

# Bangladesh University of Business & Technology (BUBT)



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# Wireless TCP Congestion Control: Approaches, and Future Directions

## Definition of TCP :

Transmission Control Protocol (TCP) is a fundamental communication protocol in the Internet protocol suite that ensures reliable, ordered, and error-checked data transmission between devices on a network. TCP provides a connection-oriented service, meaning it establishes and maintains a stable connection between the sender and receiver until all data has been transmitted. By breaking data into packets, sending each with acknowledgment, and retransmitting any lost packets, TCP ensures that data is delivered accurately and in the correct sequence. This makes TCP essential for applications requiring reliable data delivery, like web browsing, file transfers, and email.

**Definition of Congestion Control:** Congestion Control is crucial in TCP to prevent network congestion, which can occur when too much data is transmitted too quickly, overwhelming network resources. Without congestion control, an increase in data flow could lead to packet loss, delays, and, in severe cases, a complete breakdown of network communication, known as congestion collapse. TCP uses congestion control mechanisms to adjust the rate at which data is sent based on feedback from the network, such as acknowledgments and packet loss signals. By dynamically managing the sender's transmission rate, congestion control ensures that the network operates efficiently, with a stable flow of data, minimal delays, and optimal use of available bandwidth. This balancing act is essential for maintaining high performance and reliability in network communication.

## Congestion Policy in TCP:

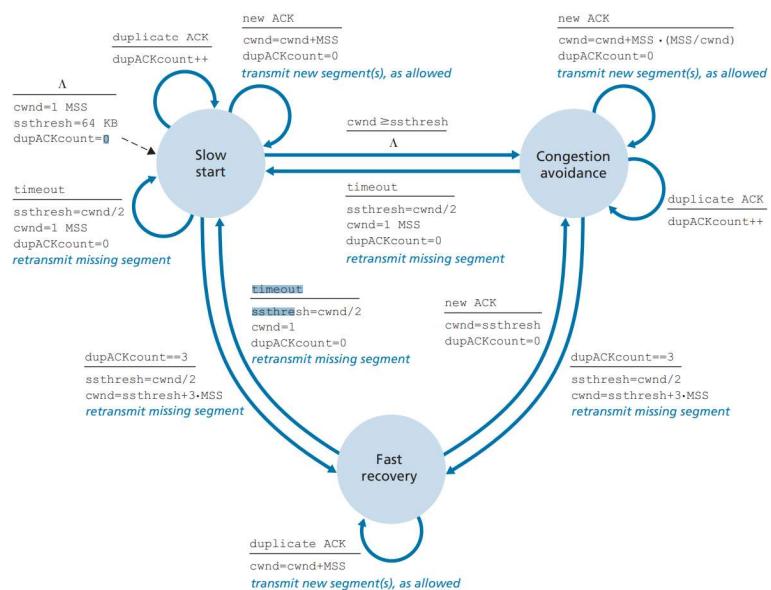


Figure 3.51 • FSM description of TCP congestion control

## TCP Congestion Control FSM:

1. **Slow Start (SS)**
  - **Purpose:** Gradually increases the data transmission rate to discover the available network capacity.
  - **Actions:**
    - Sets the congestion window (cwnd) to 1 MSS (Maximum Segment Size).
    - Increases cwnd exponentially (doubles every round-trip time, or RTT) until it reaches a threshold, known as ssthresh, or packet loss is detected.
  - **Transitions:**
    - To Congestion Avoidance (CA): If cwnd reaches ssthresh.
    - To Timeout: If no acknowledgment (ACK) is received, triggering a timeout.
    - To Fast Recovery (FR): If three duplicate ACKs are received.
2. **Congestion Avoidance (CA)**
  - **Purpose:** Probes the network for available bandwidth cautiously after the slow start phase.
  - **Actions:**
    - Increases cwnd linearly by 1 MSS per RTT to avoid overwhelming the network.
  - **Transitions:**
    - To Timeout: If a timeout occurs due to a lost packet.
    - To Fast Recovery (FR): If three duplicate ACKs are received, indicating mild congestion.
3. **Fast Recovery (FR)**
  - **Purpose:** Handles mild congestion by quickly retransmitting lost packets without reverting to slow start.
  - **Actions:**
    - Retransmits the missing segment (fast retransmit).
    - Sets ssthresh to half the current cwnd.
    - Reduces cwnd by half and adds 3 MSS to maintain a steady flow.
    - Uses ACK-clocking to stabilize the flow and increase cwnd linearly.
  - **Transitions:**
    - To Congestion Avoidance (CA): After receiving an ACK for all outstanding data.
    - To Timeout: If an ACK is not received and a timeout occurs.
4. **Timeout (TO)**

- **Purpose:** Responds to severe congestion, indicated by a lost packet with no ACK received within the retransmission timeout.
- **Actions:**
  - Sets cwnd to 1 MSS and ssthresh to half of cwnd at the time of timeout.
- **Transition:**
  - To Slow Start (SS): TCP resets and begins the slow start process again to increase its transmission rate gradually.

