1 Crypto Recap

1.1 Objectives:

- **Confidentiality**
- **Integrity**
- **Authenticity**
- **Availability**
- Authorization
- Non-Repudiation, Accountability
- Freshness
- Anonymity, Unlinkability
- Intervenability, Contro
- Transparency

1.2 Confidentiality-Encryption

1.2.1 Symmetric Ciphers

- Secret key for en- and decryption
- Much more efficient
- **Block cipher:** encryps a plaintext block of fixed len e.g.: *Advanced Encryption Standard (AES)*
- **Stream cipher:** encrypts a bitstream e.g.:*ChaCha20*

1.2.2 Asymmetric Ciphers

- Public key for encryption
- Private key for decryption
- Ex.: RSA-based encryption

1.3 Integrity, Authenticity-Signatures, MACs

1.3.1 MACs

- Symmetric cryptography
- Protects data integrity & authenticity
- Ex.: Hash-based MAC

1.3.2 Digital Signatures

- Asymmetric cryptography
  - **Signing with** private key
- Protects data integrity & authenticity
- Provices non-repudiation

1.4 Block Cipher Modes of Operation

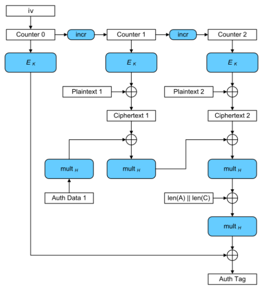
1.4.1 Electronic Code Book (ECB)

- Each plaintext block is encrypted seperatly
- Inheritly insecure! -> Smae block = Same cipher

1.4.2 Cipher Block Chainning (CBC)

- Plaintext is chained to previous ciphertext by XOR and encrypted afterwards
- Difficult to apply securely -> implementations often vulnerable

1.4.3 Galois Counter Mode (GCM)



2 Tranport Layer Security (TLS)

2.1 TLS handshake protocol

- Parameter Negotiation
- Key exchange
- Authentication

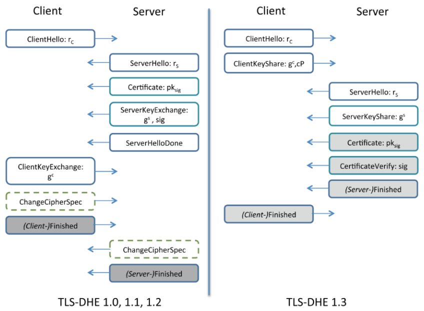
2.2 TLS record protocol

- Protection of integrity, authenticiy and confidentiality
- **Symmetric Cryptography:** e.g., block cipher, usually AES

2.3 Attacks

- Attacks on the record layer
- Attacks on the session key
- Attacks on the private server key
  - Attacks on implmentations: Timing Attacks, Heratbleed, Invalid Point Attacks
- Attacks on TLs eco system
  - Attacks on certificates and the PKI
  - Attacks on the browser GUI

2.4 Overview TLS 1.0-1.2 & TLS 1.3



2.5 HKDF Key Derivation Function

2.6 Forward Secrecy

- TLS 1.3 using certificate-based Authentification: **forward secrecy**
- TLS 1.3 using pre-shared keys (PSK):
  - PSK using *elliptic-curve* Diffie-Hellman: **forward secrecy**
  - PSK without EC-DHE (symmetric-only) and zero-round-trip data: **no forward secrecy**

2.7 Datagramm TLS

- DTLS is identical to TLS where possible
- DTLS has to introcue new mechanisms
  - Explicit sequence numbers
  - Retransmission timer for handshake message
  - Message re-ordering for the handshake
  - Fragmentation of large handshake messages into serveral DTLS records
  - Optional replay detection
  - Invalid records are discarded (silently)
  - Denial-of-Service countermeasures: statless cookies, HelloRetryRequest

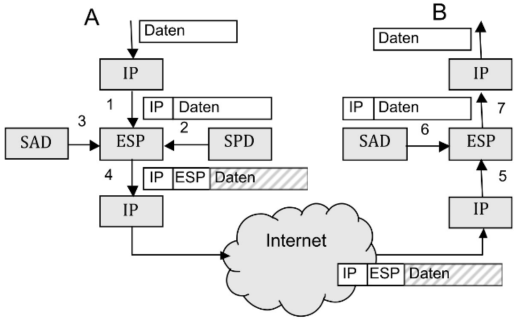
3 Network Layer Security: IPsec

3.1 TLS limitations

- Does not protect all traffic between hosts
  - Protects only a single connection; new connection => new key agreement or session resumption necessary
  - Non-TCP traffic (resp. non-UDP trafic for DTLS) cannto be protected
- Does not protect the TCP layer (RST attacks on TCP are possible which terminate TLS connection)
- Application specific: applications have to be modified to use TLS/DTLS
- Using a TLS-based tunel for VPNs has disadvangates (TCP) (DTLS good option tho)

3.2 Overview IPsec

- Goal: Protect IP packets cryptographically
  - Confidentiality
  - Integrity & Authenticity
- Seperation of packet protection from key exchange
  - Protocols for packet encryption and authentification: symmetric crypto, implemented in the TCP/IP stack
  - Key Exchange completly unrelated: asymmetric (+symmetric) crypto, implemented as network daemon



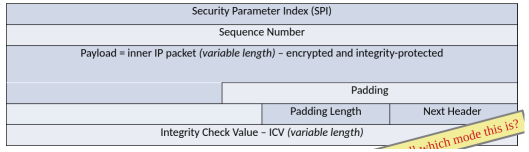
3.3 Packet Formats and Operational Modes

3.3.1 Authentification Header (AH)

- Integrity & Authenticity only
- Partially protects "outer" IP header
  - Variable fields cannot be includes
    - Flags, Fragment Offset, TTL, Header Checksume
  - Other fields are included in MAC computation
    - Version, IP header length, total length, identification, Protocol (must be AH), source/dest Address

3.3.2 Encapsulating Security Payload (ESP)

- Confidentiality, Integrity & Authenticity
- Does not protect "outer" IP header



- SPI: SA-Identifier
- Next Header: type of payload data (e.g. IPV4)
- Integrity Check Value: data for authentification / integrity protection
  - Message Authentication Code (MAC)
- SAs are negotiated in the key exchange
- Sender side: Packet must be categorized to determine which SA applies (By parameters such as destination=)
- Receiver side: Determines SA from IPsec header of received packet
- SA Parameters:
  - IPsec protocol (AH or ESP)
  - Authentification alrogrithm and key
  - Encryption algorithm and key
  - IPsec mode (transport or tunnel)
  - SA lifetimne
  - Sequence number: current counter
  - On reciver side: "Sliding Window" for replay protection

3.4 Scenarios

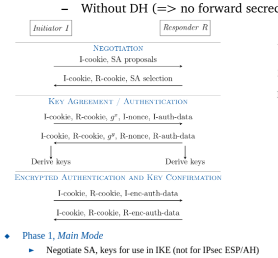
- Host to host
- Host to gateway
- Gateway to gateway

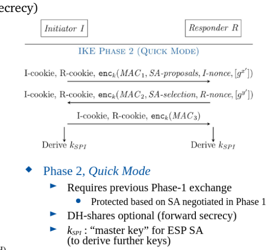
3.5 The Internet Key Exchange (IKE)

- So far, keys are already exchanges, SAs negotiated... but how?
- Authentification of the communication endpoints
- Dynamic negotiation fo algorithms and parameters
- Key establishment
  - Forward Secrecy
- Resistance to DoW attacks
- Efficiency (computation, messages, round trips)

3.6 IKEv1

- Phase 1: main mode vs. aggressive mode
- Authentification modes:
  - Digital Signatures
  - Public key encryption(PKE): two variants (rarely used)
  - Pre-shared keys(PSK)
- Phase 2 (quick mode)
  - With DH (=> forward secrecy)
  - Without DH (=> no forward secrecy)



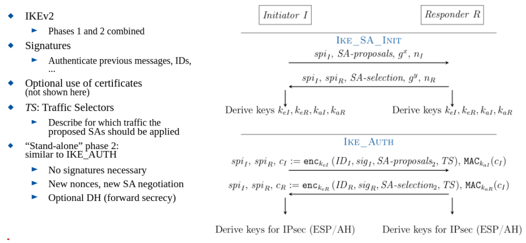


3.6.1 Discussion

- Complicated
  - Information from serveral (complex) RFCs required
  - Many options variants
- Generic
  - Clean seperation of different phases and functionalities
    - Can be advantagous in theory, but leads to inefficincies
  - Intended as general handshake and key agreement protocol, not only for IPsec
    - In practice: only used for IPsec
  - Ineficient
    - Requires too many round trips
  - Inadequate DoS protection
    - IKEv1 uses stateful cookies

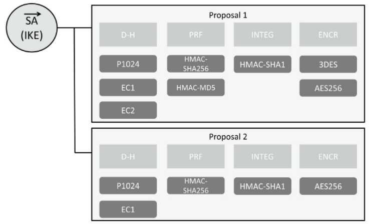
3.7 IKEv2

- Phase 2 (partially) combindes with Phase 1
  - More efficient thatn IKEv1
  - Initial negotiation of IPsec SA included
- Additional SAs can be negotiaded in furhter Phase 2 protocol runs
- Simplified specification
  - Essential information in one RFC
  - No distinction main mode vs. aggressive mode
- DoS protection using statless cookies: optional



3.8 SA Proposals

- Serverl proposals possible
- Proposal contains transforms
- Differnten options for each transform possible
  - Exactly one transform has to be selected



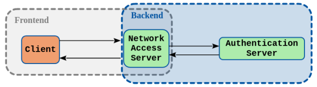
4 Security on Layer 2 (MAC Layer, Ethernet)

4.1 Attacks

- MAC address spoofing
- ARP spoofing
- ARP cache poisoning

4.2 Network Access Control

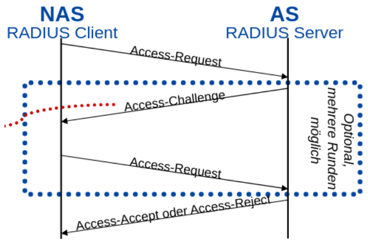
- **Frontend** protocols: Cient -> Network Access Server
  - Point-to-Point connections: PPP
  - LAN: PPPoE, EAPoL
  - WLAN: WPA/WPA2/WPA3, EAPoL
- **Backend** protocols: Network Access Server –> Authentication Server AAA protocols (Authentication, Authorization, Accounting)
  - Radius, Diameter
  - TACACS+



