory.

WireGuard's cryptography is based on the **Noise Protocol Framework**[\[Per18\]](#). Noise is another recent effort that applies the ideas of TLS in a simplified way. It serves as a blueprint for designing use-case-specific protocols for establishing secure communication channels based on **Elliptic Curve Diffie-Hellman (ECDH)** handshake patterns. It powers the end-to-end encryption in messaging applications such as WhatsApp and Signal, and **Virtual Private Network (VPN)** software such as WireGuard and Nebula.

The snippets below show a minimal set of configuration options that need to be provided for two peers to be able to form secure tunnels with each other.

```
1 # peer1.conf
2 [Interface]
3 Address = 101.0.0.1/32
4 ListenPort = 53063
5 PrivateKey = ePTiXXhHjvAHdWUr8Bimk30n0gh3m241RAzsNOJZDWO=
6
7 [Peer]
8 PublicKey = BSn0ejd1Y3bKuD+Xpg0ZZeOf+Ies/oq10NZxw+S0mkc=
9 AllowedIPs = 101.0.0.2/32
10 Endpoint = peer1.example.com:38133
```

```
1 # peer2.conf
2 [Interface]
3 Address = 101.0.0.2/32
4 ListenPort = 38133
5 PrivateKey = sN/d6XUPEVPGSziVgCC0n0ivDK+qAoYC3nxxnssQ5Rls=
6
7 [Peer]
8 PublicKey = e/TxvPmrgcc1G4cSH2bHv5J0PRHXKjYxTFoU8r+G93E=
9 AllowedIPs = 101.0.0.1/32
```

Each peer has a public/private key pair that is used for authentication and encryption based on the Noise Protocol Framework [\[Per18\]](#). The **Address** field specifies the virtual IP address that the local network interface will use, while the **AllowedIPs** field specifies what virtual IP addresses are associated with a peer's public key. A peer's **Endpoint** field specifies the URL at which it can be reached. Only one of the peers must be configured with a reachable endpoint for the other one. In the above example once **peer1** initiates communication with **peer2**, **peer2** will learn the current endpoint of **peer1** and will be able to communicate back with it.

2.3 Challenges and Solutions for Multiparty Communications

The version of the Internet Protocol, that was originally deployed globally (IPv4), uses 32-bit numbers as IP addresses, allowing for around 4 billion unique addresses. Due to the popularity of the Internet, there are many more devices than available IPv4 addresses, which has caused challenges. IPv6 is a newer version of the protocol that uses a larger 128-bit address space

elaborate

noise is
transport
agnostic

noise has
limited ci-
pher suites

CIDR is a
common
notation for
describing
IP address
ranges, e.g.
'192.168.0.1/16'
where the
number
after the
slash de-
scribes the
bit-length
of the fixed
prefix for a
subnet.

which is sufficient for assigning 100 addresses for each atom on Earth. However, its adoption has been slow, as according to Google[Goo23] as of 2023 around 41% of their users access their services over IPv6. Additionally, despite that IPv6 allows for all devices to be addressable on the Internet, for security reasons, most of them would use firewalls to block incoming remote traffic that is not associated with outgoing connections.

A widespread solution to the addressing problem is **Network Address Translation (NAT)**. It allows many devices without globally unique IP addresses to initiate connections to publicly addressable devices on the Internet via a limited number of gateways that must have globally unique IP addresses. A NAT gateway replaces the local source IP address of each outgoing IP datagram with its own public IP address before passing it on to the next link on the way to the destination while maintaining a mapping between the source and destination IPs in a translation table. The destination host can then address its responses back to the NAT gateway's public IP address, which in turn replaces its own IP from the incoming datagrams with the IP of the local device and forwards them to it. If the IP datagrams encapsulate TCP/UDP packets, the gateway additionally rewrites the source and destination ports, which means that NAT techniques can be placed somewhere between Layers 3 and 4 of the OSI model.

The effect of NAT on connectivity is similar to an IPv6 firewall as they both allow devices on a local network to initiate bidirectional communication to remote devices with public IP addresses, but connections cannot be natively initiated by the remote devices. As Figure 2.2 shows, it follows that when two devices are behind separate NATs, neither can contact the other first. **Client/Server** communication is less affected by this limitation because Servers are usually deployed to a public IP address that can be contacted by Clients with local IP addresses. **Peer-to-Peer** communication, however, is more challenging because the peers are often devices in separate residential networks behind different NATs. Several **NAT traversal** techniques try to solve this with different performance tradeoffs and success that varies depending on the NAT [JA07] and its behavior when mapping ports and IP addresses.