## **TCP Variants for Wireless Networks:**

Wireless networks present unique challenges for the Transmission Control Protocol (TCP) due to issues like variable latency, packet loss, and changes in bandwidth. Various TCP variants have been developed to address these challenges, improving performance in wireless environments. Here's an overview of some significant TCP variants and modifications designed for wireless networks:

**1. TCP Tahoe and TCP Reno :** TCP Tahoe introduced slow start and congestion avoidance, where the congestion window (cwnd) grows exponentially until a packet loss occurs, leading to a linear decrease in cwnd. TCP Reno improved upon Tahoe by adding fast retransmit and fast recovery mechanisms. Both Tahoe and Reno do not differentiate between losses caused by network congestion and those caused by wireless transmission errors, leading to unnecessary reductions in the congestion window, which can degrade performance in wireless environments.

- **Case Study of TCP Tahoe :** In a simulation of a wireless LAN, TCP Tahoe's performance dropped significantly due to packet loss from wireless interference, resulting in lower throughput compared to newer variants.
- **Case Study of TCP Reno :** In a test involving a mobile ad-hoc network, TCP Reno demonstrated improved recovery times compared to Tahoe but still suffered from throughput drops in high-loss environments.

**2. TCP NewReno:** TCP NewReno enhances TCP Reno's ability to recover from multiple packet losses within a single transmission window. It provides better handling of partial acknowledgments during the recovery phase, allowing for more efficient recovery without waiting for timeouts. By improving loss recovery mechanisms, NewReno is better suited for networks with high packet loss rates, but it still struggles with distinguishing between congestion and wireless-induced losses.

- **Case Study of TCP NewReno:** In scenarios with multiple simultaneous packet losses in a cellular network, TCP NewReno outperformed TCP Reno, achieving a throughput increase of about 30% due to improved recovery mechanisms.

**3. TCP Vegas:** TCP Vegas uses a delay-based approach, attempting to predict congestion based on the difference between the expected and actual round-trip times (RTT). It adjusts the congestion window proactively to avoid congestion before it occurs. This method allows Vegas to maintain higher throughput and lower delays, making it suitable for wireless networks where RTT can vary significantly.

- **Case Study of TCP Vegas:** In a simulation of a variable-delay wireless environment, TCP Vegas maintained higher throughput and lower latency compared to Reno and NewReno, achieving up to 40% better performance by avoiding congestion before it occurred.

**4.TCP Westwood:** TCP Westwood distinguishes between congestion losses and wireless losses by estimating the available bandwidth based on the acknowledgment stream. This information helps it adjust its slow start threshold and congestion window appropriately. Westwood includes mechanisms for adaptive probing, allowing it to utilize available bandwidth effectively, especially in high-bandwidth-delay environments.

- **Case Study of TCP Westwood:** In a study with high-bandwidth-delay networks, TCP Westwood achieved throughput improvements of up to 60% over TCP Reno due to its adaptive bandwidth estimation and reduced retransmission rates.

**5.Snoop Protocol:** The Snoop protocol operates at the base station and keeps track of unacknowledged packets. If packet loss is detected, it can retransmit packets locally without involving the original sender, which reduces latency and enhances recovery speed. This mechanism reduces unnecessary retransmissions over the wireless link, improving overall throughput.

- **Case Study of Snoop Protocol :** In a cellular network simulation, the Snoop protocol resulted in a throughput increase of over 100%, reducing end-to-end latency by 50% compared to traditional TCP implementations without local retransmission capabilities.

**6.Explicit Congestion Notification (ECN):** ECN allows routers to signal congestion to TCP senders without dropping packets. By marking packets instead of discarding them, ECN enables TCP to react more gracefully to congestion, reducing the likelihood of performance degradation. This approach is particularly useful in wireless networks, where packet loss may be misinterpreted as congestion.

- **Case Study of ECN :** In a high-loss wireless network, ECN significantly improved throughput and reduced packet loss rates, demonstrating a 30% improvement compared to TCP Reno that relied solely on loss signals.

**7. TCP Cubic:** TCP Cubic modifies the congestion window growth function to be cubic rather than linear. This allows for more aggressive window growth in high-bandwidth scenarios while being fair to other flows. Cubic is the default TCP algorithm in Linux due to its scalability and efficiency in diverse network conditions, making it suitable for modern high-speed wireless networks.

