Wireless TCP and Its Variants

1. Introduction to TCP in Wireless Networks

- **TCP (Transmission Control Protocol)** is a connection-oriented protocol that ensures reliable data delivery over networks.
- In **wireless networks**, TCP faces challenges due to factors like packet loss, mobility, and varying bandwidth.
- Traditional TCP assumes packet loss is due to congestion, but in wireless networks, packet loss can also occur due to **channel errors**, **handoffs**, or **interference**.

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2. Challenges of TCP in Wireless Networks

- **High Bit Error Rate (BER):** Wireless channels are prone to errors, leading to packet loss.
- **Mobility:** Handoffs between base stations or access points can cause packet loss or delays.
- **Bandwidth Fluctuations:** Wireless networks often experience varying bandwidth due to interference or shared medium.
- **Congestion Misinterpretation:** TCP misinterprets wireless packet loss as congestion, leading to unnecessary congestion control measures.

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3. Wireless TCP Variants

To address the challenges, several TCP variants have been proposed for wireless networks:

- **TCP Reno:** The standard TCP variant that uses congestion avoidance and fast retransmit mechanisms. It performs poorly in wireless environments.
- **TCP Vegas:** Focuses on congestion avoidance by estimating round-trip time (RTT) and adjusting the window size accordingly. It is more proactive but still struggles with wireless-specific issues.
- **TCP NewReno:** An improvement over TCP Reno, it handles multiple packet losses better but still assumes packet loss is due to congestion.
- **TCP SACK (Selective Acknowledgment):** Allows the receiver to acknowledge non-contiguous data blocks, improving performance in lossy environments.
- **TCP Westwood:** Estimates available bandwidth and adjusts the congestion window accordingly. It is more suitable for wireless networks.
- **TCP CUBIC:** A high-speed TCP variant designed for modern networks, including wireless. It uses a cubic function to manage the congestion window.

- **Explicit Congestion Notification (ECN):** Allows routers to notify endpoints of congestion before packet loss occurs.
- **Wireless TCP Variants:**
  - **TCP FACK (Forward Acknowledgment):** Focuses on recovering from multiple packet losses.
  - **TCP Hybla:** Designed for high-latency networks, such as satellite links.
  - **TCP Veno:** Combines TCP Vegas and TCP Reno to distinguish between congestion and wireless losses.
  - **TCP Jersey:** Uses delay-based congestion detection to improve performance in wireless networks.

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4. Key Concepts in Wireless TCP

- **Split-Connection Approaches:**
  - The connection is split into two segments: wired and wireless.
  - Example: **Indirect TCP (I-TCP)** splits the connection at the base station, isolating wireless losses from the wired network.
- **End-to-End Approaches:**
  - Modifications are made to the TCP protocol to handle wireless losses without splitting the connection.
  - Example: **Snoop Protocol** caches packets at the base station and retransmits them locally in case of loss.
- **Cross-Layer Optimization:**
  - Involves collaboration between TCP and lower layers (e.g., MAC layer) to improve performance.
  - Example: **Explicit Loss Notification (ELN)** informs TCP about wireless losses to avoid unnecessary congestion control.

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5. Performance Metrics for Wireless TCP

- **Throughput:** The amount of data successfully transmitted per unit time.
- **Fairness:** Ensuring all users get a fair share of the network resources.
- **Latency:** The time taken for a packet to travel from sender to receiver.
- **Packet Loss Rate:** The percentage of packets lost during transmission.
- **Energy Efficiency:** Important for battery-powered devices in wireless networks.

Hop-by-Hop Congestion Control

1. Introduction to Hop-by-Hop Congestion Control

- **Congestion Control** is a mechanism used in networks to prevent congestion and ensure efficient data flow.
- **Hop-by-Hop Congestion Control** is a decentralized approach where each node (router or switch) in the network is responsible for managing congestion locally.
- Unlike **end-to-end congestion control** (e.g., TCP), which relies on feedback from the receiver, hop-by-hop control addresses congestion at every intermediate node.

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2. Why Hop-by-Hop Congestion Control?

- **End-to-End Limitations:** In large or high-speed networks, end-to-end congestion control (like TCP) may not react quickly enough to prevent congestion.
- **Scalability:** Hop-by-hop control is more scalable for large networks with multiple hops.
- **Localized Response:** Congestion can be detected and mitigated at the source (the congested node), reducing the impact on the entire network.