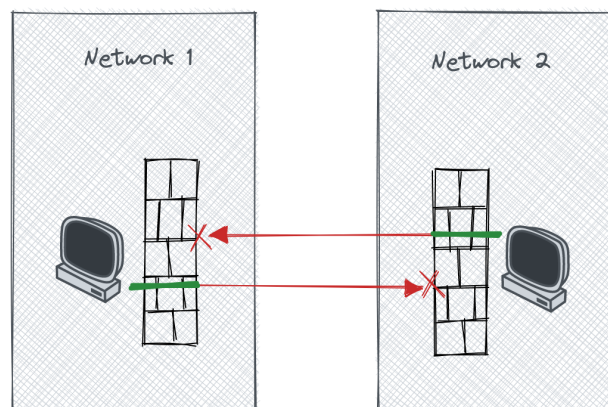


Figure 2.2: Two parties behind separate NATs

One approach based on the Client/Server model is to use a publicly addressable **relay** server that is contacted by the NATed devices and then forwards the Peer-to-Peer traffic to the intended recipient. Compared to direct communication, relaying results in a higher network latency due to the longer path that each packet must travel. Maintaining a relay server requires

describe some of the nat behaviors, e.g. if the source IP address/-port vary per destination are changed depending on the destination/port mapping algorithms, if it maps ports, IPs, whether the mapped IPs are different per destination and others.

some technical expertise and may be costly depending on the expected throughput. Despite the drawbacks, relaying works under most networking scenarios and is therefore often used as a fallback in case all other approaches fail to find a direct path. Protocols such as [Traversal Using Relays around NAT \(TURN\)](#) [Red+20] and [Designated Encrypted Relay for Packets \(DERP\)](#) [Tai22] can be used to securely implement relaying.

The NAT gateway in many residential networks is a Router device under the customer's control that has a statically or dynamically assigned public IP address. Most routers can be manually configured through their admin page to forward all traffic that arrives at a given port to a specific device on the local network. Remote applications can then initiate a connection to the local device if they know the IP address of the router and the forwarded port. The manual configuration, however, can be inconvenient and many users may be unaware of that setting because it is not necessary for the more straightforward Client/Server communications. Some routers also support programmatic configuration of port forwarding via a Layer 7 protocol like [Universal Plug and Play \(UPnP\)](#) or its successors [NAT Port Mapping Protocol \(NAT-PMP\)](#) and [Port Control Protocol \(PCP\)](#). However, these protocols are not always supported and are often disabled by the local network administrators due to security concerns related to bugs in their implementation, vulnerable IOT devices on the local network or malicious programs being able to expose local devices to the internet.

An efficient NAT traversal approach that works with some types of NATs is to use [Session Traversal Utilities for NAT \(STUN\)](#) [Pet+20] in combination with UDP hole punching (Figure 2.3). STUN is a protocol operating at Layer 7 that allows a client application to detect the presence of NAT gateways on the network path to a public STUN server, and identify their types and the public IP address that they map to externally. The process usually involves the following steps:

- An application sends [UDP](#) datagrams to the STUN server (1, 3 in fig. 2.3)
- The STUN server responds with the source IP address and port specified inside the datagrams (2, 4 in fig. 2.3)
- The application compares its own endpoint with the source endpoint observed by the STUN server and if the values differ, it can be inferred that they were rewritten by a NAT. Additional STUN servers are contacted to determine if the NAT maps IPs and ports in a predictable fashion.

UDP hole punching is a related technique that, depending on the NAT types, can allow direct communication between two applications behind separate NATs. The applications must discover each other's externally mapped endpoints, perhaps via the STUN server. If the NATs use the same external port regardless of the remote destination:

- The two applications simultaneously send UDP packets to each other's external endpoints (5 in fig. 2.3)
- Their respective NATs will process the outgoing packets to the other peer and create a port mapping for the reverse traffic - a "punched hole"
- When the incoming traffic from a peer arrives at the other peer's NAT, it will be forwarded correctly due to the port mapping that was created earlier

NATs that map different ports per remote destination sometimes allocate port numbers predictably, which can be used by the peers to try to guess the port that will be opened by the opposing side's NAT.

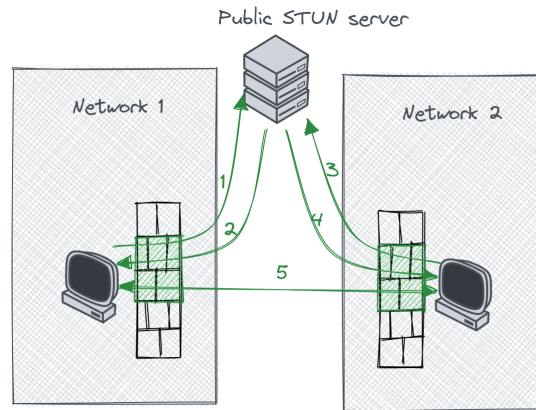


Figure 2.3: NAT traversal via STUN

In mobile networks like 4G and 5G, the **ISP** often utilizes a **Carrier-Grade NAT (CGNAT)** as part of their infrastructure, while all devices under the user's control, including the router, only have local IP addresses. STUN techniques would fail to discover a direct path between two parties behind separate CGNATs or other unpredictable NAT algorithms. The only remaining possibility is to relay the traffic via a publicly reachable third-party host using a protocol similar to TURN.