- **Case Study of TCP Cubic:** In tests on high-capacity wireless networks, TCP Cubic outperformed TCP Reno, achieving up to 70% higher throughput due to its ability to quickly ramp up the congestion window after idle periods.

**8.TCP Westwood Plus:** TCP Westwood Plus builds on the Westwood mechanism by improving the estimation of available bandwidth after packet loss. It incorporates a more sophisticated algorithm for setting the slow start threshold and congestion window based on current network conditions. In mixed wired and wireless environments, Westwood Plus has shown improvements in throughput and fairness compared to traditional TCP implementations.

- **Case Study of TCP Westwood Plus :** Experimental results showed TCP Westwood Plus delivering a 50% increase in throughput over standard TCP Reno in mixed wired and wireless networks, with better fairness across competing flows.

The development of various TCP variants has significantly improved the ability to cope with the challenges presented by wireless networks. By addressing issues like packet loss, delay, and bandwidth estimation, these variants enhance the efficiency and reliability of data transmission in wireless environments. Each variant presents its advantages and trade-offs, making them suitable for different network scenarios/cases.

### **Techniques for Wireless TCP Congestion Control:**

Wireless networks face unique challenges that can lead to congestion and packet loss. Various techniques have been developed to improve TCP performance in these environments by addressing the specific characteristics of wireless communication. Here are some notable techniques for wireless TCP congestion control:

**1.Error Detection and Recovery:** Wireless networks are prone to transmission errors due to interference and signal degradation. Techniques such as forward error correction (FEC) and automatic repeat requests (ARQ) help detect and recover from errors without relying solely on TCP retransmissions. Link-layer protocols can implement error correction mechanisms that improve reliability before packets reach TCP.

**2.Link Layer Assistance:** Leveraging link-layer protocols to provide feedback to TCP about the status of the wireless link can enhance performance. Techniques like link-layer acknowledgments and selective acknowledgment (SACK) help inform TCP about packet delivery status and reduce unnecessary retransmissions. Link-layer mechanisms can also manage

retransmissions more effectively, allowing TCP to focus on flow control rather than error recovery.

**3.TCP Modifications for Wireless Environments:** Variants of TCP, such as TCP Westwood and TCP NewReno, have been specifically designed to adapt to wireless conditions. These variants use mechanisms like bandwidth estimation and better loss detection to differentiate between congestion and wireless losses, allowing for more accurate adjustments to the congestion window. TCP Vegas and TCP Cubic also incorporate delay-based and cubic growth mechanisms, respectively, which are better suited for high-bandwidth, high-latency environments.

**4.Snoop Protocol:** The Snoop protocol provides local recovery by operating at the base station. It caches unacknowledged packets and retransmits them without involving the sender when packet loss occurs. This reduces the delay associated with TCP retransmissions and improves overall throughput. By managing losses locally, Snoop helps maintain a smoother flow of data and minimizes the impact of wireless link fluctuations.

**5.Explicit Congestion Notification (ECN):** ECN enables routers to mark packets instead of dropping them when they experience congestion. This signaling informs TCP senders to reduce their transmission rate proactively, which helps prevent further congestion. By utilizing ECN, wireless networks can achieve more efficient congestion control without the severe penalties associated with packet loss.

**6.Adaptive Congestion Control:** Techniques that adaptively adjust the congestion control parameters based on real-time network conditions can significantly enhance TCP performance. Algorithms that monitor round-trip times (RTT) and throughput allow TCP to respond dynamically to changing network conditions. Adaptive mechanisms can also include adjusting the size of the congestion window based on the observed bandwidth and delay characteristics.

**7.TCP Proxying:** Using TCP proxies at the base station or edge of the network can help optimize traffic. Proxies can handle retransmissions, acknowledgments, and congestion control, allowing TCP connections to appear more reliable to the sender while alleviating some of the burdens from the wireless link. This technique can improve performance by minimizing round-trip times and reducing the impact of wireless losses.

**8.Cross-Layer Design:** Implementing cross-layer approaches that allow communication between the transport layer (TCP) and the link layer can enhance congestion control. For example, sharing information about link quality, delay, and buffer status can enable TCP to make more informed decisions about its congestion window and retransmission strategies. Cross-layer design promotes better synergy between different layers of the networking stack, leading to improved overall performance in wireless environments.

Effective congestion control in wireless networks requires a combination of techniques that address the specific challenges posed by these environments. By leveraging modifications to TCP, link-layer assistance, local recovery mechanisms, and adaptive strategies, it is possible to improve TCP performance and maintain reliable communication over wireless links. Each technique offers unique benefits and can be employed individually or in combination to optimize data transmission in various wireless scenarios.