4.2.1 Radius - Remote Authentification Dial-In User Service

- Backend protocol
- Dial-In Server
  - E.g. DSL
  - Company infrastructure

Packet Format



Security

- Old protocol
  - Tries to protect sesitive data only
  - Insecure cryptography
- Uses only over secure protocols
  - Usually TLS
- RADIUS successor: Diameter
  - Fmore flexible, extensible, application-aware
  - "Security" features removed, no more insecure crypto of RADIUS => To be used over secure protocols TLS/DTLS/IPsec

4.2.2 Point-to-Point Protocol (PPP)

- **PPP:** Frontend protocol to connect two devices
  - Typically used for dial-up connections (e.g. DSL)
  - Transported over Layer 2 protocol (e.g. ethernet)
- Authentification mechanisms
  - PAP: username/password
  - CHAP: Challange Handshake Authentification Protocol
  - EAP: Extensible Authentification Protocol
- **PPPoE:** PPP over Ethernet (e.g. used for DSL connections)
  - Discovery: Client negotiates session with network access server
  - PPP Session: PPP frames are encapsulated in ethernet frames; potentially several hops

4.2.3 Extensible Authentification Protocol (EAP)

- Extensible authentification framework
  - Fronted protocol for lcient authentification
  - Server send request (e.g. challenge, ident. request, ..)
  - Client responds
  - Server sends success or failure message
  - EAP messages can be transported in RADIUS messages (as RADIUS attribute) for backend communication
- EAPoL: EAP over LAN

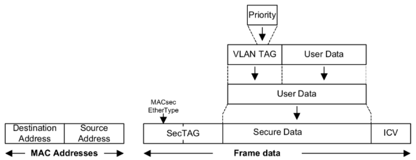
4.2.4 Port Based Network Access Control (PNAC)

- Authentification of clients befre they can use the network (LAN)
  - Client connect to the network
    - ⋆ Authentification traffic is allowed
  - Switch port can only be used for other purposes after successful authentification
  - Re-authentification after timeouts, link-down, etc.
- PNAC uses EAPoL
- Terminology: Port Access Entities (PAE)
  - Client: supplicant
  - Netowrk access server: authenticator
  - Attention: "port"

4.3 MACsec

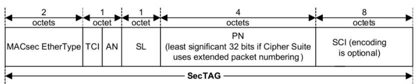
- cryptographically protect the ethernet layer
- Based on MACsec Key Agreeement (MKA)
  - After successful authentification (typically EAP)
  - Derives key from CAK - connectivity association key (pre-shared)
  - Key can be set up by EAP (e.g. EAP-TLS)

4.3.1 Frame



- Data cen be encryped and/or authentificated
- AES-GCM is supported

Security TAG (SecTAG)



- TCI: TAG Control Information
- AN: Association Number
- SL: Short Length (payload length; for short frames only)
- PN: Packet Number
- SCI: Secre Channel Identifier (edentify SA, when CA needs ore than 4)
  - SA is identified by SCI (optional) and AN

4.4 Summary

- Security on Layer 2 can protect all higher Layer
  - But: only in same network
  - Does nt work accross Layer 3 routers
- Network Access Control protects access to the network
  - Client Authentification
  - RADIUS/DIAMETER
  - EAP
  - Port-Based Access Control
- MACsec protects traffic
  - Encryption & authentification

5 Wireless Security

5.1 WiFi Security

5.1.1 Historic Overview

- 1999: WEP (Wired Equivilaent Privacy)
  - Goal: "as secure as a wired LAN"
  - Insecure, various attacks known
- 2003: WPA (WiFi Protected Access)
  - Improved protocols; most known attacks on WEP prevented
  - Enterprice Mode
  - But: Requirement ofr hardware-compatibility with WEP devices => Encryption improved, but still based on obsolete stream cipher
- 2004: WPA2 (still used)
  - Similar to WPA, but AES-based encryption: AES-CCMP
- 2018: WPA3 (supported by new devices)
  - Serveral improvements: Prevention of offline-attacks on pre-shared keys, forward secrecy, encryption for "open" WLANs

5.1.2 WPA/WPA2 Security

- Personal Mode
  - Pre-Shared Keys
- Enterprise Mode
  - EAP-TLS, PEAP, EAP-TTLS

AES-CCMP

- Authenticated Encryption with Associated Data (AED)
- AES-CCM
  - Authentication: CBC-MAC
  - Encryption: Counter Mode (CTR)
  - MAC and encryption: computed simultaneously

4-Way Handshake

- Based on Pairwise Master Key (PMK)
  - Personal Mode (WPA-PSK): Computed from passphrase and SSID (as "salt") using PBKDF2 (password-based key derivation function)
  - Enterprise Mode: Established by key exchange protocol (e.g. EAP-TLS, PEAP)
- 4-Way HS to derive Pairwise Transient Key (PTK)
  - Exchance nonces
  - PTK is derived by hashing PMK, nonces, MAC addrs
  - Furhter key (for differnet purposes) derived from PTK
  - Client gets Group Temporary Key from AP (encrypted)
  - Message Integrity Code(MIC): MACs for integrity protection, key confirmation
- KRACK (2018): Key reinstallation attacks => meanwhile prevented by software/-firmware updates
- Problem: Offline attacks against passphrase

5.1.3 WPA 3 Improvements

- Mandatory Protected Managment Frames
  - Prevents deauthentication attacks (DoS)
- Replace PSK Authentication with SAW protocol
  - Simultaneous Authentication among Equals (SAE): "Dragonfly" handshake
  - Prevents offline attacks on passphrase
  - Based on elliptic curve cryptography by default
- Forward Secrecy based on Diffie-Hellman
- 192-bit Security Mode (optional)
  - AES-256 (GCM)
  - SHA-384
  - 284-bit elliptic curves or RSA with at least 3K bits

5.1.4 Simultaneous Authentication among Equals

- SAE "Dragonfly" authenicates participants and establishes PMK
  - Based on passphrase and (EC-)Diffie-Hellman
  - Can be initiated simultaneously by both parties (useful for mesh networking)
- 4-Way Handshake
  - Esablishes PTK basen on PMK
  - Same as in WPA2
  - But now: PMK with much higher entropy => Offlione attacks not practical
- Hash-to-Group: "Hunting and Pecking"
  - Generate point on elliptic curve from pasphrase (and MAC addresses, etc.)
  - Cryptographic has function generates pseudo random numbers (by including a counter in the input)
    - ⋆ Both parties must use the exact same inputs in the same order
  - Fixed procedure to derive x-coordinate
    - ⋆ Check if point on curve can be generated
    - ⋆ If check fails: increase coutner and try again
- Auth-Commit messages
  - Exchange ECDH shares
- Auth-Confirm messages
  - Key confirmation, authentication of messages

5.2 Bluetooth Security

- Authentication: device authentication, no user authentication
- Pairing/bondig: create shared keys; used in connections later on
- Confidentiality: encryption of BT communication
- Message Integrity: MACs (authenticated encryption) to protect BT communication
- Authorization: control access to resources (based on devices, not users)
- Security Modes
  - Mode 1: no security
  - Mode 2: service level (only for backward compatibility)
  - Mode 3: link-level enforces security (only for backward compatibility)
  - Mode 4: authenticated link key using "Secure Connections", based on device pairing
- Eavesdroppting not trivial: Bluetooth uses frequency hoppting (not a security feature)

5.2.1 Device Pairing

- Authentication and generation of link key / long term key
- PIN/Legacy Pairing: enter PIN on both devices
  - Key generation based on PIN, device address, and random values
- Secure Simple Pairing (SSP): since Bluetooth 2.1
  - Numeric Comparison
    - ⋆ Compare 6-digit numbers
  - Passkey Entry
    - ⋆ Read 6-digit form one device, enter on the other one
  - Just Works
    - ⋆ User accepts connection without verification
  - Out of Band (OOB)
    - ⋆ Transmit data using other communication channels (e.g. NFC)

5.2.2 Simple Secure Pairing (SSP)

- Unauthenticated ECDH
- 2-Stage Authentication
  - Stage 2: depends on pariing method
  - Stage 2: Cryptographic authentication based on Stage 1 values and ECDH secret
- Key derivation to generate link key / long term key

5.2.3 Secure Authentication

- Paired (bonded) devices authenticate each other
- Challenge-Response scheme
  - 128-bit random challanges
  - Response: HMAC of BT addresses and challanges (using link key from pairing)
    - ⋆ Before Bluetooth 4.1: based on Bluetooth-specific algorithm E1
- Authenication failure: introcude delay (exponential back-off)

5.2.4 Confidentiality

- Bluetooth-specific stream cipher E0
  - Designed for efficiency
  - Serious attacks hve been published
  - "Practical" in theory (but complex, hard to apply in practice)
- AES-CCM
  - Used since Bluetooth 4.1
  - Key derived from link key (pairing) and the authentication step

5.2.5 Privacy

- Privacy problem: Devices (users) can be identified by Bluetooth MAC addresses
- Mitigation: BLE private device addresses
  - Resolvable Private Address (RPA) is changed periodically
  - Identity Address remains constant (but is not transmitted over the air)
  - Identity Resolving Key to map RPA to Identity Address
  - Especially imprtant to discoverable devices (which advertice identity info)

5.2.6 5.x Security

- No major changes to security protocols and algorithms
- Bluetooth 5.0
  - PHY improvements, no relevant security changes
- Bluetooth 5.1
  - HCI support for debug keys (should not be relevant in production systems)
- Bluetooth 5.2: adds new features (Extended Attributes, Isochronous Communication, ...)
  - Isochronous communication: connection-oriented or connection-less
    - ⋆ Group communication: group keys need to be established
    - ⋆ Broadcast Authenication
- Bluetooth 5.3: Key Size Negotiation
  - Enables host to define minimun key size

5.2.7 BLUFFS

- BLUFFS: New attacks against bluetooth
  - Breaks Forward Secrecy and Future Secrecy
  - Enables man-in-the-middle attacks, impersonation if one session key compromised
  - Forces weak key: spec allows minimus of 7 Bytes entropy (56 Bits)
    - ⋆ Brute-force attack: offline, parallelizable
    - ⋆ Forces reuse of compromised key
  - Attack against bluetooth spec (BR/EDR: "Bluetooth Classic" versions 4.2 to 5.4): All compliant devices are affected
  - Published and presented at ACM CCS 2023