Interactive Connectivity Establishment (ICE) is a protocol that describes a standard way for peers to gather candidate addresses for direct communication via STUN and TURN and then exchange them via a signaling server. The protocol continuously checks which candidates provide the best connection and adjusts them.

Web Real-Time Communication (WebRTC) is a framework that allows peer-to-peer communications between Web applications in Web browsers. Web applications are normally limited to HTTP connections and cannot use raw UDP or TCP connections. WebRTC implements the ICE functionality in Web browsers and provides an API to Web applications.

only 65000 ports per IP address means that CGNATs that provide more than 65000 connections from client devices require more than one public IP address

hairpinning - Hairpinning, also known as NAT loop-back or NAT reflection, is a technique used by NAT devices to allow hosts on a private network to access a public server using

Chapter 3

Overlay Networks

An **overlay network** is a higher-order solution that provides additional networking functionality on top of an existing underlay network like the Internet. From the point of view of its consumers, an overlay network may appear at a lower OSI layer, despite being implemented using protocols from higher layers. For example [VPNs](#) can provide virtual interfaces to the Operating System at the Link layer (L2) or Network layer (L3) while being implemented on top of a Transport layer (L4) protocol like [User Datagram Protocol \(UDP\)](#) or a Presentation layer (L6) protocol like [Transport Layer Security \(TLS\)](#). Virtual IP addresses can be assigned to the hosts and applications that are already designed to work with TCP/IP can directly use the virtual network interfaces via the regular TCP/IP mechanisms provided by the operating system.

Other overlay networks are both implemented and used at the Application layer (L7). To communicate via such an overlay network, applications often have to implement specific functionality in their software by utilizing a framework or a library.

Figure [10.1](#) shows an approximate OSI model mapping of several protocols and network overlay solutions from the point of view of the systems that use them and the arrows show dependency relations between them.