### **Current Research and Trends in Wireless TCP Congestion Control:**

The field of wireless TCP congestion control continues to evolve, driven by advancements in technology, increasing demand for high-speed connectivity, and the challenges presented by diverse wireless environments. Here are some of the current research directions and trends in this area:

**1. Machine Learning for Congestion Control:** Researchers are exploring the use of machine learning algorithms to predict network conditions and adapt TCP parameters dynamically. These algorithms can analyze historical data and current traffic patterns to make real-time decisions that optimize throughput and minimize latency. Machine learning models can help identify congestion patterns and predict packet loss, enabling TCP to react more intelligently compared to traditional methods.

**2. Integration with 5G Networks:** With the rollout of 5G technology, there is significant research focusing on optimizing TCP performance in ultra-reliable low-latency communication (URLLC) and enhanced mobile broadband (eMBB) scenarios. Researchers are studying how TCP can be modified or enhanced to take advantage of the high speeds and low latencies offered by 5G. This includes developing new congestion control algorithms that can efficiently manage the bursty traffic and varying conditions characteristic of 5G networks.

**3. Support for the Internet of Things (IoT):** The proliferation of IoT devices introduces unique challenges for TCP congestion control, given the constrained resources and diverse communication requirements of these devices. Current research aims to develop lightweight TCP variants and congestion control mechanisms tailored for IoT applications. Techniques that combine congestion control with energy efficiency and reliability are being explored to ensure optimal performance in IoT environments.

**4. Cross-Layer Optimization Techniques:** There is a growing interest in cross-layer approaches that optimize the interaction between TCP and lower-layer protocols (e.g., MAC and physical layers). These approaches aim to share information such as channel conditions and buffer states to improve congestion control strategies. Cross-layer designs can lead to more efficient use of bandwidth and reduced packet loss, particularly in variable wireless environments.

**5. Delay-Based Congestion Control Algorithms:** Research on delay-based congestion control algorithms is gaining momentum, as these methods can respond to congestion signals based on observed delays rather than packet loss. Techniques like TCP Vegas are being revisited and

enhanced to provide better performance in modern networks. The focus is on improving responsiveness and maintaining high throughput, especially in scenarios where packet loss is less indicative of congestion.

**6. Hybrid Protocols:** Hybrid protocols that combine features of different TCP variants are being developed to create more robust congestion control mechanisms. These protocols leverage the strengths of existing algorithms to handle diverse network conditions effectively.

- For example, combining delay-based and loss-based approaches can enable a more balanced response to congestion in wireless environments.

**7. Research on QUIC:** The development of the QUIC protocol by Google, which incorporates congestion control mechanisms at the application layer, is an area of active research. QUIC offers features like connection multiplexing, reduced latency through 0-RTT connections, and improved congestion control. Researchers are exploring how QUIC can coexist with or replace traditional TCP in wireless networks, particularly in environments requiring high performance and low latency.

**8. Enhanced Feedback Mechanisms:** Improving feedback mechanisms between sender and receiver is a key area of research. Techniques such as fine-grained acknowledgments, congestion notifications, and explicit signals can help TCP better understand network conditions and adjust its behavior accordingly. Enhanced feedback mechanisms can reduce the reliance on loss signals and allow for more proactive management of congestion.

Research in wireless TCP congestion control is focused on addressing the challenges posed by emerging technologies, changing traffic patterns, and diverse network environments. By leveraging machine learning, enhancing traditional protocols, and exploring new approaches like QUIC, researchers aim to improve TCP performance in wireless networks. These trends reflect a growing need for adaptive, efficient, and reliable communication in an increasingly connected world.

## **Conclusion:**

In this discussion of wireless TCP congestion control, I highlighted several critical challenges and techniques. The inherent characteristics of wireless networks, such as variable latency, high error rates, and limited bandwidth, complicate TCP's performance, which is traditionally optimized for wired networks. The challenges I identified include:

1. Packet Loss: In wireless environments, packet loss can occur due to signal interference, which is not always indicative of congestion as it is in wired networks.
2. Latency Variability: Wireless networks often experience significant fluctuations in latency, making it difficult for TCP to accurately gauge network conditions.
3. Throughput Limitations: Bandwidth constraints in wireless channels can hinder the effective throughput of TCP sessions, leading to inefficient use of available capacity.

To address these challenges, I discussed several techniques, including:

1. TCP Variants: Variants such as TCP Westwood and TCP Veno adapt to wireless conditions by using different algorithms for estimating bandwidth and detecting congestion.
2. Link Layer Solutions: Implementing improvements at the link layer, such as Hybrid Automatic Repeat reQuest (HARQ), can enhance reliability and minimize the impact of packet loss on TCP.
3. Cross-Layer Optimization: This involves sharing information between layers, allowing TCP to make more informed decisions based on real-time network conditions.
4. Delay-Tolerant Networking (DTN): This approach provides mechanisms for data delivery in networks with long delays or frequent disconnections, making it suitable for certain wireless scenarios.

