CS60203: Design Optimization of Computing Systems *November 17, 2024*

Network Virtualization (Till TCAM Architecture)

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1 Network Interfacing in the TCP/IP Stack

The primary task of the protocol stack is to facilitate the transfer of data across hosts, a function managed by the Data Plane. However, to ensure that the data is reliably delivered to the intended recipient, the network must also perform various control and management tasks, which fall under the responsibilities of the Control Plane. Together, these two planes work in tandem to enable efficient and reliable communication within the network.

Table 1: Comparison Between Data Plane and Control Plane

Aspect	**Data Plane**	**Control Plane**
Purpose	Transfers data across hosts.	Ensures reliable delivery of data to the intended host.
Primary Tasks	• Read packet header. • Determine destination IP/MAC. • Decide next hop interface. • Forward packet to intended interface.	• Prepare routing/forwarding tables. • Manage input/output buffers for flow control.
Operation Scope	Operates on individual packets.	Operates on overall network management.
Execution Time	Fast, real-time operation.	Slower, typically occurs during setup or reconfiguration.

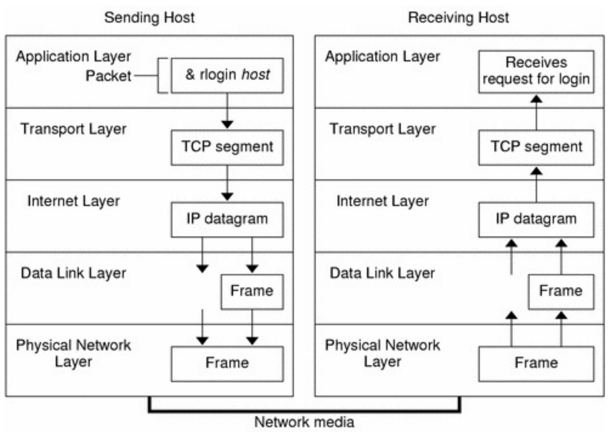

Figure 1: Network Flow

2 Routers and Routing Functionalities

2.1 The Life of a Router

The life of a router revolves around two fundamental tasks: finding the optimal path and forwarding packets. These tasks are managed by two distinct operational planes—the **control plane** and the **data plane**—working in tandem to sustain reliable network communication.

- **Constructing the Routing Table (Control Plane):**
  The first critical operation in a router's lifecycle is constructing and maintaining the routing table, a responsibility of the control plane. This table serves as the router's roadmap, containing the necessary information to determine the best path for delivering packets to their destinations. The routing table is continuously updated to reflect changes in the network topology, ensuring that the paths remain efficient and reliable.

- **Forwarding Packets (Data Plane):**
  Once the routing table is established, the data plane takes over to execute the second key operation: forwarding packets. For each incoming packet, the router identifies its destination by performing a routing match against the routing table. It then forwards the packet to the appropriate interface. This task occurs in real time, enabling seamless communication between hosts.

- **An Endless Cycle of Operations:**
  The router's life is a repetitive cycle of constructing paths and forwarding packets. The control plane updates routing tables as needed to accommodate dynamic network conditions, while the data plane ensures uninterrupted packet delivery.