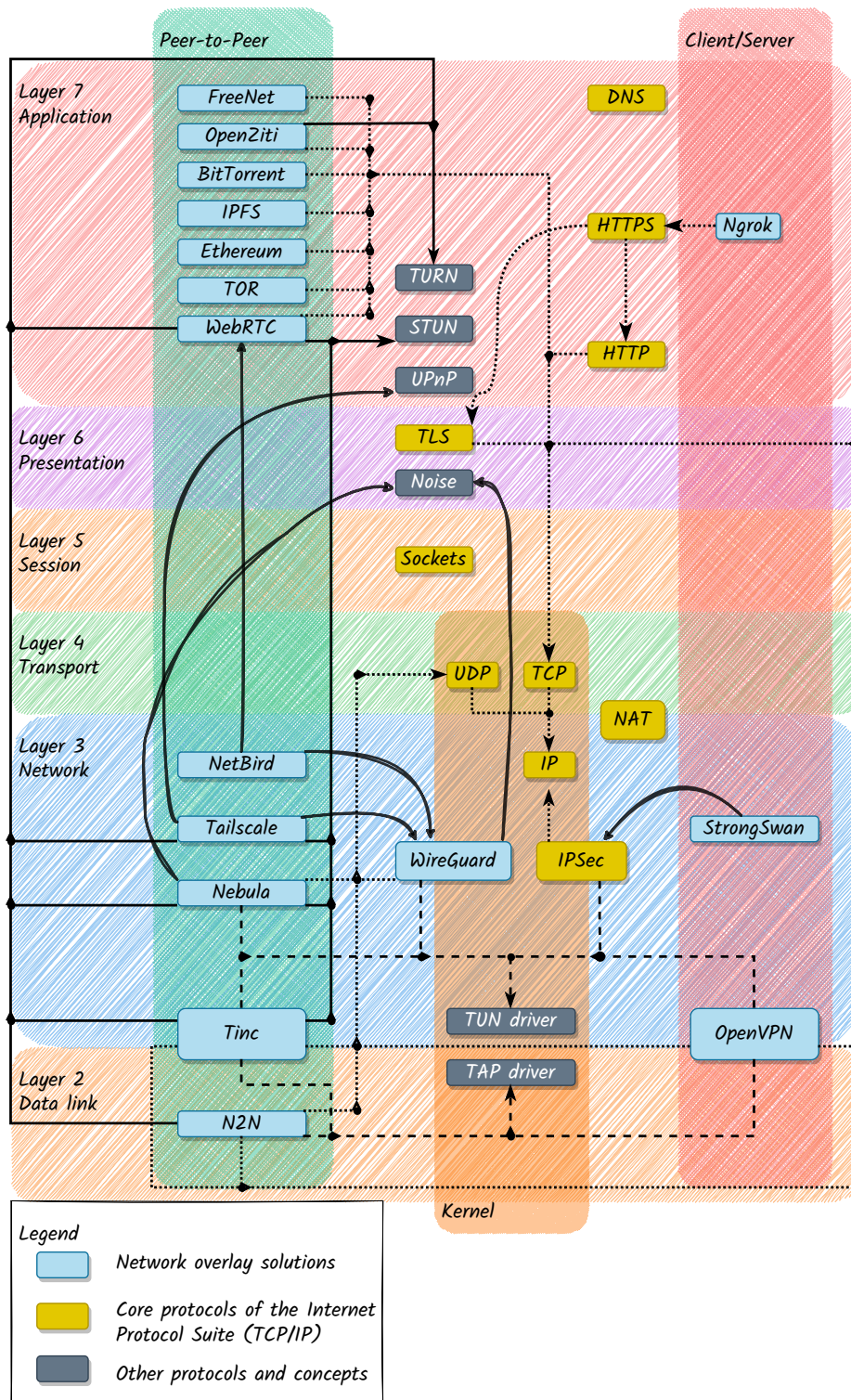


Figure 3.1: OSI model mapping of various protocols

3.1 Data Link Layer (L2) and Network Layer (L3)

3.1.1 Client/Server VPNs

Layer 2 virtual networks provide a virtual network switch that allows remote machines to be on the same virtual LAN and share the same IP address range. Layer 3 virtual networks provide a virtual network router that allows remote machines to be on separate LANs. Depending on the specific implementation, the overlay network can either be implemented directly in the Operating System's kernel, or on top of a driver like **TUN** or **TAP**.

- Layer 2 vs Layer 3 Networks
 - Layer 2 overlay networks bridge other networks
 - * virtual network switch
 - * remote machines are on the same virtual LAN and can share the same IP address range
 - * allows broadcast/multicast
 - * TAP driver
 - Layer 3 overlays route traffic between separate local networks
 - * virtual network router
 - * remote machines are on separate LANs
 - * simpler to configure
 - * TUN driver
 - * the low-level solutions from the previous section are complex to set up.
 - * overlay networks package some of those solutions for a specific use case Most overlay networks use a combination of the NAT traversal techniques mentioned previously. They can be placed in Layers 2, 3 or 7. Layer 2 overlays act as a virtual network switch, while Layer 3 overlays act as a virtual network router. Layer 7 overlays are implemented in user-space as libraries or applications that run on top of the network stack of the host operating system. Layer 2 and 3 overlays can either be implemented as kernel modules or as user-space applications that use a **TUN/TAP** driver to interface with the kernel.
 - * The term “VPN” is somewhat overloaded as it can refer to different related concepts.

VPNs are implemented as Layer 2 or 3 network overlays. They are commonly used for securely connecting machines from different **LANs**. They provide software emulation of a network interface controller via a TUN/TAP driver on the operating system level and allow other software to transparently use the functionality of the **Internet Protocol (IP)** suite without requiring extra changes. Traditional **VPNs** such as IPsec [FK11] and OpenVPN [Ope22] use a centralized service that all (encrypted) client communications must pass through. This introduces a single point of failure and a potential bottleneck that might negatively impact the performance of the multiparty computations due to their **Peer to Peer (P2P)** nature.

explain the names

tls vs ipsec vpns. TLS vpns offer a virtual network interface at layer 3, but run over L7 TLS

OpenVPN Client/Server

We already discussed the VPN protocol behind OpenVPN. Here we will go into the client and server software and how they are implemented and discuss the typical network topologies.

3.1.2 Mesh VPNs

- Tinc
- N2N
- Tailscale
- Nebula
- ZeroTier

Mesh VPNs such as Tinc [Sli22], Tailscale [Tai] and Nebula [Def22] utilize NAT Traversal techniques to create direct P2P links between the clients for the data traffic. Authentication, authorization and traffic encryption are performed using certificates based on public key cryptography.

All three are open-source, except Tailscale's coordination service which handles peer discovery and identity management. Headscale [Fon22] is a community-driven open-source alternative for that component. Tinc is the oldest of the three but has a relatively small community. It is mainly developed by a single author and appears to be more academic than industry motivated. Nebula and Tailscale are both business driven. Tailscale was started by some high-profile ex-googlers and is the most end-user-focused of the three, providing a service that allows people to sign up using identity providers such as Google, Microsoft, GitHub and others. They also provide an Admin console that allows a user to easily add their personal devices to a network or share them with others. It also has support for automation tools like Terraform for creating authorization keys and managing an Access Control List (ACL) based firewall. Nebula was originally developed at the instant messaging company Slack to create overlay networks for their cross-region cloud infrastructure, but the authors later started a new company and are currently developing a user-centric platform similar to Tailscale's. Nebula is more customizable than Tailscale and since it is completely open-source it can be adapted to different use cases, but it is also more involved to set up. A certificate authority needs to be configured for issuing the identities of the participating hosts. Furthermore, publicly accessible coordination servers need to be deployed to facilitate the host discovery. Tailscale employs a distributed relay network of Designated Encrypted Relay for Packets (DERP) servers, while Nebula can be configured to route via one of the other peers in the VPN.