5.2.8 implementations Vulnerabilities

- BlueBorn(2017): Collection of implementation Vulnerabilities
  - On Windows, IOS, Linux, Android
  - Buffer overflow, integer overflows, ..
- Android (2018): implementation flaws in L2CAP and SMP
  - Remote Memory Disclousure
- BleedingTooth(2020): several bugin in Linux
  - Can even lead to arbitrary code execution in kernal mode
- Windows (2021): BT Driver Elevation of Privilege
- BrakTooth(2021)
  - Bluetooth controllers: SoC firmware Vulnerabilities(Link Manager)
  - Estimation 1400 bluetooth chips/modules affected

5.2.9 Summary

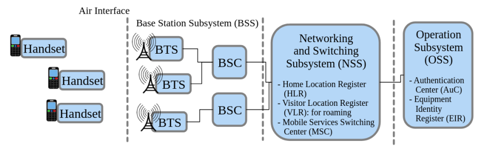
- Complex protocol stack, not easy to implement
- Many attacks in the past
  - on cryptography algorithms
- Bluetooth versions before 2.1 are basically completely insecure
- Bluetooth versions sinde 4.2 are relativly secure (...but: "BLUFFS"!)
  - But the implementations not necessarily!
- Bluetooth 5.2 architecture similar to 4.x
  - Introduces new features and minor security improvements

6 Security Mobile Networks

6.1 Overview

- **First generation:** *analog telephony networks* (voice only)
- **2nd generation (2G):** GSM *1990s*
  - ► Digital, circuit-switched, SIM-based; introduced **cryptographic protection**
  - ► Generation 2.5: GPRS (packet-switched data traffic)
  - ► Generation 2.75: EDGE (increased bandwidth)
- **3rd generation (3G):** UMTS *2000s*
  - ► Much higher bandwidth
  - ► Improved security: **mutual authentication**, better crypto algorithms
  - ► Generation 3.5: HSDPA/HSUPA (increased bandwidth)
- **4th generation (4G):** LTE *2010s*
  - ► Higher bandwidth
  - ► Completely new **IP-based** core network
  - ► Changes to security
- **5th generation (5G):** *2020-?*
  - ► ... even better, of course ;-) ...

6.2 GSM Network



BTS: Base Tranceiver Station
BSC: Base Station Controller

- Circuit-switched network, designed for voice communication
  - Stable channel between communication partners is reserved
  - Seperate channel for signaling (different time slices)
  - Slow, expensive
  - GSM introduces SMS: small texts can be transferred in signaling channel

6.2.1 Secuirty

- Goal: "At least as secure as a landline"
- Security functions
  - Autentication and Key Agreement (AKA)
    - ⋆ Shared secren in AuC and SIM
    - ⋆ Authentication via challenge-response protocol
    - ⋆ "Agreement" on short term session keys for encryption
  - Confidentiality Protection
    - ⋆ Encryption of user data ("user plane")
    - ⋆ Encryption of signalling ("control plane")
  - Integrity Protection
    - ⋆ Only for signalling
    - ⋆ Often "implicitly" by encryption

6.2.2 (U)SIM

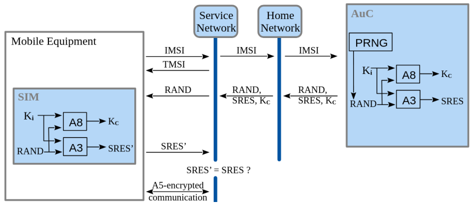
- **SIM card** introduced with **GSM**
  - **SIM:** *Subscriber Identity Module*
  - **International mobile subscriber identity (IMSI)**
    - ⋆ *Temporary mobile subscriber identity (TMSI):* derived from IMSI
  - **Security token (smartcard)** of the network operator
    - ⋆ Typically implemented on a JavaCard
    - ⋆ Identifies the network subscriber (*customer* of the **MNO**)

- ⋆ Subscriber key K_i (128 bit)
- **Standardized crypto** ⇒ roaming possible
- Independent from mobile equipment (**ME**)
  - ⋆ **International Mobile Equipment Identifier (IMEI)** identifies the device
  - ⋆ SIM can be used with any **ME** (but: SIM-Lock prevents changing SIM for some devices)
- **USIM: Universal SIM → UMTS** (typically implemented in UICC, together with (GSM-) SIM)

6.2.3 Crypto Algorithms

- **Authentication: A3**
  - *Variants: COMP128 (broken)*
  - *Later: COMP128-2 (only 54 key bits), COMP128-3 (64 key bits), COMP128-4*
- **Key Generation: A8**
  - *Variants: COMP128, COMP128-2, COMP128-3, COMP128-4*
- **Encryption: A5 (stream cipher)**
  - *A5/0 (no encryption), A5/1 (broken), A5/2 (weakened version of A5/1)*
  - *Later: A5/3 (KASUMI – also broken)*

6.2.4 Authentication



- The **Service Network** sends a **RAND** (random challenge) to the Mobile Equipment (ME).
- The SIM card computes:
  - **SRES'**: The signed response, using the authentication algorithm A3 and the subscriber key (K_i).
  - K_c: The session key for encryption, generated using algorithm A8 and K_i.
- The **Authentication Center (AuC)** in the Home Network performs the same computations (using K_i stored in its database) to generate **SRES**.
- The network compares the **SRES'** received from the ME with its own **SRES**. If they match, authentication is successful.
- Communication is encrypted using the generated K_c and the A5 stream cipher.

Glossary:

- **IMSI:** International Mobile Subscriber Identity, a unique identifier for the subscriber.
- **TMSI:** Temporary Mobile Subscriber Identity, a pseudonym for the IMSI used for privacy.
- K_i: Subscriber key, stored on the SIM and at the network's Authentication Center.
- **PRNG:** Pseudo-Random Number Generator, used to generate the RAND challenge.

6.2.5 IMSI Catcher

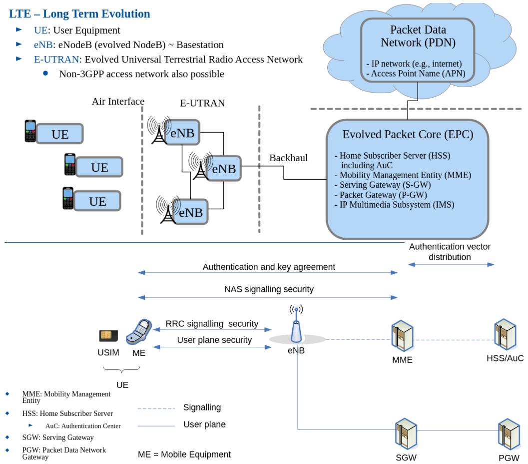
- **Man-in-the-Middle attack:**
  - **IMSI Catcher:** A device (e.g., Stingray) impersonates a legitimate Base Station to intercept communications.
  - **Step-by-step process:**
    - ⋆ The IMSI catcher pretends to be a Base Station with a strong signal, forcing nearby mobile devices to connect.
    - ⋆ The mobile device sends its IMSI (International Mobile Subscriber Identity) to the catcher for authentication.
    - ⋆ The IMSI catcher forwards authentication requests to the real Base Station, acting as a mobile phone.
    - ⋆ Once connected, the IMSI catcher can:
      - · Intercept data and voice traffic.
      - · Disable encryption by negotiating an unencrypted or weaker cipher mode.
      - · Track users by capturing their IMSI or location data.
  - This method exploits the lack of mutual authentication in GSM networks (i.e., the mobile phone does not verify the Base Station's authenticity).

6.3 UMTS

6.3.1 Security Improvements

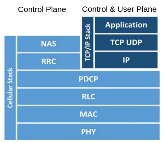
- **3GPP** (*3rd Generation Partnership Project*)
  - Responsible for specifications, including issuing *5G standards*.
- **Old GSM SIM cards** can still be used:
  - Backwards compatibility supports GSM authentication protocols.
- **Circuit and Packet Switching:** Both methods available for communication.
- **Improved Crypto:**
  - *3GPP publishes cryptographic algorithms.*
  - Encryption is applied **not only on the air**, enhancing security.
- **New Encryption Algorithms:**
  - Initially introduced **KASUMI**, used for encryption and CBC-MAC.
  - Later replaced by more secure algorithms, as **KASUMI was broken**.
- **Mutual Authentication:**
  - *Both user and network authenticate each other (not mandatory).*
- **Main Problems:**
  - Backwards compatibility creates vulnerabilities.
  - *Fallback to GSM weakens overall security.*

6.4 LTE- Long Term Evolution



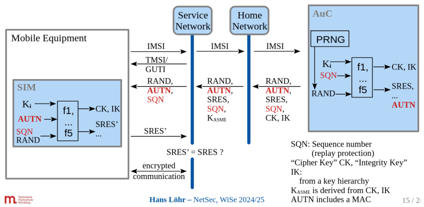
6.4.1 Protocol Stack

6.4.2 LTE Protocol Stack



- **Control Plane:**
  - Handles signaling, network resource management, and routing.
  - Ensures communication setup and maintenance.
- **User Plane:**
  - Responsible for transferring user data (e.g., voice, video, and application data).
  - Integrates directly with applications via the TCP/IP stack.
- **Key Protocols (Cellular Stack):**
  - **NAS (Non-Access Stratum):**
    - ⋆ Manages mobility and session-related signaling between the UE and the core network (e.g., authentication, location updates).
  - **RRC (Radio Resource Control):**
    - ⋆ Handles signaling at the radio level, such as connection setup, handovers, and state management.
  - **PDCP (Packet Data Convergence Protocol):**
    - ⋆ Provides header compression, encryption, and integrity protection for user and control plane data.
  - **RLC (Radio Link Control):**
    - ⋆ Ensures data reliability through retransmissions and error correction.
  - **MAC (Medium Access Control):**
    - ⋆ Manages resource allocation and data multiplexing for multiple UEs.
  - **PHY (Physical Layer):**
    - ⋆ Deals with the actual transmission of radio signals over the air interface.
- **Integration with Applications:**
  - The LTE stack works alongside the TCP/IP stack for application-level data transfer:
    - ⋆ Application protocols (e.g., HTTP, VoIP) run on top of **TCP/UDP**.
    - ⋆ **IP** ensures routing and addressing across networks.
    - ⋆ PDCP compresses and encrypts packets before passing them to the lower layers for radio transmission.