2.2 Architecture of Router

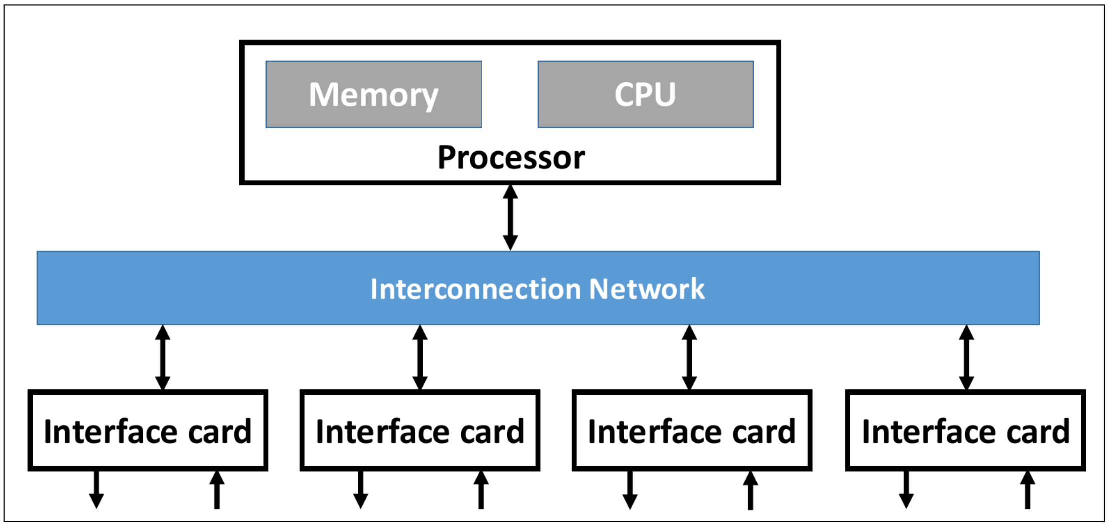

Figure 2: Basic Architectural Components of a Router

2.2.1 Router Hardware and Operations

- **Processor and Control Functions:**
  - The processor (route processor) handles control functions within the router.
  - It is responsible for constructing the routing table based on routing algorithms.
- **Forwarding Operations:**

  - Forwarding of packets is performed at the interface card in the router.
  - The router must perform route matching quickly to ensure fast packet forwarding.

- **Specialized Hardware - Ternary Content-Addressable Memory (TCAM):**
  - TCAM is used for fast route matching and lookup operations.
  - It allows the router to identify the correct output interface efficiently.

- **Separation of Planes: Control and Data:**
  - **Control Plane:** Handles the construction and maintenance of the routing table using routing algorithms. It is computationally intensive but less frequent.
  - **Data Plane:** Responsible for forwarding packets in real time based on the routing table. This requires high speed to maintain network performance.

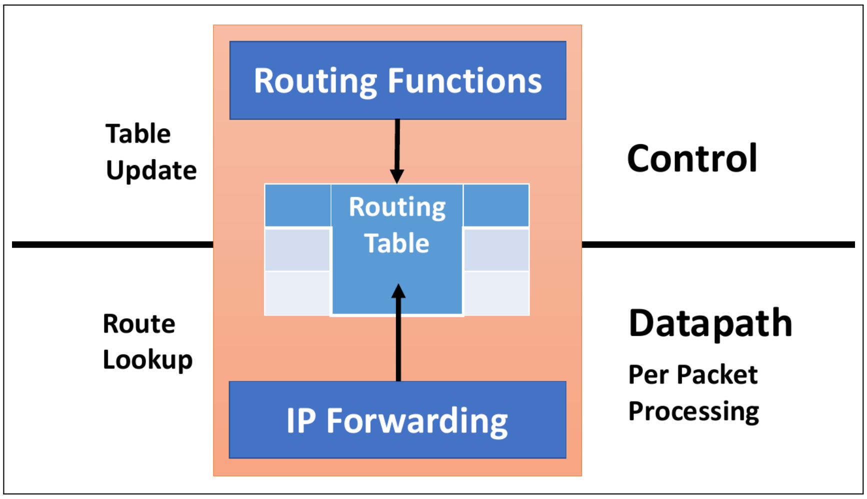

Figure 3: Functional Components of a Router

2.2.2 Control Plane and its functionalities in a Router

A router operates as a specialized computer, designed specifically for routing data across networks. The control plane, which governs the router's management and decision-making processes, is implemented through software known as the router's operating system (Router OS). This software supports the fundamental computing functions required to run the router, as well as the specific routing functionalities that determine how data is forwarded through the network.

- **Router Operating System (Router OS):** The router's operating system plays a crucial role in enabling routing capabilities. It not only handles the basic computing operations but also includes implementations of various routing protocols. These protocols are responsible for determining the best paths for data to travel across the network. A well-known example of a router OS is **Cisco IOS**.