3.2 Application Layer (L7)

3.2.1 OpenZiti

OpenZiti is a commercial product that provides an SDK for creating P2P overlay networks. It is developed by NetFoundry, a company that provides a Software as a Service platform for creating and managing P2P overlay networks. The SDK is open-source and can be used to create custom overlay networks. The SDK is written in Go and provides a high-level Application Programming Interface (API) for creating and managing the overlay network. It uses a centralized service for peer discovery and identity management. The data traffic is routed via a P2P network of relays. The relays are hosted by NetFoundry and are not open-source. The SDK is available for Go, Java, Python, C# and C++.

- uses relays

3.2.2 LibP2P

- libP2P
- ngrok
- TOR
- BitTorrent
- IPFS
- Ethereum
- Teleport
- Freenet

Chapter 4

Digital Identities for Multiparty Computations

Digital identity mechanisms provide standardized ways for referring to entities in the context of digital interactions. We have already seen some examples of digital identities in the previous chapter:

- [MAC](#) addresses - host identities at the Data link layer (L2)
- [IP](#) addresses - host identities at the Network layer (L3)
- Digital Certificates - identities that can be cryptographically verified

Key concepts related to digital identity mechanisms include:

- Issuance - the process of assigning a digital identity to an entity. Often this involves a trusted third party like a government or a digital identity provider like Google or GitHub. Another option is [SSI](#) where a user manages their own identity.
- Authentication - the process of verifying the identity of an entity
- Credentials - use case-specific attributes associated with an identity
- Authorization - the process of verifying if an identity's owner is allowed to perform an action on a resource

Other notable examples include:

- Email addresses - identities for entities participating in email communications
- User names - user identities in various digital platforms that can be verified via a password
- ID cards - government-issued identity documents are increasingly able to support digital interactions
- Biometrics - used to prove an identity via sensor data
- IP addresses
 - Cryptographically Generated Addresses - [rfc3972](#)
 - Privacy Extensions - [rfc4941](#)
 - DNS
- MAC addresses
- Government
 - ID Cards / Passports

- * NFC
 - Estonia’s Digital Government
 - DigiD in NL
 -
- Certificates
- TLS
- IPSec
- WireGuard
- OpenID Connect
- Crypto currency addresses
 - Hierarchical Deterministic Keys
 - ENS
- Self-Sovereign Identity
 - Decentralized Identifiers
 - Verifiable Credentials
 - Identity Overlay Network (ION) from Microsoft
 - * DPKI
- Social Networks
 - Centralized
 - * Facebook
 - * Twitter
 - * Reddit
 - Decentralized
 - * Mastodon - Mastodon is an open-source, decentralized social networking platform that provides an alternative to traditional social media giants like Twitter. It operates on a federated model, which means that instead of being a single, centralized platform, it is a network of independently operated servers, known as “instances”. Each instance hosts its own community with its own rules, but users on any instance can interact with users on other instances thanks to a common protocol, creating a connected, distributed social network.
 - * Bluesky - An ex-twitter initiative to move away from centralized social media platforms, where a single organization controls the network. Instead, Bluesky aims to develop a standard protocol for social media that would enable the development of a variety of interoperable, decentralized platforms.
 - * Nostr
- Identity Privacy

Part II

Proof of Concepts and Evaluation

Chapter 5

Testing methodology

In the following chapters, we will design and implement several solutions for ad hoc MPC sessions based on a subset of the previously discussed related works:

- Internet protocol
- Wireguard
- Tailscale
- Headscale
- ? Headscale with DID identity?
- ? WebRTC?
- A custom solution that automates the WireGuard configuration by visiting a web page

Additionally, we will analyze and compare them in terms of performance, security and usability

5.1 Measuring performance

During the preparation phase of the project, we developed the [Extensible Evaluation Environment \(\$E^3\$ \)](#) framework which simplifies and automates the process of deploying machines in different geographical regions, connecting them via an overlay network and executing multiparty computations between them, where each machine represents a different party.