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3. Key Concepts in Hop-by-Hop Congestion Control

- **Local Decision Making:** Each node monitors its own buffer occupancy and link utilization to detect congestion.
- **Feedback Mechanisms:** Nodes communicate congestion information to their neighbors using explicit signals or implicit indicators (e.g., packet drops).
- **Rate Adjustment:** Nodes adjust their transmission rates based on local congestion information.

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4. Techniques for Hop-by-Hop Congestion Control

- **Explicit Congestion Notification (ECN):**
  - Routers mark packets to indicate congestion, and the receiver sends this information back to the sender.
  - Example: ECN in IP networks.
- **Backpressure Mechanism:**
  - A congested node signals upstream nodes to reduce their transmission rates.

    - Example: Used in data center networks and ATM networks.
- **Queue Management Algorithms:**
    - Algorithms like **RED (Random Early Detection)** or **CoDel (Controlled Delay)** proactively manage queue lengths to prevent congestion.
- **Credit-Based Flow Control:**
    - Nodes exchange credits to control the amount of data transmitted, ensuring no node is overwhelmed.
    - Example: Used in InfiniBand and some high-performance computing networks.

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5. Advantages of Hop-by-Hop Congestion Control

- **Faster Reaction:** Congestion is addressed locally, reducing the time taken to mitigate it.
- **Improved Fairness:** Resources are allocated more fairly among flows.
- **Scalability:** Suitable for large networks with many hops.
- **Reduced Packet Loss:** Proactive congestion management minimizes packet drops.

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6. Disadvantages of Hop-by-Hop Congestion Control

- **Complexity:** Requires coordination between nodes, increasing implementation complexity.
- **Overhead:** Additional signaling and processing are needed at each node.
- **Potential for Oscillations:** Poorly designed algorithms can cause oscillations in transmission rates.

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7. Examples of Hop-by-Hop Congestion Control

- **Data Center Networks:**
    - Techniques like **DCQCN (Data Center Quantized Congestion Notification)** use hop-by-hop control to manage congestion in large data centers.
- **Wireless Sensor Networks:**
    - Nodes adjust their transmission rates based on local congestion to conserve energy and prevent packet loss.
- **ATM Networks:**
    - ATM uses hop-by-hop flow control mechanisms like **ABR (Available Bit Rate)** to manage congestion.

Rate-Based Congestion Control

1. Introduction to Rate-Based Congestion Control

- **Congestion Control** is a mechanism used to prevent network congestion and ensure efficient data flow.
- **Rate-Based Congestion Control** focuses on regulating the **transmission rate** of data sources to match the available network capacity.
- Unlike **window-based congestion control** (e.g., TCP), which adjusts the number of packets in flight, rate-based control directly adjusts the sending rate.

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2. Why Rate-Based Congestion Control?

- **High-Speed Networks:** Rate-based control is more suitable for high-speed networks where window-based mechanisms may not react quickly enough.
- **Real-Time Applications:** It is ideal for real-time applications (e.g., video streaming, VoIP) that require consistent data rates.
- **Fairness:** Rate-based control can ensure fair bandwidth allocation among multiple flows.

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3. Key Concepts in Rate-Based Congestion Control

- **Transmission Rate:** The rate at which a sender transmits data, typically measured in bits per second (bps).
- **Feedback Mechanism:** Receivers or intermediate nodes provide feedback about network conditions (e.g., congestion, available bandwidth).
- **Rate Adjustment:** The sender adjusts its transmission rate based on feedback to avoid congestion.

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4. Techniques for Rate-Based Congestion Control

- **Explicit Rate Feedback:**
    - Intermediate nodes (e.g., routers) explicitly inform the sender about the allowed transmission rate.
    - Example: **ERM (Explicit Rate Marking)** in ATM networks.
- **Additive Increase Multiplicative Decrease (AIMD):**
    - The sender gradually increases its rate (additive increase) and reduces it sharply (multiplicative decrease) in response to congestion.
    - Example: Used in some variants of TCP.

- **Equation-Based Rate Control:**
  - The sender calculates the transmission rate using a mathematical model based on network conditions.
  - Example: **TFRC (TCP-Friendly Rate Control)**.
- **Credit-Based Flow Control:**
  - The sender transmits data based on credits received from the receiver or intermediate nodes.
  - Example: Used in InfiniBand and some high-performance networks.