- **Routing Functions:** The control plane is responsible for several key routing functions that ensure efficient data transfer across networks:
  - **Route Calculation:** The router calculates the most efficient paths for data packets to reach their destinations based on routing algorithms and protocols.
  - **Maintenance of the Routing Table:** The router continuously updates and maintains its routing table, ensuring that it has the most up-to-date information about network paths and destinations.

  - **Execution of the Routing Protocol:** The router executes various routing protocols (e.g., OSPF, BGP, RIP) to dynamically adapt to changes in the network, such as new routes or failures.

- **Route Processor:** In commercial routers, these routing functions are typically handled by a **single general-purpose processor**, often referred to as the **route processor**. This processor ensures that the router can calculate routes, update the routing table, and run the necessary protocols in real-time to ensure reliable packet forwarding.

2.2.3 Data Plane of a Router

The **data plane** of a router is responsible for forwarding packets based on the information in the routing table. Unlike the control plane, which handles the management of the routing table, the data plane ensures that packets are transmitted from one interface to another in real-time, enabling smooth network communication.

- **Forwarding Functionality:** The data plane implements the core functionality of packet forwarding. For each incoming packet, the router performs a **route lookup** to identify the appropriate next hop and then forwards the packet to the destination interface. This process ensures that the packet reaches the correct destination based on the routing decisions made earlier by the control plane.

- **Similarity to Layer 2 Switch:** The forwarding mechanism in the data plane is similar to that of a **Layer 2 switch**. Routers use a technique known as **switch fabric** to map input ports to output ports. This allows packets to be quickly forwarded from one interface to another, just like a switch that forwards Ethernet frames based on MAC addresses.

- **Interface Buffers:** To ensure efficient packet handling, the data plane also maintains **interface buffers**. These buffers temporarily store incoming packets before they are forwarded, implementing the **store and forward** functionality. This ensures that packets are processed in an orderly fashion and that network congestion is minimized.

IP Forwarding:
IP forwarding is a crucial task within the data plane, specifically designed to handle the transmission of IP packets.

- **Per-Packet Processing:** Each IP packet is processed individually, and the router performs a route lookup for each packet to determine the best path for forwarding. This ensures that every packet is routed based on the most up-to-date information available.

- **Distributed Processing:** IP forwarding is a distributed process, with individual **interface controllers** handling the forwarding tasks for each interface. This allows the router to manage multiple interfaces efficiently and forward packets concurrently, optimizing the use of resources.

- **Special Hardware for Speed:** To speed up the forwarding process, routers use specialized hardware, such as **Ternary Content-Addressable Memory (TCAM)**. TCAM enables extremely fast lookups, allowing the router to match routing rules in a matter of nanoseconds and ensuring that packets are forwarded with minimal delay.

This combination of efficient packet forwarding, switch fabric, and specialized hardware enables the data plane to deliver high-performance routing, ensuring that packets reach their destination quickly and reliably.