To summarize, E^3 is a set of scripts that use several automation tools:

- Terraform - declarative provisioning
- NixOS - declarative Linux distribution
- Colmena - declarative deployment for NixOS
- PSSH - parallel execution of remote scripts over ssh
- DigitalOcean - a cloud provider

It allows us to quickly provision cloud virtual machines in multiple regions and reproducibly deploy all necessary software for running a multiparty computation over a chosen network overlay solution. The source code of E^3 can be found on [GitHub](#)

Each solution will be deployed using the E^3 framework and the performance will be quantitatively measured in terms of the time it takes to execute several MPyC demos. The selected

demos have different complexities in terms of communication rounds and message sizes which will allow us to observe their impact on the overall performance.

1. Secret Santa - high round complexity with small messages
2. Convolutional Neural Network (CNN) MNIST classifier - low round complexity with large messages

The demos will be configured at three different input size levels

- Low,
- Medium
- High

Furthermore, the demos will be executed in several networking scenarios:

1. 1-10 parties in the same geographic region
2. 1-10 parties evenly distributed across two nearby regions
3. 1-10 parties evenly distributed across two distant regions
4. 1-10 parties distributed across multiple distant regions

5.2 Security

We will analyze aspects such as

- key distribution
- trust model - are there any trusted third parties and what would be the consequences if they are corrupted or breached
- traffic encryption
- identity strength

5.3 Usability

For each solution, we will describe the steps that the parties need to perform to execute a joint multiparty computation. Those steps will be analyzed in terms of:

- Complexity - how much technical expertise is expected from the parties to be able to execute the steps
- Initial effort - how much effort is each party expected to put in preparing for their first joint computation
- Repeated effort - after the initial setup, how much effort is required to perform another computation
 - with the same set of parties
 - with another set of parties
- Finalization effort - how much effort is required to finalize the MPC session once it is complete and clean up any left-over artifacts or resources so that the machine of each party is in its original state

Chapter 6

Internet Protocol based solution

This solution focuses on directly using the internet protocol without involving an overlay network. Our goal is to analyze the implications of using only the functionalities that MPyC directly supports to serve as the reference for our later experiments.

6.1 Implementation details

We will manually set up the multiparty computations via the public IP addresses of the machines and DNS.

6.2 Performance analysis

6.3 Security analysis

6.4 Usability analysis

Chapter 7

WireGuard based solution

This solution creates an overlay network by manually configuring WireGuard on each machine.

7.1 Implementation details

7.2 Performance analysis

7.3 Security analysis

7.4 Usability analysis

Chapter 8

Tailscale based solution

Tailscale is a VPN solution that configures a mesh of direct Wireguard tunnels between the peers.

8.1 Implementation details

8.2 Performance analysis

8.3 Security analysis

8.3.1 Trust model

There is a centralized service that deals with the key distribution, which needs to be trusted to provide the correct public keys for the correct parties

8.3.2 Identity

Identity is based on third party identity providers such as Microsoft and GitHub

- Magic DNS
-

8.4 Usability analysis

With tailscale each party needs to

- register a Tailscale account
- Download and install tailscale on the machine they want to run a multiparty computation
- Run tailscale on their machine and logs into their account in order to link it to their own Tailnet
- Share their Tailscale machine with the Tailnets of each of the other parties
- Download the demo they want to run
- Form the flags for running the chosen demo

- add -P \$HOST:\$PORT for each party using their Tailscale hostname/virtual IP
- Run the demo

Chapter 9

Headscale based solution

This solution is similar to the Tailscale one, but it uses Headscale - a self-hosted open-source alternative to the closed-source Tailscale coordination service.

9.1 Implementation details

9.2 Performance analysis

9.3 Security analysis

9.3.1 Trust model

There still is a centralized service like in the Tailscale solution, but here it is self-deployed.

9.3.2 Identity

9.4 Usability analysis

Chapter 10

MPyC Web

This chapter presents the design of MPyC Web - an MPC connectivity solution based on web technologies (L7) that can run in web browsers.

Design goals:

- Runs in browsers (client-side) on both PCs and smartphones
- Uses the MPyC Python framework with as few modifications as possible
- Peer-to-peer with a fallback to relaying
- Secure
- Simple to use

10.1 Python Runtime Selection

10.1.1 Selection Criteria

While web browsers natively support only [JavaScript \(JS\)](#), there are approaches with different tradeoffs that can enable other languages, including Python. In this section we will investigate several web-based Python runtimes and choose the most appropriate one for MPyC Web.

MPyC depends on several Python packages that are implemented in C, such as `numpy`, `gmpy2`, `scipy` and relies heavily on `asyncio` and TCP sockets from Python's standard library. The runtime we choose should support as many of those dependencies as possible to avoid having to find alternatives or reimplement them.

Another important aspect is the runtime performance due to the heavy operations involved in [MPCs](#). We will benchmark each runtime by measuring the time it takes to execute a simple Python script that adds numbers in a loop.

Fast startup time, low build and deployment complexity are less crucial but nice to have properties of the runtime, as they offer a better experience for both users and developers.