6.4.3 Authentication



- **Authentication Process:**
  - The **Home Network** sends a random challenge (**RAND**), an authentication token (**AUTN**), and a sequence number (**SQN**) to the **Mobile Equipment (ME)**.
  - The **SIM card** in the ME uses the **subscriber key** (K_i) and predefined functions ($f1, f2, \ldots, f5$) to compute:
    - ⋆ **SRES'**: Signed response for authentication.
    - ⋆ **CK:** Cipher key for encryption.
    - ⋆ **IK:** Integrity key for data integrity.
  - The **ME** sends **SRES'** back to the network for verification.
  - If **SRES'** matches the expected **SRES**, authentication is successful, and encrypted communication begins.
- **Acronyms:**
  - **RAND:** Random number used for the challenge.
  - **AUTN:** Authentication token, includes a MAC (Message Authentication Code).
  - **SQN:** Sequence number for replay protection.
  - K_i: Subscriber key shared between SIM and the Home Network.
  - **CK:** Cipher key, used for encrypting data.
  - **IK:** Integrity key, used for ensuring data integrity.
  - K_{ASME}: Key derived from **CK** and **IK**, used for session management.
- **Security Features:**
  - Protects against replay attacks using **SQN**.
  - Ensures mutual authentication with **AUTN** and **SRES**.
  - Enables encrypted communication using **CK**.

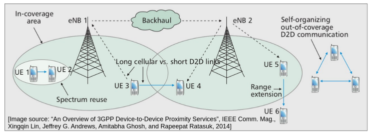
6.4.4 Crypto Algorithms

- **Authentication Algorithms:**
  - $f1, f2$: Message Authentication Codes (MACs), inherited from UMTS.
  - Operator-specific (**MNO-dependent**); 3GPP recommends AES-based algorithms.
- **Key Generation Algorithms (Key Derivation):**
  - $f3, f4, f5$: Used for deriving keys (e.g., K_c, K_i), also inherited from UMTS.
  - Operator-specific (**MNO-dependent**); 3GPP recommends AES-based algorithms.
- **Encryption Algorithms:**
  - **EEA0:** "Null cipher" (no encryption).
  - **128-EEA1:** SNOW 3G (stream cipher).
  - **128-EEA2:** AES-based encryption algorithm (strong and widely used).
  - **128-EEA3:** ZUC (Chinese stream cipher).
- **Integrity Algorithms (EIA):**
  - Similar to encryption, used to ensure data integrity during transmission.

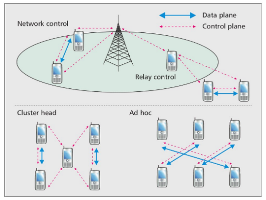
6.4.5 Privacy

- **Fact:** Mobile Network Operators (MNOs) can always track their users (this is by design).
- **Additional Problem:** Eavesdropping on radio communication.
  - **IMSI:** A unique identifier for a user:
    - ⋆ **GSM:** Used by the UE only when no **TMSI** is available.
    - ⋆ **LTE: IMSI** replaced by **GUTI** (Globally Unique Temporary Identifier).
  - **TMSI/GUTI:**
    - ⋆ Can (and should) be **updated frequently** to avoid tracking by third parties.
    - ⋆ Changes must be **unpredictable** to prevent tracking or identification.
  - Research findings:
    - ⋆ 19 out of 28 MNOs used **very simple, predictable patterns**, such as monotonic counters.
    - ⋆ Earlier research found **no or very rare changes**, allowing tracking.

6.4.6 LTE Proximity Services (ProSe)



- **ProSe:** Cellular Device-to-Device (D2D) Communication
  - Enables communication between devices directly, bypassing base stations.
  - Can operate **with or without network coverage.**
  - Commonly used in **public safety networks**, such as emergencies or disasters.
  - **Applications:**
    - ⋆ Peer-to-peer applications.
    - ⋆ Location-based services.
    - ⋆ Range extension through device relays.
- **Control Modes:**



  - **Network-Controlled Mode:**
    - ⋆ ProSe communication is managed via the LTE network for reliability and resource allocation.
  - **Cluster Head Mode:**
    - ⋆ A device (cluster head) acts as a local coordinator for nearby devices.
    - ⋆ Manages intra-cluster communication and relays data to the LTE network or other clusters.
  - **Ad Hoc Mode:**
    - ⋆ Devices communicate directly without centralized control.
    - ⋆ Suitable for completely out-of-coverage scenarios.
- **Key Management:**
  - **Authorization:** User Equipment (UE) must be authorized unless pre-configured on the USIM.
  - **MIKEY (Multimedia Internet Keying):**
    - ⋆ Used for VoIP key exchange.
    - ⋆ Supports different modes (e.g., pre-shared keys or PKI-based).
  - **Key Hierarchy:**
    - ⋆ ProSe MIKEY Key (PMK) Temporary ProSe Group Key (PGK).
    - ⋆ PGK ProSe Traffic Key (PTK) ProSe Encryption Key (PEK).

6.5 5G: The 5th Generation Mobile Network

- **5G:** Represents the next and current generation of mobile networks.
- **Deployment:** Has already started, though some specifications are still evolving.
- **Performance:**
  - Much faster than 4G.
  - Provides significantly lower latency and higher reliability.
- **Advancements:**
  - Builds on software-defined networking principles, initiated with LTE.
  - Includes advanced **Quality-of-Service (QoS)** features.
- **New Application Scenarios:**
  - **Industry 4.0:** Automation and IoT for manufacturing and logistics.
  - **Device-to-Device Communication:** Key for vehicular networks and ProSe.
  - **Private Networks:** Operated by non-traditional operators, such as manufacturing industries.

6.5.1 5G Security: Relevant Entities (Functions)

- **AMF (Access and Mobility Management Function):** Manages device access and mobility in the Serving Network.
- **SEAF (Security Anchor Functionality):** Handles initial authentication and acts as the anchor point for security in the Serving Network.
- **AUSF (Authentication Server Function):** Processes authentication in the Home Network, replacing the HSS from LTE.
- **ARPF (Authentication Credential Repository and Processing Function):** Stores and processes authentication keys, like the AuC in LTE.
- **SEPP (Security Edge Protection Proxy):** Secures inter-operator communication (e.g., roaming) by protecting signaling messages exchanged between networks.

- **IMSI SUPI (Subscription Permanent Identifier):**
  - **SUPI:** Replaces IMSI and is never transmitted unencrypted over the air.
  - **SUCI (Subscription Concealed Identifier):**
    - ⋆ SUPI is encrypted using the network's public key to create SUCI for secure transmission.
  - **TMSI 5G-S-TMSI:** Mandatory to change after paging (e.g., during basestation handover).
  - **GUTI 5G-GUTI:** Requirements for dynamic GUTI changes to improve privacy.
- **Authentication (AKA):**
  - Protocol improvements to better protect security features and enhance user privacy.
- **IMSI Catcher Detection:**
  - **Measurement Reports:** Enable network-based and UE-assisted detection.
  - Makes IMSI/SUCI catchers harder to deploy without being detected.
- **Security in 5G Standalone Mode:**
  - Many advanced features are available only in 5G "Standalone" mode.
  - Current usage is mainly **5G NSA (Non-Standalone)** for cooperation with 4G (LTE).

6.5.2 Authentication and Key Agreement

- **Authentication Options:**
  - **EAP-AKA'**:
    - ⋆ Defined in RFC5448.
    - ⋆ Based on pre-shared keys.
    - ⋆ Fits into the EAP (Extensible Authentication Protocol) framework.
  - **5G AKA**:
    - ⋆ Derived from LTE AKA for backward compatibility.
- **Privacy Concerns:**
  - Flaws in 5G AKA found via formal protocol analysis:
    - ⋆ *David Basin et al., "A Formal Analysis of 5G Authentication", ACM CCS 2018.*
  - Practical attacks require targeting specific users:
    - ⋆ *Chlosta, Rupprecht, Pöpper, Holz, "5G SUCI-Catchers: Still catching them all?", ACM WiSec 2021.*

6.5.3 Service-Based Interfaces

- **Network Operators and 3rd Parties Offering "Services":**
  - **Network Functions (NF):** Core network features exposed as services.
  - **Other Services:** Additional functionalities provided by the network.
  - **TLS Support:** Ensures secure communication between entities.
  - **OAuth 2.0-based Authorization:** Allows secure access control using access tokens.
- **Network Slices:**
  - Provides virtualized and isolated network partitions with specific **QoS (Quality of Service)** properties.
  - Uses **EAP-based Authorization** for access control.

7 Firewalls, Intrusion Detection and Prevention

7.1 Firewalls

- Firewalls separate networks
  - Restricts traffic: enforces policy
  - Logging
  - Implemented in SW and/or HW)

7.1.1 Packet Filtering

- **Packet filtering firewalls:**
  - Policies defined by filtering rules (source, destination, port, protocol, etc.).
  - Rules decide actions: accept, block, log, or modify packets.
  - Advanced filters can modify packets (e.g., NAT or port translation).
- **Advantages:**
  - Cheap, widely available, and efficient.
  - Examples: Linux `netfilter`, Windows firewall.
  - Simple implementation; no modification to applications required.
- **Limitations:**
  - Susceptible to IP and port spoofing attacks.
  - Rules limited to individual packets and lack comprehensive state awareness.
  - Cannot enforce application-specific filtering; lacks deeper protocol knowledge.
  - Usually not capable of rejecting specific packets within a particular application session.
- **Niche Aspects:**
  - Filters can reject IP spoofing by blocking packets from internal addresses arriving at external interfaces.
  - Access control by ports can restrict services to specific source addresses (e.g., SMTP limited to internal IPs).
  - Can filter based on packet type (TCP, UDP) or flags (e.g., SYN for connection establishment).

7.1.2 Connection Tracking and Stateful Firewalls

- **Connection Tracking:**
  - Tracks packets belonging to the same logical "connection" (not limited to TCP).
  - Examples:
    - UDP-based connections (e.g., DTLS).
    - DNS requests/responses and ICMP echo/replies.
  - Supports protocols with separate control and data connections (e.g., active FTP).
  - Enables NAT functionality by rewriting addresses for complex protocols.
- **Stateful Firewalls:**
  - Maintain state information about active connections.
  - Rules can dynamically adapt based on connection states (e.g., allow replies to outgoing requests).