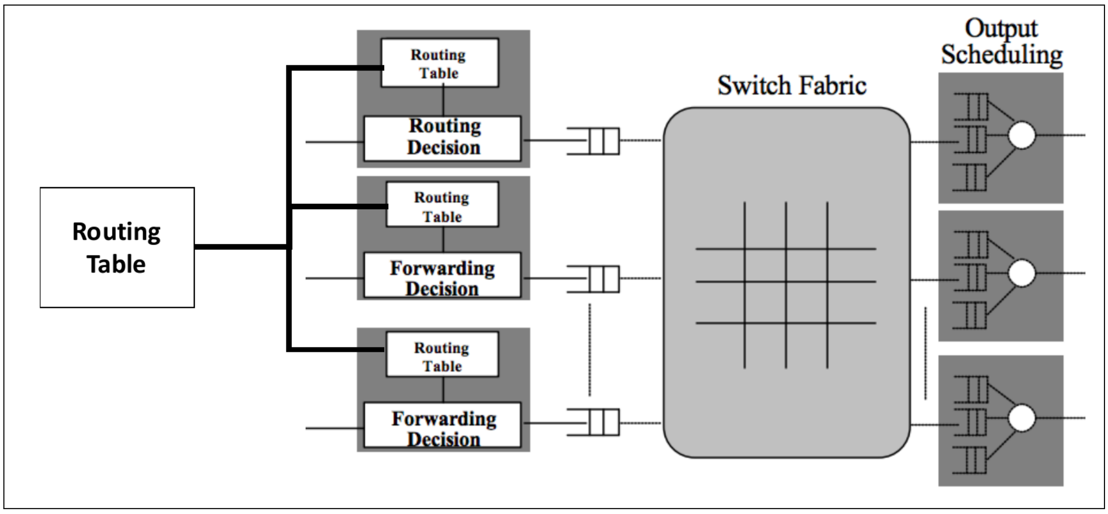

Figure 4: Per packet processing in Router

Understanding the Forwarding Information Base (FIB) and Routing Information Base (RIB)

In modern network routing, the **Forwarding Information Base (FIB)** and **Routing Information Base (RIB)** play distinct but complementary roles in ensuring efficient packet delivery. Together, they enable routers and network devices to manage and forward packets to their correct destinations. Let us explore their functionalities and interactions.

2.2.4 Routing Information Base (RIB)

The **Routing Information Base (RIB)** is a data structure that stores all routing information within a router. It is built and updated by routing protocols such as OSPF, BGP, or RIP. Key features of the RIB include:

- **Comprehensive Routing Information**: The RIB contains all possible routes to network destinations, along with associated metadata like next-hop IP addresses, subnet masks, and administrative metrics.
- **Decision-Making**: It serves as the decision point for selecting the *best path* to each destination based on protocol-defined metrics (e.g., shortest path, lowest cost, or best performance).
- **Static and Dynamic Updates**: The RIB is populated via both static routes (manually configured) and dynamic routes (learned from routing protocols).
- **Data Format**: A typical RIB entry includes:
  - *Destination IP/Subnet*: The network the route points to.
  - *Next-Hop Address*: The IP address of the next router in the path.
  - *Interface*: The network interface through which packets should be forwarded.
  - *Subnet Mask*: Defines the network size for IP matching.

Example RIB Entries:

Destination	Subnet Mask	Next-Hop Address	Interface
172.16.1.0	255.255.255.0	172.16.1.2	Eth0
10.3.0.0	255.255.0.0	10.3.1.1	Eth3
10.9.0.0	255.255.0.0	10.9.1.1	Eth4

2.2.5 Forwarding Information Base (FIB)

The **Forwarding Information Base (FIB)** is a streamlined version of the RIB used for fast packet forwarding. It is optimized for speed and resides in the hardware (e.g., ASICs or TCAM) of routers and switches.

- **Derived from the RIB**: The FIB is essentially a subset of the RIB. It contains only the most optimal routes selected by the router, discarding alternative or less efficient paths.
- **Direct Lookup for Packet Forwarding**: When a packet arrives at a router interface:
  - If a match is found (**FIB HIT**), the packet is forwarded to the corresponding output interface.
  - If no match is found (**FIB MISS**), the router performs a route lookup in the RIB or drops the packet.
- **Interface-Specific Data**: Each network interface may maintain its own FIB, depending on the device's architecture, to further optimize lookup speeds.

Example FIB Entries at Interface Eth1:

Destination	Subnet Mask	Next-Hop Address	Interface
172.16.1.0	255.255.255.0	172.16.1.2	Eth0
10.3.0.0	255.255.0.0	10.3.1.1	Eth3

2.2.6 How FIB and RIB Work Together

1. **Routing Protocols Update the RIB**: Routing protocols such as OSPF or BGP collect information about network topology and populate the RIB. The RIB continuously evolves, reflecting changes in the network (e.g., new links, link failures, or updated metrics).
2. **FIB Generation from RIB**: The router selects the *best route* for each destination in the RIB and copies it to the FIB. This ensures the FIB remains lightweight and optimized for rapid lookups.
3. **Packet Forwarding**:
   - **Step 1**: The router performs a FIB lookup based on the destination IP.
   - **Step 2**: If the FIB contains a match, the packet is forwarded via the associated output interface.
   - **Step 3**: If no match is found, the router queries the RIB for a possible route or drops the packet.
4. **Dynamic Updates**: Any changes in the network (e.g., link failures) are reflected in the RIB first. The FIB is then updated to incorporate the new best paths.