To summarize, our criteria for runtime selection are:

- Python ecosystem/package availability
- Runtime performance
- Startup, build and deployment time

10.1.2 Available Solutions

There are a number of available solutions for using Python in web browsers, falling under three main categories[Moz19] [Anv19]:

1. Transcrypt[Tra24] - [Ahead-Of-Time \(AOT\)](#) JavaScript transpiler - the Python code is transpiled to JavaScript and the resulting code is executed by the browser at runtime. is an example project
2. Skulpt[Skul], Brython[Bry24] - [Just-In-Time \(JIT\)](#) JavaScript interpreters - the Python code is converted to JavaScript in the browser at runtime
3. Pyodide[Pyo], MicroPython[Mic], RustPython[Rus] - [WebAssembly \(WASM\)](#)[WAS17] interpreters - a Python interpreter is implemented in a compiled language like C/C++/Rust/Go that can target WASM - a secure and efficient binary instruction format for a virtual machine that can run in browsers with close to native performance.

10.1.3 Preliminary Runtime Benchmarks

-
-
-
-

Table 10.1: Benchmark results of the Python runtimes measured in operations per second for inputs of size 100 000

	Benchmark		Results (ops/sec)					
Project	assign	multiply	bigint	randlist	cpylist	sortlist	fibonacci	primes
JavaScript	19,327	19,413	19,351	713	4,227	35	3,271	1,029
CPython	775	380	69	21	4,280	81	168	200
Transcrypt	1,289	1,285	1,282	176	6,135	35	337	1124
Skulpt	40	27	1	16	6,232	5.2	8	18
Brython	292	166	45	0.7	5,076	67	9	45
Pyodide	400	111	26	5	4,425	45	53	73
MicroPython	69	36	6	16	403	41	22	10
RustPython	60	59	8	0.8	525	0.1	6	6

```
1 import itertools
2 import random
3 import sys
4 import time
5
6 bench_input_size = 100000
7 bench_min_duration = 0.2
```

```

8 bench_best_of = 3
9
10 def is_brython():
11     return "Brython" in str(sys.version)
12 def is_skulpt():
13     return "Skulpt" in str(sys.version)
14 def is_micropython():
15     return "MicroPython" in str(sys.version)
16 def is_rustpython():
17     return "rustc" in str(sys.version)
18 if is_micropython():
19     import js
20     def print(s):
21         js.document.currentScript.target.innerHTML += s + "<br />"
22 if is_brython() or is_skulpt() or is_micropython():
23     range_fn = range
24 else:
25     range_fn = lambda iters: itertools.repeat(None, iters) # Pyodide
26
27 if hasattr(time, "ticks_ms"):
28     default_timer = time.ticks_ms
29     default_time_diff = lambda a, b: time.ticks_diff(a, b) / 1000.0
30 elif hasattr(time, "time"):
31     default_timer = time.time
32     default_time_diff = lambda a, b: a - b
33 def timeit(func, iterations=bench_input_size, timer=default_timer, time_diff=default_time_diff):
34     t1 = timer()
35     res = func()
36     for _ in range_fn(iterations - 1):
37         func()
38     timing = time_diff(timer(), t1)
39     return timing, res
40 def autorange(func):
41     i = 1
42     while True:
43         for j in 1, 2, 5:
44             iterations = i * j
45             time_taken, res = timeit(func, iterations)
46             if time_taken >= bench_min_duration:
47                 return (round(iterations / time_taken, 2), res)
48         i *= 10
49 def bench(func):
50     def wrapper(*args, **kwargs):
51         maxOpS = 0
52         res = None
53         def handle():
54             return func(*args, **kwargs)
55         for _ in range(bench_best_of):
56             ops, res = autorange(handle)
57             maxOpS = max(maxOpS, ops)
58         print_bench(func.__name__, maxOpS, *args, **kwargs)
59         return res
60     return wrapper
61 def print_bench(name, t, *args, **kwargs):
62     args_repr = [repr(arg) for arg in args]
63     kwargs_repr = [{"key"}={repr(value)}" for key, value in kwargs.items()]
64     args_fmt = ", ".join(args_repr + kwargs_repr)