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5. Advantages of Rate-Based Congestion Control

- **Smooth Rate Adjustment:** Provides more stable and predictable data rates, suitable for real-time applications.
- **Scalability:** Works well in high-speed and large-scale networks.
- **Fairness:** Ensures fair bandwidth allocation among competing flows.

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6. Disadvantages of Rate-Based Congestion Control

- **Complexity:** Requires accurate feedback and rate calculation mechanisms.
- **Overhead:** Additional signaling and processing are needed to provide feedback and adjust rates.
- **Latency:** Feedback delays can affect the responsiveness of rate adjustments.

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7. Examples of Rate-Based Congestion Control

- **TFRC (TCP-Friendly Rate Control):**
  - A rate-based protocol designed for real-time applications. It adjusts the transmission rate based on a mathematical model to compete fairly with TCP flows.
- **ATM ABR (Available Bit Rate):**
  - Uses explicit rate feedback to dynamically adjust the transmission rate based on network conditions.
- **DCTCP (Data Center TCP):**
  - A variant of TCP used in data centers that combines rate-based and window-based control for efficient congestion management.
- **QUIC (Quick UDP Internet Connections):**
  - A modern transport protocol that uses rate-based control for efficient congestion management in real-time applications.

Quality of Service (QoS) in Wireless Networks

1. Introduction to QoS in Wireless Networks

- **Quality of Service (QoS)** refers to the ability of a network to provide differentiated services to various types of traffic, ensuring that critical applications receive the necessary resources (e.g., bandwidth, latency, jitter, and packet loss).
- In **wireless networks**, providing QoS is challenging due to factors like limited bandwidth, interference, mobility, and varying channel conditions.

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2. Why is QoS Important in Wireless Networks?

- **Diverse Traffic Types:** Wireless networks carry a mix of traffic, including voice, video, and data, each with different requirements.
- **Resource Constraints:** Wireless networks have limited bandwidth and are prone to interference, making efficient resource allocation critical.
- **User Expectations:** Users expect reliable and high-quality service, especially for real-time applications like VoIP and video streaming.

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3. Key QoS Parameters

- **Bandwidth:** The amount of data that can be transmitted per unit time.
- **Latency:** The time taken for a packet to travel from source to destination.
- **Jitter:** The variation in latency between packets.
- **Packet Loss:** The percentage of packets lost during transmission.
- **Reliability:** The ability of the network to deliver packets without errors.

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4. QoS Mechanisms in Wireless Networks

- **Traffic Prioritization:**
    - Assigns priority levels to different types of traffic (e.g., voice over data).
    - Example: **IEEE 802.11e** for Wi-Fi networks.
- **Admission Control:**
    - Determines whether a new flow can be admitted into the network without degrading the QoS of existing flows.
- **Resource Reservation:**
    - Reserves network resources (e.g., bandwidth) for specific flows.
    - Example: **RSVP (Resource Reservation Protocol)**.
- **Scheduling Algorithms:**

    - Determines the order in which packets are transmitted.
    - Examples: **Weighted Fair Queuing (WFQ)**, **Priority Queuing**.
- **Congestion Management:**
    - Prevents network congestion by regulating traffic flow.
    - Example: **Random Early Detection (RED)**.
- **Error Control:**
    - Uses techniques like **Forward Error Correction (FEC)** and **Automatic Repeat Request (ARQ)** to reduce packet loss.

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5. QoS in Specific Wireless Technologies

- **Wi-Fi (IEEE 802.11):**
    - **IEEE 802.11e** introduces QoS support through **Enhanced Distributed Channel Access (EDCA)**, which prioritizes traffic into different access categories (e.g., voice, video, best effort, background).
- **Cellular Networks (4G/5G):**
    - **4G LTE** uses **QoS Class Identifiers (QCIs)** to differentiate traffic types.
    - **5G** introduces more granular QoS control with **5G QoS Identifiers (5QIs)** and supports network slicing for customized QoS.
- **Bluetooth:**
    - Provides QoS through **Synchronous Connection-Oriented (SCO)** links for voice traffic and **Advanced Audio Distribution Profile (A2DP)** for high-quality audio streaming.