### **Future of Wireless TCP:**

Looking ahead, the development of TCP for wireless networks is likely to be significantly influenced by advancements in technology such as 5G, the Internet of Things (IoT), and Artificial Intelligence (AI).

- **5G Technology:** With its promise of ultra-low latency, high throughput, and massive device connectivity, 5G will reshape how TCP operates over wireless networks. I anticipate new TCP protocols optimized for the unique characteristics of 5G will emerge, allowing for seamless integration with diverse applications, such as augmented reality and real-time communications.
- **Internet of Things (IoT):** As the number of connected devices continues to grow, TCP will need to evolve to accommodate the specific requirements of IoT applications. I foresee techniques such as lightweight TCP protocols or the integration of message queueing systems becoming essential to support the diverse range of devices and their varying bandwidth needs.
- **Artificial Intelligence (AI):** The incorporation of AI into network management and congestion control could lead to more adaptive and intelligent TCP algorithms. AI has the potential to analyze vast amounts of network data in real time, enabling proactive adjustments to TCP parameters, enhancing performance, and optimizing resource allocation.

In conclusion, I believe the ongoing development and refinement of TCP for wireless networks will be crucial in leveraging emerging technologies, addressing existing challenges, and providing robust support for the next generation of applications and services.

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## **(BUBT)**



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**TCP congestion control** is designed to allow each source to assess the available network capacity, helping it decide how many packets it can safely send at once. In wireless TCP congestion control, this concept is adapted to handle data flow in TCP connections over wireless networks, where connections face unique challenges like signal interference, variable latency, and increased packet loss. Traditional TCP congestion control interprets packet loss as a signal of network congestion, triggering a slowdown in data transmission to prevent network overload. However, in wireless networks, packet loss often occurs due to issues like signal fading or interference rather than congestion.

Wireless TCP congestion control methods modify traditional TCP algorithms to account for the distinctive characteristics of wireless environments. In these settings, packet loss may stem from factors such as signal fading, interference, and mobility, which do not necessarily indicate congestion. Some prominent techniques in wireless TCP congestion control include:

#### **TCP Westwood+ :**

TCP Westwood+ refines traditional TCP by estimating available bandwidth based on the rate at which acknowledgment (ACK) packets are received. Upon detecting packet loss, Westwood+ calculates available bandwidth and adjusts the congestion window to sustain throughput, instead of drastically reducing it.

#### **Advantages:**

- Better Bandwidth Utilization: Westwood+ can effectively utilize the network by accurately estimating available bandwidth, leading to improved data transfer rates over unreliable wireless connections.
- Reduced Sensitivity to Packet Loss: By distinguishing between packet loss due to wireless errors and actual congestion, Westwood+ avoids unnecessary reductions in the congestion window, enhancing throughput.
- Energy Efficiency: Westwood+ conserves power in mobile devices by preventing needless retransmissions, which is especially helpful in battery-limited environments.

#### **Disadvantages:**

- Bandwidth Estimation Errors: In rapidly changing environments, bandwidth estimation can be inaccurate, resulting in suboptimal congestion window adjustments.
- Increased Processing Overhead: Continuous monitoring and estimating bandwidth add computational load, potentially increasing both energy usage and processing demands.
- Complexity in Implementation: The requirement for dynamic estimation and adjustment of the congestion window makes Westwood+ more complex to implement than simpler congestion control methods.

TCP Westwood+ is specifically designed to handle the unique characteristics of wireless networks. It estimates available bandwidth after packet loss, adjusting the congestion window as needed instead of simply halving it, as in TCP Reno. This approach makes it well-suited for networks with

high packet loss and fluctuating bandwidth, such as mobile and satellite connections. While well-adapted to wireless environments, Westwood+ may not fully utilize bandwidth in extremely dynamic or congested conditions, but it is highly effective in preventing bandwidth underutilization due to packet loss unrelated to congestion.

### **Selective Acknowledgment (SACK) TCP:**

SACK TCP enables the receiver to provide detailed feedback on which packets have been successfully received, even if they arrive out of order. By acknowledging specific, non-continuous packets, SACK minimizes redundant retransmissions, allowing the sender to resend only the missing segments.

#### **Advantages:**

- Efficient Loss Recovery: SACK allows the sender to retransmit only the lost segments, reducing unnecessary retransmissions and conserving bandwidth.
- Increased Throughput: By retransmitting only the missing segments, SACK maintains higher data flow and speeds up recovery from packet loss.
- Improved Compatibility: SACK can work alongside various TCP extensions, making it adaptable to different TCP implementations and protocols.