```

```
65     print(f"{name}({args_fmt}): {t:.,} ops/sec")
66 @bench
67 def assign(iters=bench_input_size):
68     for _ in range_fn(iters):
69         x = 1
70 @bench
71 def multiply(iters=bench_input_size):
72     a, b = 17, 41
73     for _ in range_fn(iters):
74         x = a * b
75 @bench
76 def bigints(iters=bench_input_size):
77     n = 60
78     for _ in range_fn(iters):
79         2**n
80 @bench
81 def randlist(size=bench_input_size):
82     return [random.randint(0, size) for _ in range(size)]
83 l = None
84 @bench
85 def cpylist():
86     return l.copy()
87 @bench
88 def cpylist2():
89     return l[:]
90 @bench
91 def sortlist():
92     return l.copy().sort()
93 @bench
94 def fibonacci(n=bench_input_size):
95     if n < 2:
96         return n
97     a, b = 1, 2
98     for _ in range_fn(n - 1):
99         a, b = b, (a + b) % 100000
100     return a
101 @bench
102 def primes(n=bench_input_size):
103     if n == 2:
104         return [2]
105     if n < 2:
106         return []
107     s = list(range(3, n + 1, 2))
108     mroot = n**0.5
109     half = (n + 1) // 2 - 1
110     i = 0
111     m = 3
112     while m <= mroot:
113         if s[i]:
114             j = (m * m - 3) // 2
115             s[j] = 0
116             while j < half:
117                 s[j] = 0
118                 j += m
119             i = i + 1
120             m = 2 * i + 3
121     return [2] + [x for x in s if x]
```

```
122 | assign()
123 | multiply()
124 | bigints()
125 | l = randlist()
126 | cpylist()
127 | cpylist2()
128 | sortlist()
129 | fibonacci()
130 | primes()
```

Out of the discussed runtime options, Pyodide offers the widest support for packages from the standard library and third-party packages. None of the options support the sockets package due to browser limitations, but an alternative implementation can be built on top of the WebRTC API.

Out of those projects, Py

Table 10.2: Summary of Python runtimes for browsers

Project	Approach	Startup	Benchmark	Ecosystem
Transcrypt	transpiler (AOT)	0s	slow	(-) n/a
Skulpt	JS-based interpreter (JIT)	0s	slow	(-) n/a
Brython	JS-based interpreter (JIT)	0s	1,370 op/s	(-) no numpy
Pyodide	WASM-based interpreter (JIT)	5s	298 op/s	(+) asyncio (+) numpy (+) gmpy2 (+) scipy (+) python wheels (+) filesystem (-) no sockets
MicroPython	WASM-based interpreter (JIT)	1s	fast	(-) n/a
RustPython	WASM-based interpreter (JIT)	5s	fast	(-) n/a

10.2 Design of MPyC Web

Web based solution for running MPC in browsers on the client side via WebAssembly and WebRTC for peer-to-peer connectivity.

The lifecycle of a message between the workers of 2 peers, “Peer A” and “Peer B” looks like this:

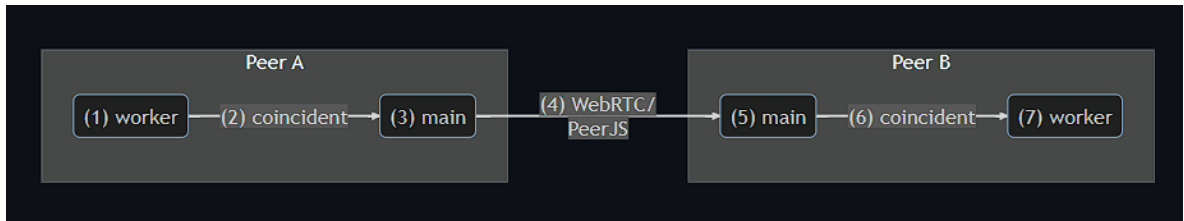


Figure 10.1: MPyC Web

1. Python Worker on Peer A

- creates a message that contains a secret share computed via the mpyc, which serializes it to binary via `struct.pack()`. The resulting message is non-ascii, but when escaped can look like this:

```
1 b'\x06\x00\x00\x00\xc9\x93\\\xc0\xff\xff\xff\xff\x04\x00\x80\x99\x1b\x01'
```

- worker calls a main thread function (`sendRuntimeMessage`) via a coincident proxy and passes the serialized value, as well as the destination Peer’s ID (Peer B). The worker does not need to await the result of this call, but it does because of `xworker.sync`.

2. Coincident handles the message by:
 - (Worker) `JSON.stringify()` -> `Atoms.wait()`
 - (Main) `JSON.parse()` -> Run the Main Thread function -> `Atoms.notify()`
3. Main thread on Peer A fires an event to notify PeerJS that it needs to transport the message and immediately returns in order to not block the Worker
4. PeerJS serializes the message with some added fields via `MessagePack` and transmits it to Peer B
5. Main thread on Peer B receives the message and forwards it to the appropriate worker callback via `coincident`
6. Coincident does the `JSON.stringify()` -> `Atoms.wait()` stuff (?) from main to worker on Peer B
7. Worker on Peer B handles the message by passing it to an `asyncio` coroutine that is waiting for it or stores it for later use

10.3 Implementation details

10.4 Performance analysis

10.5 Security analysis

10.5.1 Trust model

There still is a centralized service like in the Tailscale solution, but here it is self-deployed.

10.5.2 Identity

10.6 Usability analysis

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