7.1.3 Linux Firewall: Netfilter

Netfilter, part of the Linux kernel, is a framework for packet filtering and network address translation (NAT). It operates using a series of hooks in the network stack where rules, organized into **tables** and **chains**, are applied.

Chains and Their Functions:

- **Input Chain:** Handles packets destined for the local system (e.g., filtering SSH traffic).
- **Output Chain:** Manages packets generated locally and leaving the system (e.g., limiting outgoing ICMP traffic).
- **Forward Chain:** Processes packets passing through the system but not destined for it (e.g., traffic routing in a gateway).
- **Prerouting Chain:** Alters incoming packets before routing decisions (e.g., DNAT for port redirection).
- **Postrouting Chain:** Alters outgoing packets after routing decisions (e.g., SNAT for source IP modification).

Key Components:

- **Tables:** Contain chains for specific tasks:
  - **Filter Table:** Default table for packet filtering (Input, Output, Forward chains).
  - **NAT Table:** Used for network address translation (Prerouting, Postrouting chains).
  - **Mangle Table:** For modifying packet headers.
- **Tools:**
  - `iptables`: Legacy tool for managing rules.
  - `nftables`: Modern replacement offering simplified syntax and better performance.

Use Case Example: A packet enters the system through the **Prerouting Chain**, is routed to the appropriate interface (via **Forward Chain** if being forwarded or **Input Chain** if destined locally), and exits through the **Postrouting Chain** after necessary modifications. Netfilters modularity and flexibility make it a powerful tool for managing network traffic.

7.1.4 Application-Level Gateways

An **Application-Level Gateway (ALG)** acts as an intermediary between clients and applications, offering fine-grained control and monitoring of traffic specific to application protocols. It provides a specialized interface tailored for applications, such as SMTP or HTTP, allowing for filtering, logging, and user profiling at the application layer.

Functionality:

- **Connection Handling:** Clients connect to the gateway, which filters and analyzes the traffic before forwarding it to the application server.
- **Protocol Awareness:** Equipped with detailed knowledge of application-specific protocols, enabling in-depth traffic inspection and filtering.
- **State Management:** Tracks the state of connections or application data to enforce security or logging policies effectively.
- In-depth analysis and traffic filtering based on application logic.
- Enables user profiling, attack detection, and intrusion prevention.
- Provides application-specific caching and potential for secure communication.
- App extensions for additional features, such as authentication, without modifying the original application.

Limitations:

- **Performance Overhead:** The inspection and filtering process can reduce throughput.
- **Maintenance Effort:** Requires frequent updates to stay compatible with evolving application protocols.
- **Limited Scope:** Only supports predefined applications, limiting flexibility in heterogeneous environments.

Use Case: ALGs are frequently employed in enterprise environments for managing email servers (e.g., SMTP gateways) or for secure access to critical applications by acting as a filter and logging interface for external traffic.

7.1.5 Proxy Firewalls

Proxy firewalls act as a generic proxy on the transport layer, enabling advanced traffic control and enhancing communication security.

Key Features:

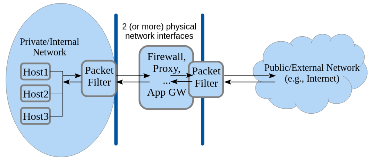
- **Connection State Tracking:** Monitors and manages the state of connections.
- **Authentication and Security:** Adds user authentication and communication security.
  - Frequently used in corporate environments:
    - Outgoing traffic is routed only via the proxy.
    - User authentication is required before access.
    - Only specific ports or applications are allowed.
- **Flexibility:** Can extend functionality toward application-level filtering (e.g., web proxies or caches).

Comparison to Application-Level Gateways:

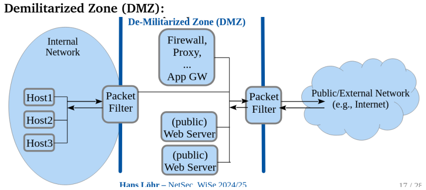
- Proxy firewalls are more general than application-level gateways.
- The distinction between proxy firewalls and application gateways is not always clear.

Firewall Architectures: Dual-Homed Firewall vs. DMZ

- **Dual-Homed Firewall:**



  - *Concept:* Firewall with two interfaces separating internal and external networks.
  - *Operation:* Traffic flows through the firewall, using packet filters or proxies for mediation.
  - *Advantages:*
    - Strong physical isolation.
    - Centralized traffic control.
    - Flexible integration of security mechanisms.
  - *Disadvantages:*
    - Requires additional hardware resources.
    - Limited scalability for complex networks.
  - *Use Cases:* Suitable for small/medium networks needing strict isolation.
- **Demilitarized Zone (DMZ):**



  - *Concept:* Segregated network zone for public-facing services (e.g., web servers).
  - *Operation:* Packet filters manage traffic to/from DMZ, preventing direct internal access.
  - *Advantages:*
    - Protects internal networks from compromised public-facing services.
    - Granular traffic control for specific services.
    - Limits exposure of internal systems.
  - *Disadvantages:*
    - Adds configuration and maintenance complexity.
  - *Use Cases:* Ideal for hosting public services (e.g., web hosting, e-commerce).
- Key Differences:
  - Dual-Homed focuses on isolation, while DMZ separates public services from internal systems.
  - DMZ adds a dedicated network segment for external-facing servers.

7.2 Intrusion Detection and Prevention System (IDPS)

- **Intrusion Detection Systems (IDSs):**
  - Detect attempts to attack or intrusions.
  - Focused on monitoring and logging suspicious activities.
- **Prevention:**
  - React to detected intrusions to prevent successful attacks.
  - Goal: Stop attacks in progress by blocking or responding.
- **IDPS = IDS + Prevention:** Combines detection and prevention to ensure proactive and reactive defense mechanisms.
- **Historical Work:**
  - James Anderson: *Computer Security Threat Monitoring and Surveillance* (1980).
  - Dorothy Denning: *An Intrusion Detection Model* (1987).

Why Use IDPS?

- Identify incidents effectively.
- Support incident response to minimize damage.
- Identify gaps in security policy and practices.
- Deter insiders from violating policies.

7.2.1 IDPS Functionality (High-Level)

- **Record Events:**
  - Logging and accounting for detected activities.
  - Observations useful for detecting and analyzing incidents.
  - Integration with Security Information and Event Management (SIEM) systems.
- **Notify Administrators:**
  - Alert administrators to take appropriate action.
- **Produce Reports:**
  - Summarize activities and detected threats for analysis.
- **Automated First-Level Reaction:**
  - Stop attacks or intrusion attempts automatically.
  - Dynamically change the security environment, e.g., reconfigure firewalls.

7.2.2 Intrusion Detection Model (Denning, 1987)

- **Components:**
  - **Subjects:** Entities initiating actions.
  - **Objects:** Resources being accessed or affected.
  - **Audit Records:** Logs of subject actions for monitoring.
  - **Profiles:** Behavioral characterizations based on metrics.
  - **Anomaly Records:** Highlight abnormal activities.
  - **Activity Rules:** Define responses to anomalies (e.g., profile updates, intrusion reporting).
- **Metrics:**
  - Event Counters
  - Interval Timers
  - Resource Measures
- **Models:**
  - **Statistical Models:** Identify statistical anomalies.
    - Mean and Standard Deviation Model
    - Multivariate Correlation Model
    - Markov Process Model
    - Time Series Model
  - **Operational Models:** Compare metrics against predefined thresholds.
  - **Modern Approaches:** Incorporate Machine Learning/AI for advanced anomaly detection.

7.2.3 Types of IDPS

- **Network-Based Intrusion Detection System (NIDS):**
  - Monitors and analyzes network traffic.
  - Often integrated with firewalls (tightly or loosely).
  - Includes specialized Wireless IDPS for wireless networks.
  - Incorporates Network Behavior Analysis (NBA) for deeper traffic insights.
- **Host-Based Intrusion Detection System (HIDS):**
  - Monitors activity on a specific host (server or end-user device).
  - Analyzes system and application logs, network activity, running processes, and system calls.
  - Tracks file accesses and configuration changes for anomaly detection.

7.2.4 IDPS Architecture

- **Sensors (Agents):** Monitor and analyze activity.
- **IDPS Management Server:** Collects information from sensors and manages them.
- **Database:** Serves as a repository for audit records.
- **Admin Console:** Provides a user interface for administrators.

7.2.5 Detection Methodologies: Categorization

- **Signature-Based Intrusion Detection**
  - Uses fixed patterns to identify *known threats* (e.g., hash values of malware).
  - Limited to known threats and can be evaded by intelligent attackers.
- **Anomaly-Based Intrusion Detection**
  - Detects previously unknown threats by modeling normal/abnormal behavior.
  - Requires a *training/learning phase* for data collection and profiling.
  - Often uses Machine Learning or AI; main focus of current research.
- **Specification-Based Intrusion Detection (Stateful Protocol Analysis)**
  - Compares observations to models/specifications of legitimate behavior.
  - Can be integrated into application-level gateways.

7.3 Summary

- **Firewalls**
  - Essential building block for network security.
  - Alone cannot effectively prevent attacks.
  - Various types:
    - Packet filters.
    - Application-level gateways/proxies.
  - Example: Linux firewall (netfilter, iptables/nftables).
- **Intrusion Detection and Prevention Systems (IDPS)**
  - Detect and prevent intrusion attempts.
  - Types:
    - Host-based vs. Network-based IDPS.
  - Detection methodologies:
    - Signature-based.
    - Behavior-based (e.g., anomaly detection).
  - Specialized IDPS for specific systems (e.g., industrial automation, vehicle networks).

8 Border Gateway Protocol (BGP), Domain Name System (DNS)

8.1 Routing

- **Routing:** Finding the best path from source to destination.
  - *Internal routing:* Within a network or AS (Autonomous System).
  - *External routing:* Between networks or ASes.
  - Different types of routing algorithms exist.
- **Distance Vector Algorithms (e.g., Bellman-Ford):**
  - Practical for networks of limited size ⇒ used for internal routing.
- **Link-State Algorithms (e.g., Dijkstra):**
  - Computes the shortest path.
  - Suitable for networks of limited size ⇒ used for internal routing.
- **Path-Vector Algorithms:**
  - Advertises paths to reach destinations.
  - Suitable for external routing between networks.