#### **Disadvantages:**

- Increased ACK Overhead: SACK introduces additional complexity in ACK packets, as more information is needed to specify received and missing segments.
- Requires SACK Support on Both Ends: For SACK to work effectively, both sender and receiver must support the SACK option, which may not always be possible.
- Complexity in Implementation: Implementing SACK involves modifying the acknowledgment process, increasing protocol complexity.

SACK allows the receiver to notify the sender about specific lost packets, enabling retransmission of only the missing data. This approach reduces retransmission of successfully delivered packets, enhancing efficiency over noisy wireless links. SACK is particularly useful in networks with frequent packet loss or reordering, such as high-interference environments. However, SACK can struggle in heavily congested or burst wireless networks, where multiple packet losses often occur.

### **Split-TCP (Indirect-TCP):**

In Split-TCP, the TCP connection is divided into two distinct segments at a base station or proxy. This proxy splits the connection into a "wired" and a "wireless" segment, each with independent TCP congestion control.

#### **Advantages:**

- Improved Performance on Wireless Links: By isolating the wireless segment, Split-TCP ensures that issues on the wireless link do not affect the entire connection.

- Enhanced Error Handling: Packet retransmissions can be managed locally by the base station or proxy, reducing latency and speeding up recovery from packet loss.
- Flexibility for Network Conditions: Each segment can use optimized TCP settings, allowing better adaptation to diverse conditions on the wired and wireless segments.

#### **Disadvantages:**

- Security and Privacy Concerns: Dividing the connection at a proxy can compromise end-to-end encryption, leading to potential privacy issues.
- Dependency on Intermediary Node: This method depends on the base station or proxy, which can be a single point of failure and may create a bottleneck.
- Additional Latency: Managing traffic for both segments may cause delays, especially if the base station is overloaded.

Split-TCP divides the connection into wired and wireless segments, optimizing each part separately. The wireless segment manages losses locally, while the wired segment remains unaffected by wireless issues. It is particularly effective in environments with a combination of wired and wireless segments, such as Wi-Fi or satellite connected to wired infrastructure.

#### **Snooping TCP (Snoop Protocol):**

The Snoop Protocol operates at the base station, monitoring TCP packets as they pass between sender and receiver. It caches unacknowledged packets, and if it detects a lost packet (indicated by duplicate ACKs), the base station locally retransmits it on the wireless link, preventing congestion window reduction.

#### **Advantages:**

- Localized Packet Recovery: By managing retransmissions at the base station, Snoop conserves bandwidth and improves speed by avoiding unnecessary end-to-end retransmissions.
- Stable Transmission Rate: Prevents unnecessary shrinking of the sender's congestion window, maintaining a stable data rate even when the wireless link is unreliable.
- Compatibility with Standard TCP: Snoop works with existing TCP implementations without requiring changes at the sender or receiver.

#### **Disadvantages:**

- Requires Infrastructure Modification: Implementing Snoop requires changes to base stations, which can be costly and complex.
- Not Suitable for Encrypted Data: Snooping relies on inspecting packet headers, making it incompatible with encrypted traffic.
- Limited Scope: Effective only in networks with fixed infrastructure (e.g., cellular networks) and less suitable for ad hoc or highly mobile wireless environments.

### **Freeze-TCP:**

Freeze-TCP enables mobile devices to instruct the sender to "freeze" the congestion window during anticipated short disconnections (e.g., during cell handoff). The sender pauses data transmission, avoiding unnecessary retransmissions and congestion window reduction.

#### **Advantages:**

- Reduced Retransmission Cost: By pausing transmission during short disconnections, Freeze-TCP conserves bandwidth by avoiding unnecessary retransmissions.
- Energy Conservation: Reduces energy consumption by avoiding retransmissions when the receiver is temporarily disconnected, which is beneficial for mobile devices.
- Maintains High Throughput: Prevents unnecessary congestion window reductions, allowing the sender to resume data transfer quickly at full speed once reconnected.

#### **Disadvantages:**

- Delay in Data Transmission: Freezing the connection may introduce delays, especially if disconnections are frequent.
- Dependency on Accurate Signal Prediction: Requires reliable detection of potential disconnections, which is challenging in environments with variable signal quality.
- Limited Application: Best suited for networks with predictable short disconnections, like cell handoffs, and less effective in unstable networks.

Freeze-TCP is ideal for mobile networks with intermittent connectivity, such as those involving devices or vehicles moving between cells. By pausing the TCP session during expected disconnections, it minimizes throughput loss and avoids unnecessary congestion window reductions.