Key Differences

Aspect	RIB	FIB
Purpose	Stores all routing information.	Stores only the best routes for fast forwarding.
Update Frequency	Updated dynamically by routing protocols.	Updated less frequently, derived from RIB.
Storage	Software-based (in RAM).	Hardware-based (in ASIC/TCAM).
Functionality	Decision-making for route selection.	Lookup for packet forwarding.

2.3 Architecture and Working of TCAM for Packet Forwarding

Ternary Content Addressable Memory (TCAM) is a specialized type of high-speed memory used in networking devices for tasks such as packet forwarding, access control, and routing. Unlike traditional memory, TCAM is optimized for searching and matching data patterns at extremely high speeds, making it ideal for real-time decision-making in network routing and switching.

2.3.1 Architecture of TCAM

1. **Memory Structure**:
   - TCAM cells are organized in rows and columns.
   - Each row contains fields for:
     - *Data (Key)*: The value to match (e.g., an IP address).
     - *Mask*: Specifies relevant bits for comparison (`0`, `1`, or `X`).
     - *Action or Output*: Specifies the associated forwarding decision.
2. **Ternary Logic**:
   - Supports three states (`0`, `1`, and `X`) for flexible pattern matching.
3. **Parallel Matching**:
   - All entries are searched simultaneously, enabling constant-time lookups.
4. **Priority Encoder**:
   - Resolves multiple matches by selecting the highest-priority entry.

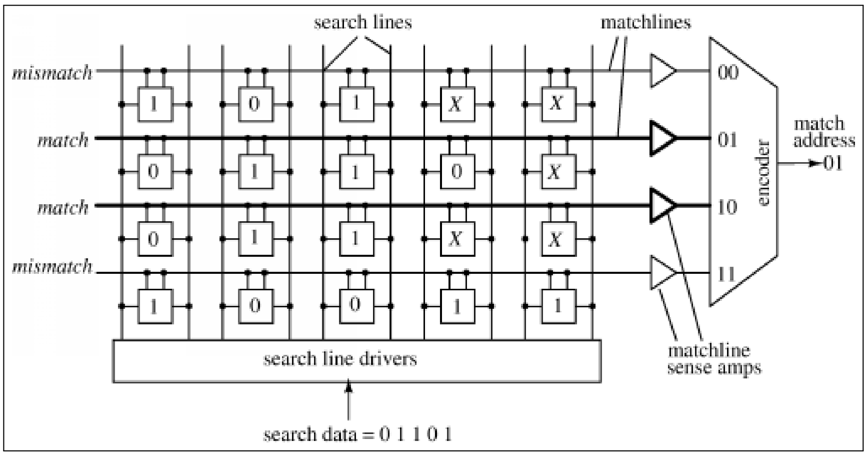

Figure 5: TCAM architecture

2.3.2 Working of TCAM for Packet Forwarding

1. **Input (Key) Search**:
   - The router extracts the packet's destination IP address to form a *search key*.
   - The key is matched against TCAM entries.
2. **Matching Process**:
   - The key is compared with stored rows, considering the mask.

- Matches are determined based on specific bits or wildcards.

3. **Action Selection**:
    - If a match is found, the corresponding action is retrieved.
    - If no match is found, the router may fall back on a route lookup or drop the packet.
4. **Output and Forwarding**:
    - The packet is forwarded based on the retrieved action.

2.3.3 Advantages of TCAM

- **High Speed**: Enables constant-time lookups, crucial for high-throughput traffic.
- **Complex Matching**: Supports longest prefix matching (LPM) and multi-field searches.
- **Flexibility**: Ternary logic allows partial and wildcard matching.

2.3.4 Limitations of TCAM

- **Power Consumption**: High power usage due to parallel search operations.
- **Cost**: Expensive to produce, limiting its size in many devices.
- **Scalability**: Physical and cost constraints limit its capacity for large routing tables.