8.2 Border Gateway Protocol (BGP)

- **Border Gateway Protocol (BGP):**
  - Originally specified in RFC 1105 (1989).
  - Current version: BGP4 (RFC 4271, 2006).
- **Border Routers:** Connect Autonomous Systems (AS).
- **External BGP (eBGP):**
  - Operates between ASes.
  - Uses Classless Inter-Domain Routing (CIDR) prefixes.
  - Advertises:
    - Routing prefixes for the router's own network.
    - Prefixes from connected ASes (includes the *AS path*).
- **Internal BGP (iBGP):**
  - Operates within an AS.
  - Used to propagate BGP information internally.

8.2.1 Internet Interconnection Ecosystem

- **Internet Exchange Points (IXP):**
  - Locations where ISPs and ASes exchange traffic.
  - Examples: DE-CIX, AMS-IX, N-IX.
- **Connections between Autonomous Systems:**
  - **Peering:**
    - ASes agree to exchange traffic without charge.
    - Typically between ASes of similar size.
  - **Transit:**
    - One AS pays another for interconnection services.
- **Challenges:**
  - Missing economic incentives to improve interconnection infrastructure.

8.2.2 Resilience and Security

- **Route Filtering:**
  - Best practices: filter route announcements to limit accepted routes.
  - Issues: not universally supported; mainly benefits others.
  - Example: lack of IP spoofing packet filtering.
- **Enormous Scale:**
  - Hard to attack large portions of the internet due to diversity.
  - Increasing centralization: few large players (e.g., Google, Akamai, Cloudflare).
- **Missing Data and Metrics:**
  - Lack of global transparency; commercial secrecy.
  - Difficult to evaluate network interconnection resilience.
  - Historically robust, but future concerns exist.
- **Regulation:**
  - Historically minimal.
  - Country-dependent: some regulations harm free/open internet.
  - Market concentration may require anti-trust regulation (e.g., oligopolies).
- **Future:** Moving towards **BGPsec** for improved security.

8.2.3 BGPsec: Simplified Overview

- **Definition:** BGPsec (RFC 8205, 2017) focuses on AS path validation.
- **Key Features:**
  - Utilizes **Resource PKI (RPKI)** to certify which AS is responsible for specific IP prefixes.
  - AS explicitly authorizes the next AS in the path to announce the route.
    - BGP UPDATE message includes `AS_PATH` (BGP) → `BGPsec_PATH`.
    - Each BGPsec-capable AS:
      - Needs an RPKI certificate.
      - Signs prefix and `BGPsec_PATH` with its private key.
    - Recipient verifies all ASes on the path were explicitly authorized.
- **Issues:**
  - Lack of incentives for ASes to support BGPsec.
  - Cryptographic overhead may impact resilience (e.g., handling unsigned announcements during recovery).
  - Preventing malicious ASes (with legitimate IPs) from injecting routes.

8.2.4 Summary

- **BGP seems fragile?**
  - Easily disturbed by failures or attacks.
  - **No global view:** Each AS has only local knowledge of its network and direct neighbors.
  - Explicit contracts/partnerships only with direct neighbors.
  - **Limited technical security:** Relies on trust, contracts, and decentralized motivation.
- **Little is known about the internet interconnection ecosystem:**
  - Lack of global view and detailed measurement data.
  - Effects of incidents are unpredictable.
- **BGP seems resilient?**
  - Internet functions well despite limitations.
  - Disaster recovery has been effective in the past.

8.3 DNS

- **DNS lookup retrieves a resource record:**
  - **Types of records:**
    - **A:** IPv4 address (domain name → IP address)
    - **AAAA:** IPv6 address
    - **MX:** Mail server responsible for the domain
    - **NS:** Authoritative name server for the domain
    - **TXT:** Textual descriptions
      - E.g., used for data that does not fit other record types
    - ...other types exist

8.3.1 DNS Attacks

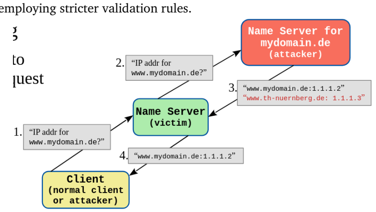
DNS (Domain Name System) attacks exploit vulnerabilities in the DNS infrastructure to misdirect users, disrupt services, or compromise sensitive data. This subsection details two common types of DNS cache poisoning attacks, the Kaminsky attack, and effective countermeasures.

- **Local Attack:** Malware modifies the `/etc/hosts` file on Unix-like systems, redirecting requests to malicious IPs.
- **Compromised Name Server:** Attackers exploit vulnerabilities in DNS server software to take control of legitimate name servers.
- **Spoofing:** Fake responses are sent to queries by forging the name server's IP address (e.g., by spoofing UDP packets).
- **DNS Cache Poisoning:**
  - Insert fake records in DNS responses, causing the victim to cache wrong IPs.
  - Effect: Users are redirected to malicious websites.

DNS Cache Poisoning: Insert Fake Record In this attack, an attacker inserts a fake DNS record into a legitimate DNS response. The steps are as follows:

- **Step 1:** A client (or attacker) queries the victim's name server for the IP address of a domain (e.g., `www.mydomain.de`).
- **Step 2:** The victim name server forwards the query to the authoritative name server for the domain.
- **Step 3:** The attacker, controlling the authoritative server, sends a fake response containing false DNS records (e.g., redirecting another domain to a malicious IP).
- **Step 4:** The victim name server caches the malicious response and serves it to the client.

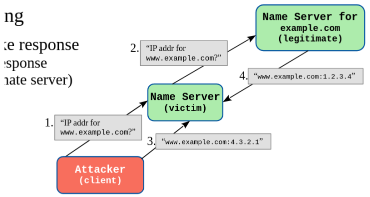
The effect is that users querying the victim name server are redirected to the wrong IP address. This attack can be mitigated by randomizing query IDs, validating responses using DNSSEC, and employing stricter validation rules.



DNS Cache Poisoning: Fake Response Faster than Legitimate Server This attack involves the attacker sending a fake DNS response faster than the legitimate authoritative server. The steps are:

- **Step 1:** The attacker sends a DNS query for a domain (e.g., `www.example.com`) to the victim's name server.
- **Step 2:** The victim forwards the query to the legitimate authoritative name server.
- **Step 3:** The attacker sends a forged response containing a malicious IP address before the legitimate server can reply.
- **Step 4:** The victim name server caches the fake response and returns it to the attacker.

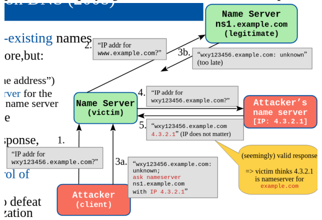
The result is that the legitimate response is ignored, and the malicious IP address is cached. Countermeasures include randomizing ports and query IDs, implementing DNSSEC, and stricter validation rules.



Kaminsky Attack The Kaminsky attack is a sophisticated DNS cache poisoning technique that exploits a vulnerability in DNS protocol design to inject malicious entries into DNS caches. The steps are as follows:

- **Step 1:** The attacker repeatedly queries the victim name server for non-existent subdomains (e.g., `xyz123.example.com`).
- **Step 2:** The victim name server forwards the query to the authoritative server but receives a fake response from the attacker instead.
- **Step 3:** The fake response contains an authoritative NS record pointing to a malicious name server controlled by the attacker.
- **Step 4:** The victim caches the malicious name server as authoritative for the domain.
- **Step 5:** All subsequent DNS queries for the domain are redirected to the attacker's malicious name server.

This attack is particularly dangerous as it allows the attacker to poison entire DNS zones, redirecting all traffic for affected domains. Mitigations include randomizing query IDs, query source ports, and deploying DNSSEC to authenticate responses.



Countermeasures Against DNS Cache Poisoning To protect against DNS cache poisoning and related attacks, the following countermeasures are commonly implemented:

- **Randomized Query IDs:** Use randomized 16-bit query IDs to reduce predictability.
- **Randomized Source Ports:** Use random UDP source ports to add an additional layer of entropy.
- **DNSSEC:** Deploy DNSSEC to authenticate DNS responses and ensure their integrity.
- **Rate Limiting:** Implement rate limiting for queries and responses to reduce the likelihood of brute-force attacks.
- **Strict Validation:** Enforce strict validation rules for DNS responses.

These countermeasures significantly increase the difficulty for attackers to successfully perform DNS cache poisoning or similar attacks.

8.3.2 DNSSEC (Domain Name System Security Extensions)

Goal of DNSSEC:

- **Origin Authentication:** Ensures authenticity of DNS data.
- **Authenticated Denial of Existence:** Proof of non-existence of records.
- **Data Integrity:** Verifies DNS data has not been tampered with.

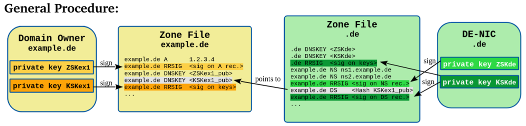
History:

- 1993: Discussions and development started.
- 1997, 1999: Initial proposals (RFCs 2065, 2535, now obsolete).
- 2005: Current approach (RFCs 4033-4035).
- 2010: All root servers supported DNSSEC.
- 2011: DNSSEC adopted for `.de` domains.

Key Resource Records Introduced:

- **DNSKEY:** Public keys for signing zone data, distinguishing Key Signing Keys (KSK) and Zone Signing Keys (ZSK).
- **DS:** Delegation Signer; links parent to child zones.
- **RRSIG:** Digital signatures for verifying records.
- **NSEC/NSEC3:** Proof of non-existence through authenticated linked lists of DNS records.

General Procedure:



1. Zone entries are signed with private ZSK.
2. ZSK is signed by private KSK.
3. Parent domain stores the hash of the child zones KSK in a DS record.
4. Establishes a recursive *chain of trust*, starting from the root zone.
5. Public key of the root zone acts as the *trust anchor*.

Chain of Trust:

- Starts at the root zone.
- Extends through TLDs, domain zones, and subdomains.
- Requires the public key of the root zone to be securely distributed.

NSEC: Proof of Non-Existence

- Authenticates denial of existence by creating a sorted linked list of all domain names in a zone.
- Each signed entry includes the next domain name.
- Example: If `hello.example.com` is queried but doesn't exist, the response includes proof of its neighboring domains.
- **Disadvantage:** Enables zone walking, where attackers can list all (sub-)domains.