### **TCP Reno:**

TCP Reno is a traditional congestion control protocol that uses an additive-increase, multiplicative-decrease (AIMD) approach. It gradually increases the congestion window additively until it detects packet loss, which is taken as a sign of congestion. When packet loss occurs, TCP Reno reduces the congestion window by half (multiplicative decrease). This strategy helps control congestion but presents challenges in wireless networks due to higher packet loss rates and varying signal quality.

#### **Advantages:**

- Resource-Efficient: Requires low processing and memory overhead, making it lightweight and simple to implement.
- Quick Implementation: Well-established and compatible with legacy systems, allowing easy deployment.

- Stable in Moderate Networks: Performs reliably in networks with moderate congestion or lower bandwidth.
- Adaptive to Short-Lived Connections: Effective for short sessions, such as web browsing or low-data applications.

### **Disadvantages:**

- Sensitivity to Non-Congestion Loss: Treats all packet loss as congestion, leading to unnecessary reductions in throughput in wireless networks where loss may be unrelated to congestion.
- Inconsistent Throughput in High-Loss Networks: Frequent window reductions in lossy environments cause unstable performance.
- Underutilizes High-Bandwidth Links: Has difficulty fully utilizing high-speed wireless links, such as LTE or 5G.
- Inadequate for Bursty Traffic: Slow to adjust to traffic bursts, resulting in poor performance in dynamic wireless settings.
- Limited Fairness in Mixed Environments: Struggles to compete with more aggressive TCP variants like TCP CUBIC in shared environments.

### **Best Use Case:**

TCP Reno works best in low-bandwidth, moderately stable wireless connections with infrequent packet loss. However, due to slow recovery from losses, it is less ideal than more advanced methods for high-loss or high-speed wireless networks.

### **TCP CUBIC:**

TCP CUBIC is a modern congestion control protocol optimized for high-bandwidth, long-distance connections. It uses a cubic growth function instead of linear growth, allowing it to recover bandwidth more quickly after packet loss. TCP CUBIC aggressively increases the congestion window after loss, aiming to regain the previous high window size ( $W_{max}$ ) and probe for additional capacity.

### **Advantages:**

- Higher Throughput in High-Bandwidth Networks: Efficiently utilizes available bandwidth by increasing the congestion window aggressively.
- Reduced Time in Slow Start: CUBIC's cubic growth reduces the duration spent in slow start, reaching high data rates more quickly.
- Better Performance on Long Connections: Maintains stable throughput over extended periods, making it ideal for large data transfers.
- Fairness Across TCP Variants: Coexists effectively with other TCP protocols, enhancing fairness in mixed environments.

**Disadvantages:**

- Complex Implementation: Requires more advanced algorithms and resources, adding complexity.
- Resource Intensive under High Load: May demand more CPU and memory, impacting performance under heavy load.
- Oscillation in Dynamic Conditions: The cubic function can cause fluctuations in variable network environments.
- Sensitivity to Misconfiguration: Requires careful tuning to avoid suboptimal performance.
- Less Effective in Highly Congested or Lossy Networks: Performance can degrade in networks with frequent congestion or packet loss.

**Best Use Case:**

TCP CUBIC is well-suited for high-speed wireless networks with large data transfers, such as LTE or 5G networks. Its aggressive window growth efficiently utilizes high-bandwidth wireless connections and enables faster recovery from packet loss.

**TCP Vegas:**

TCP Vegas adopts a proactive approach to congestion control, using round-trip time (RTT) to gauge network congestion and adjust the sending rate accordingly. It establishes a baseline minimum RTT, and by comparing expected versus actual throughput, TCP Vegas can adjust the congestion window to maintain stability and avoid packet loss.

**Advantages:**

- Proactive Congestion Avoidance: Adjusts sending rates based on RTT, preventing congestion before packet loss occurs.
- Efficient Bandwidth Utilization: Reduces retransmission overhead by avoiding congestion-related losses, resulting in higher efficiency.
- Lower Latency: Maintains a low-latency environment, which is beneficial for applications requiring timely data transfer.
- Stable Throughput: Provides a smooth, stable throughput by minimizing fluctuations and oscillations.
- Responsiveness for Real-Time Applications: Quickly reacts to network changes, making it ideal for real-time communications.

**Disadvantages:**

- Dependency on RTT Accuracy: Relies on precise RTT measurements, which can be challenging in dynamic conditions.
- Configuration Complexity: More complex than simpler TCP variants, requiring careful setup and tuning.
- Ineffective in Short-Lived Connections: Performs less efficiently on short connections, as time is needed to establish an accurate baseline.
- Limited Deployment: Not widely adopted, which can lead to compatibility issues across platforms.
- Challenges in Congested or Bursty Networks: Performance may suffer in highly congested or bursty networks.