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6. Challenges in Providing QoS in Wireless Networks

- **Mobility:** Users moving between cells or access points can experience service disruptions.
- **Interference:** Wireless networks are prone to interference from other devices and networks.
- **Limited Bandwidth:** Wireless networks have less bandwidth compared to wired networks, making resource allocation critical.
- **Dynamic Channel Conditions:** Wireless channels can vary rapidly due to factors like fading and multipath propagation.

(Emerging Technologies)

Bluetooth, RFID, WiMAX, Mobile IP, VoIP, and SIP

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1. Bluetooth

- **Overview:**
  - Bluetooth is a wireless technology standard for short-range communication (typically up to 10 meters).
  - Operates in the **2.4 GHz ISM band** and uses **frequency hopping** to avoid interference.
- **Key Features:**
  - Low power consumption.
  - Supports data and voice communication.
  - Used in devices like headphones, speakers, keyboards, and IoT devices.
- **Protocol Stack:**
  - **RF (Radio Frequency):** Handles wireless transmission.
  - **Baseband:** Manages physical links and packet handling.
  - **L2CAP (Logical Link Control and Adaptation Protocol):** Provides multiplexing and segmentation.
  - **Profiles:** Define specific use cases (e.g., A2DP for audio streaming, HFP for hands-free calls).
- **Applications:**
  - Wireless audio streaming.
  - File transfer between devices.
  - IoT device connectivity.

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2. RFID (Radio Frequency Identification)

- **Overview:**
  - RFID uses radio waves to identify and track objects.
  - Consists of **tags** (attached to objects) and **readers** (to read tag data).
- **Key Features:**
  - **Passive Tags:** Powered by the reader's signal.
  - **Active Tags:** Have their own power source.
  - Operates in **LF (Low Frequency)**, **HF (High Frequency)**, and **UHF (Ultra-High Frequency)** bands.
- **Applications:**

    - Inventory management.
    - Access control (e.g., keycards).
    - Supply chain tracking.

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3. WiMAX (Worldwide Interoperability for Microwave Access)

- **Overview:**
    - WiMAX is a wireless broadband technology based on the **IEEE 802.16** standard.
    - Provides high-speed internet access over long distances (up to 50 km).
- **Key Features:**
    - Supports both **fixed** and **mobile** broadband access.
    - Uses **OFDM (Orthogonal Frequency Division Multiplexing)** for efficient spectrum usage.
    - Offers high data rates (up to 1 Gbps).
- **Applications:**
    - Last-mile internet access in rural areas.
    - Backhaul for cellular networks.
    - Mobile broadband for users on the go.

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4. Mobile IP

- **Overview:**
    - Mobile IP is a protocol that allows devices to maintain the same IP address while moving across different networks.
- **Key Components:**
    - **Mobile Node (MN):** The device that moves between networks.
    - **Home Agent (HA):** A router in the home network that forwards packets to the MN.
    - **Foreign Agent (FA):** A router in the visited network that assists the MN.
- **How It Works:**
    - When the MN moves to a foreign network, it registers its new location with the HA.
    - The HA tunnels packets to the MN's current location.
- **Applications:**
    - Seamless internet access for mobile devices.
    - Support for roaming in wireless networks.

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5. **VoIP (Voice over Internet Protocol)**

- **Overview:**
  - VoIP enables voice communication over IP networks.
  - Converts analog voice signals into digital packets for transmission.
- **Key Features:**
  - Uses protocols like **RTP (Real-Time Transport Protocol)** for packet delivery and **SIP (Session Initiation Protocol)** for call setup.
  - Supports features like call forwarding, conferencing, and voicemail.
- **Advantages:**
  - Cost-effective compared to traditional telephony.
  - Integrates with other IP-based services (e.g., video calls).
- **Applications:**
  - Internet-based phone calls (e.g., Skype, Zoom).
  - Business communication systems (e.g., IP PBX).

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6. **SIP (Session Initiation Protocol)**

- **Overview:**
  - SIP is a signaling protocol used to establish, modify, and terminate multimedia sessions (e.g., voice and video calls).
- **Key Features:**
  - Text-based protocol (similar to HTTP).
  - Works with other protocols like **RTP** and **SDP** **(Session Description Protocol)**.
  - Supports features like call transfer, conferencing, and presence.
- **How It Works:**
  - A SIP client sends an **INVITE** message to initiate a session.
  - The recipient responds with a **200 OK** message to accept the session.
- **Applications:**
  - VoIP systems.
  - Video conferencing.
  - Instant messaging.