NSEC3: Mitigation of Zone Walking

- Uses hashed domain names instead of plaintext.
- Sorted hashes prevent attackers from easily enumerating domain names.
- Clients compute the hash of the requested domain and compare it to NSEC3 records.
- Dictionary attacks are still possible, but mitigated using salt and multiple hashing iterations.

Other Uses of DNSSEC DNSSEC can be utilized to enhance other security mechanisms by securely distributing associated data:

- **SSH fingerprints:** Distributed as per RFC 4244.
- **IPsec/IKE public keys:** Defined in RFC 4025.
- **TLS trust anchors via DANE (RFC 6698):**
  - DNS-Based Authentication of Named Entities (DANE).
  - Protects against clandestine TLS certificate exchange by attackers.
  - Enables referencing of X.509 certificates in DNSSEC-protected resource records (TLSA records).

DNSSEC in Practice

- **Slow Adoption:** DNSSEC uptake has been slow due to:
  - Overhead in communication, computation, delays, and administrative effort.
  - Limited operational experience despite its long history.
  - Larger resource records, increasing the potential for DoS attacks.
- **No Confidentiality:** DNSSEC was not designed to provide confidentiality.
- **Typical Deployment:**
  - The resolver is usually the nameserver of the ISP or network, not the local system.
  - Resolver verifies signatures but requires the path from the end-user system to the resolver to be secured.

8.3.3 DNS-over-TLS (DoT) and DNS-over-HTTPS (DoH)

- **DNS-over-TLS (DoT):**
  - Uses **TLS** (instead of UDP) to transport DNS queries.
  - Provides **confidentiality**, integrity, and authenticity between the client and resolver (nameserver, often referred to as the "DNS provider").
  - Does not protect traffic between nameservers (e.g., between the DNS provider and the authoritative nameserver).
- **DNS-over-HTTPS (DoH):**
  - Similar to DoT but uses **HTTPS** to send queries via POST or GET requests.
  - Supports normal query formats (as used in UDP) or even JSON.
  - Particularly suited for browsers and web applications.
  - Comes with **additional overhead and dependencies**.

8.4 Zusammenfassung DNS

- **Domain Name System (DNS)**
  - Developed without security in mind
  - Vulnerabilities: **Cache poisoning attacks**, Kaminsky's attack
- **DNSSEC**
  - Provides **digital signatures and keys** in DNS resource records
  - Ensures **integrity and authenticity** of DNS responses
  - Implements **NSEC/NSEC3** for proof of non-existence of DNS names
  - Can bootstrap other security mechanisms
- **DNS-over-HTTPS (DoH), DNS-over-TLS (DoT)**
  - Protect traffic from the end user system to the DNS resolver / nameserver
  - Both provide **confidentiality, integrity, and authenticity** via **TLS**

9 eMail and Messaging Security

9.1 eMail

9.1.1 Sending Emails: SMTP, POP3, IMAP

- **Protocols:**
  - Send: SMTP (Simple Mail Transfer Protocol)
  - Receive: POP3 or IMAP
- **Security:**
  - **TLS:**
    - SMTP over TLS: sender to mail server
    - POP3/IMAP over TLS: mail server to recipient
  - **Between Mail Servers:** Opportunistic encryption (e.g., STARTTLS)
    - Starts unprotected, upgrades to TLS if supported.
    - Falls back to plaintext if TLS fails.
    - No identity verification (certificates often not checked).

9.1.2 PGP: End-to-End Security for Emails

- **Pretty Good Privacy (PGP):**
  - Developed in 1991 by Phil Zimmermann.
  - Signs and encrypts data (not limited to email).
  - Standardized as OpenPGP (RFC 2440, 4880).
  - Implementations: commercial PGP, GnuPG (open source), others.
  - Trust model: Web of Trust (decentralized, "anarchic").
- **End-to-End Security:**
  - Hybrid encryption:
    - Symmetric key (session-specific) encrypted by recipient's public key.
    - Message encrypted with the symmetric key.
  - **Independent Signature & Encryption:**
    - PGP handles signing and encryption as separate operations.
    - Issue: Without binding the signature to the encryption context, attackers can:
      - Remove encryption and present the signature in plaintext (signature repudiation).
      - Forward signed plaintext to unintended recipients without the encryption.
      - Modify unsigned metadata or associate it with a different context.
    - Modern cryptographic standards prefer combining these operations into a single, secure AEAD process to ensure both confidentiality and integrity.
  - **Authenticated Encryption (AE):**
    - Introduced in 2001 as a partial fix (Modification Detection Code, MDC).
    - MDC ensured detection of tampering but lacked proper AE guarantees.
    - Issues with early AE:
      - MDC was not strongly integrated into the cryptographic protocol.
      - Attacks possible if MDC was not always applied correctly.
    - Recent standards include "real" AEAD (Authenticated Encryption with Associated Data):
      - Combines encryption and integrity into a single operation.
      - Protects both the ciphertext and associated metadata (e.g., headers).
      - Ensures signatures cannot be separated from encryption.
- **Main Critiques:**
  - Usability issues: easy to misuse.
  - Poor integration with many mail clients.

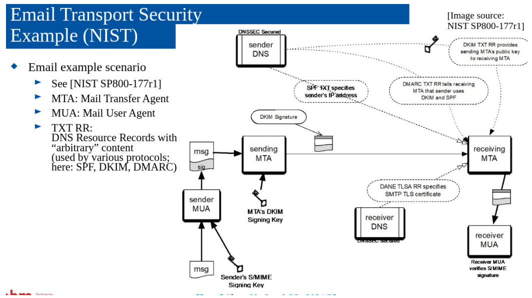
9.1.3 MIME, PGP/MIME, S/MIME

- **MIME (Multi-purpose Internet Mail Extensions):**
  - Enables email attachments and sending arbitrary data (not just text).
  - MIME header specifies transfer encoding and content type (MIME type).
- **PGP/MIME:**
  - Allows sending PGP-encrypted or signed ciphertext as MIME attachments.
- **S/MIME (Secure MIME):**
  - Alternative solution for encrypting and signing emails.
  - Based on X.509 certificates and Public Key Infrastructure (PKI).
  - Provides encryption and signing with properties similar to PGP but utilizes a different trust model.

9.1.4 E-Mail End-to-End Security: S/MIME and PGP

- **Both S/MIME and PGP are widely used for secure email communication:**
  - **S/MIME:** Better suited for corporate environments.
    - Companies can distribute certificates to employees.
    - IT departments can pre-configure email clients (e.g., install plugins).
    - Users simply click to encrypt/sign emails.
    - Works seamlessly within the organization's infrastructure.
  - **PGP:** Decentralized, popular among individuals and open-source communities.
    - No need for a centralized PKI; individuals maintain control.
    - Less user-friendly and more error-prone than S/MIME.
- **Efail attack (2018):** Affected both S/MIME and PGP by exploiting how email clients handled encrypted content.

9.1.5 Improving Transport Encryption for Email



DANE (DNS-based Authentication of Named Entities)

- DNS entry (TLSA record) acts as a trust anchor for TLS certificate verification.
- Requires DNSSEC to ensure integrity.
- Prevents downgrade attacks by enforcing TLS if TLSA records are available.

SPF, DKIM, and DMARC

- **SPF:** Specifies authorized mail servers for a domain.
- **DKIM:** Signs outgoing emails with private keys; recipients verify signatures.
- **DMARC:** Combines SPF and DKIM, defines policies for authentication and reporting.

MTA-STS (MTA Strict Transport Security)

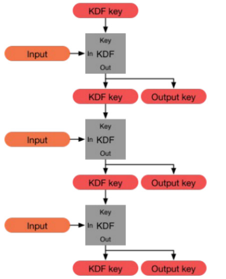
- Alternative to DANE, uses a "trust on first use" (TOFU) approach.
- Does not require DNSSEC.

9.2 Instant Messaging: Signal Protocol

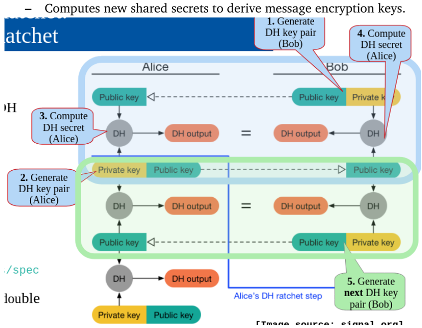
- State-of-the-art security protocol for messaging, used by apps like WhatsApp.
- **History:**
  - Developed by Open Whisper Systems (Moxie Marlinspike, Trevor Perrin) for *TextSecure* (now Signal).
  - Originates from *Off-the-Record* (OTR) protocol → TextSecure v1 (2013).
  - TextSecure v2 (2014): Introduced *Axolotl Ratchet*.
  - TextSecure v3 (2014): New cryptographic primitives and formats.
  - Signal (2016): Protocol updated and renamed.
  - Formal security analysis in 2016; published in 2017.

Key Components

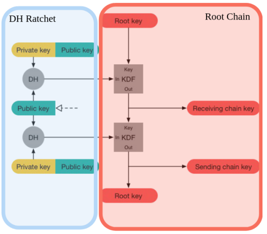
- **KDF Chain:** A Key Derivation Function (KDF) is used in a forward-only hash chain to ensure:
  - *Resilience:* Output keys appear random even if adversary controls inputs.
  - *Forward Security:* Past keys remain secure if current keys are compromised.
  - *Break-in Recovery:* Future keys remain secure with sufficient entropy.



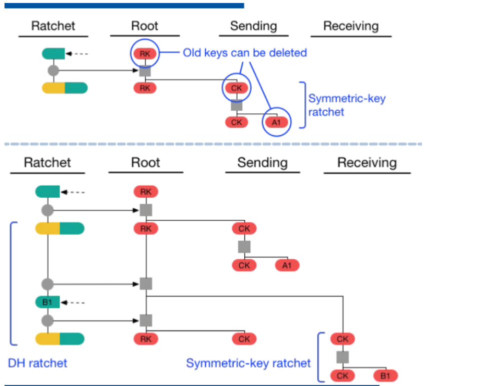
- **Double Ratchet Mechanism:** Combines two ratchets:
  - *Symmetric Key Ratchet:* Uses a KDF to generate encryption keys for messages.
  - *Diffie-Hellman (DH) Ratchet:* Updates DH key pairs for forward secrecy after every message exchange.
- **Diffie-Hellman Ratchet:**
  - Continuously performs DH key exchanges for each message.
  - Transmits DH key shares with messages.
  - Computes new shared secrets to derive message encryption keys.

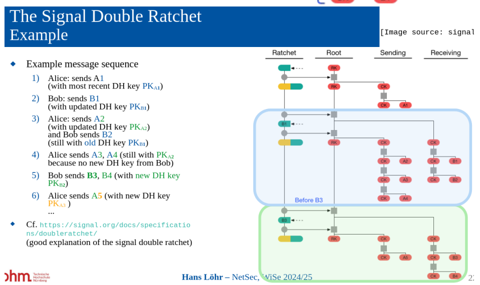


- **Root Chain:** Combines the DH ratchet and symmetric key ratchet:
  - Generates a root key (RK) through DH exchanges.
  - Derives sending and receiving chain keys (CKs) for message encryption.
  - Complete ratchet step => new root key



- **Message Keys:** Each message key is derived from the corresponding chain key (CK):
  - Sender's CK encrypts messages.
  - Receiver's CK decrypts messages.
  - Ensures messages cannot be decrypted after keys are deleted.





9.3 Summary: Email and Messaging Security

Email Security

- **End-to-End Security:**
  - Practical but rarely used due to usability issues.
  - Solutions: **PGP**, **S/MIME**.
- **Email Transport Security:**
  - Originally not designed with security in mind.
  - Improvements: **DANE**, **SPF**, **DKIM**, **DMARC**.

Instant Messaging Security

- **Modern Use Case:**
  - Instant messaging is more recent compared to "ancient" email.
  - Requires tailored security solutions.
- **Closed Ecosystems:**
  - Easier to deploy robust security.
  - High dependency on service providers, limiting competition.
- **Signal Protocol:**
  - Designed for end-to-end security and confidentiality.
  - Based on the **double ratchet** mechanism.
  - Ensures forward secrecy; used by multiple messengers.

10 Anonymous Communication

10.1 Why Anonymous Communication?

- **Anonymity:** Unlinkability zwischen Nachricht/Aktion und Identität.
- **Arten:** Sender-Anonymität, Empfänger-Anonymität.
- **Anonymitätsset:** Gruppe möglicher, nicht unterscheidbarer Teilnehmer.
- **Vorteile:** Schutz der Privatsphäre, Meinungsfreiheit, Whistleblowing.
- **Nachteile:** Missbrauch (illegale Aktivitäten), Performance-Overhead.

10.2 Dining Cryptographers (DC)

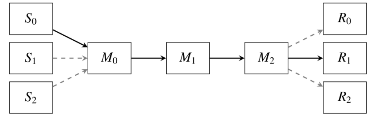
- **Szenario:** Drei Kryptographen möchten wissen, ob einer von ihnen bezahlt hat, ohne die Identität des Zahlenden zu offenbaren.
- **DC-Protokoll:**
  - Erlaubt das anonyme Senden eines Bits (jemand hat bezahlt / niemand hat bezahlt).
  - Informations-theoretische Anonymität.
  - Erweiterbar auf größere Gruppen (DC-Netzwerke).
  - Hoher Aufwand, benötigt viel Zufälligkeit.
- **Dissent:** Anonymes Kommunikationssystem basierend auf DC-Netzwerken, bietet nachweisbare Anonymitätsgarantien.

Prinzip: Teilnehmer teilen Zufallsbits mit ihren Nachbarn.

- **Bit-Berechnung:** XOR(links, rechts, eigene Nachricht).
- **Ergebnis:** Summe aller Bits (mod 2) zeigt an, ob eine Nachricht gesendet wurde.
- **Eigenschaften:**
  - Informations-theoretische Anonymität.
  - Erweiterbar auf mehrere Nachrichten (mehrere Runden).
  - Hoher Overhead (jeder muss teilnehmen).

10.3 MixNets

- **Prinzip:** Nachrichten durchlaufen eine Kette von Mixen (M_0, M_1, M_2), wobei jede Schicht der Verschlüsselung entfernt wird.



- **Ablauf:**

$$S_0 \to M_0 : \text{enc}_{PK_{M_0}}(\text{enc}_{PK_{M_1}}(\text{enc}_{PK_{M_2}}(\text{enc}_{PK_{R_1}}(\text{msg}), R_1), M_2), M_1)$$

- **Eigenschaften:**
  - Jedes Mix entschlüsselt nur eine Schicht und leitet die Nachricht weiter.
  - Sender bestimmt die Reihenfolge der Mixe.
  - Anonymität garantiert, solange mindestens ein Mix ehrlich ist.
- **Herausforderungen:**
  - Mix wartet auf alle Nachrichten Geschwindigkeit hängt vom langsamsten Sender ab.
  - Mix muss vertrauenswürdig sein (kennt Partner, aber nicht den Inhalt).
  - Probleme:
    - Zwei Sender adressieren denselben Empfänger.
    - Ein Sender sendet mehrere Nachrichten.
    - Ein Empfänger möchte antworten.

10.4 Onion Routing und Tor

- **Problem von MixNets:** Zu langsam und ineffizient für Echtzeitkommunikation (z.B. TCP-Verbindungen).
- **Idee von Onion Routing:**
  - Aufbau eines **Circuits** von Sender zu Empfänger über Onion Routers (ORs).
  - Sender wählt OR-Sequenz und baut symmetrische Sitzungsschlüssel mit Diffie-Hellman (DH) auf.
  - Jeder OR kennt nur den vorherigen und nächsten OR (First OR kennt Sender, letzter OR den Empfänger).
  - Datenübertragung erfolgt in Schichten verschlüsselt (ähnlich MixNets).
- **Tor:** Optimierte 2. Generation von Onion Routing.
  - **TLS-geschützte Verbindungen** zwischen Relays (Schutz gegen passive Angriffe).
  - Keine vollständige Sicherheit gegen Traffic-Analyse (z.B. Timing-Korrelationen).
  - Directory Server (DS) zur Veröffentlichung der OR-Public Keys.
  - Rate-Limiting und Staukontrolle verhindern Überlastung.
- **Tor Hidden Services:**
  - Server bleibt anonym, zensur- und DoS-resistent.
  - Einführungspunkte (IP) und Rendezvous-Punkt (RP) vermitteln Kommunikation über Tor-Circuits.
- **Nutzung von Tor:**
  - Tor Browser, private Fenster (z.B. Brave), lokale Tor-Proxies oder Distributionen wie Tails.
  - Achtung bei Betrieb von Tor-Relays, besonders Exit-Nodes (rechtliche Risiken).
- **Einschränkungen:**
  - Keine Sicherheit gegen Tracking auf Anwendungsebene (z.B. Browser-Fingerprinting).

11 WireGuard

11.1 Wichtige Merkmale

- **Kryptographie:**
  - Moderne, sichere und geprüfte Kryptographie.
  - Festgelegte Cipher-Suites: ChaCha20, Poly1305.
- **Kleiner Codeumfang:**
  - Nur 4000 Zeilen Code im Linux-Kernel (OpenVPN 120.000; IPsec 400.000).
  - Weniger Angriffsfläche und leichter auditierbar.
  - Verzicht auf externe Kryptobibliotheken wie OpenSSL.
- **Linux-Kernel-Integration:**
  - Seit Kernel 5.6 (2020) fester Bestandteil des Linux-Kernels.
  - Kein zusätzlicher Installationsaufwand oder Patches erforderlich.
  - Minimaler Overhead, weniger Kontextwechsel als Userspace-VPNs.
- **Performance:**
  - Hohe Leistung bei vielen gleichzeitigen Verbindungen.
  - Effizient auf Embedded Systems und einfachen Routern.
- **Plattformunterstützung:**
  - Implementierungen für Windows, macOS, Android, iOS, BSD-Systeme, Fritz!Box etc.
  - Einfache Einrichtung durch `.conf`-Dateien und QR-Codes.

11.2 Modi und deren Einsatzarten

- **Tunnel-Modus:**
  - Der gesamte IP-Verkehr wird durch den VPN-Tunnel geleitet.
  - **Einsatzarten:**
    - **Site-to-Site:**
      - Verbindung zwischen zwei Netzwerken.
      - Beispiel: Firmenstandorte miteinander verbinden, um ein einheitliches Netzwerk zu schaffen.
    - **Site-to-End:**
      - Verbindung zwischen einem Netzwerk und einem einzelnen Gerät.
      - Beispiel: Remote-Arbeitsplätze mit Zugriff auf Unternehmensressourcen.
- **Transport-Modus:**
  - Nur bestimmte Protokolle oder Dienste werden durch den VPN-Tunnel geleitet.
  - **Einsatzarten:**
    - **End-to-End:**
      - Direkte Verbindung zwischen zwei Geräten.
      - Beispiel: Peer-to-Peer-Kommunikation, wie Dateiübertragungen oder sichere Datenbanken.

11.3 Protokollablauf

- **CryptoKey Routing:**
  - Jede Netzwerkroute ist an einen öffentlichen Schlüssel gebunden.
  - Nur autorisierte Datenpakete werden akzeptiert.
- **Handshake:**
  - Ephemerer Schlüsselaustausch (ECDH mit Curve25519).
  - Sitzungsschlüssel durch HKDF abgeleitet; verwendet für ChaCha20 (Verschlüsselung) und Poly1305 (Authentifizierung).
  - Optional: Pre-Shared Keys zur zusätzlichen Absicherung.
- **Datenübertragung:**
  - Pakete werden mit dem Sitzungsschlüssel verschlüsselt und enthalten einen WireGuard-Header (inkl. Typ, Key-ID, Counter, Payload, MAC).
- **Key Rotation:**
  - Schlüsselwechsel alle 120 Sekunden oder bei Erreichen von Limits (Counter/-Data).
  - Forward Secrecy durch Zeit- und Ressourcengesteuerte Schlüsselrotation.
- **Reactivation:**
  - Verbindung wird bei Inaktivität oder Unterbrechung neu aufgebaut (Handshake).
  - Counter und alte Schlüssel werden aktualisiert.

11.4 Besonderheiten

- **Keep-Alive:**
  - Hält Verbindungen aktiv, z. B. bei NAT oder mobilen Netzwerken.
  - Konfigurierbar mit `PersistentKeepalive`.
- **Sicherheit:**
  - Schutz vor Replay-Angriffen durch Message Counter.
  - Verschlüsselung aller Pakete, minimale Angriffsfläche durch kompakten Code.