#### **Best Use Case:**

TCP Vegas is suitable for environments where maintaining stable throughput and low latency is essential, such as real-time communication networks with moderate to stable traffic conditions.

#### **TCP BBR (Bottleneck Bandwidth and Round-trip Time):**

TCP BBR (Bottleneck Bandwidth and Round-trip Time) is a congestion control mechanism that maximizes throughput by estimating the bottleneck bandwidth and RTT without relying on packet loss as an indicator of congestion. It dynamically adjusts the sending rate based on measurements of available bandwidth and latency, aiming to keep the network pipeline full without causing congestion.

#### **Advantages:**

- Maximizes Throughput Efficiently: Optimizes data flow by estimating bottleneck bandwidth, providing higher efficiency.
- Reduced Latency: Avoids congestion-based packet loss, benefiting applications that need rapid response times.
- Adaptable to Network Variability: Quickly adapts to changes in network conditions, maintaining consistent throughput.
- Scalable in High-Speed Environments: Works well in high-speed networks and data centers, achieving significant throughput improvements.
- Stable in Diverse Conditions: Reliable performance across different environments, minimizing the impact of network fluctuations.

#### **Disadvantages:**

- Complex Implementation: Requires advanced bandwidth estimation, adding complexity to configuration and resource demands.

- Sensitivity to Bandwidth Overestimation: Overestimating available bandwidth may lead to congestion, which can impact performance.
- Less Predictable in Highly Variable Conditions: May exhibit unpredictable behavior in rapidly changing networks.
- Limited Support on Legacy Systems: Compatibility with older systems can be limited, affecting its applicability across networks.
- Resource-Intensive: Monitoring and adjustments require significant CPU and memory resources.

### **Best Use Case:**

TCP BBR excels in high-speed, stable environments with large data flows, such as data centers or cloud networks. Its ability to dynamically adjust to bottleneck bandwidth and RTT makes it ideal for scenarios requiring high throughput and low latency, especially in environments that can handle its resource demands.

### **DCTCP (Data Center TCP):**

DCTCP is a congestion control protocol designed specifically for data center environments. It employs Explicit Congestion Notification (ECN) to proactively manage congestion by adjusting the sending rate based on real-time feedback from the network, which helps reduce queue lengths and improve overall latency.

### **Advantages:**

- Optimized for data center traffic patterns: Tailored for applications in data centers that require low latency and high throughput.
- Efficient queue management: Minimizes queue length, which leads to reduced delays in data transmission within the data center.
- Proactive congestion management via ECN: Utilizes ECN to signal congestion before packet loss occurs, enhancing network efficiency.
- High throughput for large data transfers: Performs exceptionally well in high-speed environments with substantial data flows, typical of data centers.
- Low packet loss rates: Maintains low packet loss rates, which is crucial for applications sensitive to latency and data loss.

### **Disadvantages:**

- Requires ECN-capable infrastructure: Relies on the availability of ECN for effective congestion signaling, which may not be present in networks outside of data centers.
- Limited to data centers: Primarily designed for use within data center environments, making it less effective in typical internet or wide-area network settings.

- Complex setup and tuning: Requires careful configuration and fine-tuning for optimal performance, especially in heterogeneous data center environments.
- Potential fairness issues in mixed traffic: May struggle with fairness when managing a mix of data center-specific traffic and general internet traffic.
- Resource constraints under high congestion: Performance can degrade significantly if the network experiences sustained high levels of congestion.

### **Comparison of TCP Westwood+ and TCP CUBIC:**

#### **TCP Westwood+:**

- Best for general wireless environments characterized by variable bandwidth and frequent packet loss.

#### **- Strengths:**

- Estimates available bandwidth to prevent underutilization.
- Ideal for mobile and lossy wireless networks due to its adaptability to fluctuating conditions.

#### **TCP CUBIC:**

- Best for high-speed wireless networks, such as LTE and 5G.

#### **- Strengths:**

- Utilizes aggressive window growth to maximize the utilization of available bandwidth.
- Effective in stable, high-throughput scenarios, providing better performance in environments where bandwidth is ample.

### **Overall summary:**

TCP Westwood+ and TCP CUBIC offer complementary advantages. Westwood+ excels in adapting to variable network conditions, making it suitable for lossy and mobile environments, while CUBIC is designed for maximizing throughput in high-speed networks, ensuring efficient bandwidth use in stable conditions. Together, they provide a balance of performance and adaptability in diverse networking situations.

In conclusion, various TCP congestion control algorithms, including TCP Reno, TCP CUBIC, TCP Vegas, TCP BBR, DCTCP, and TCP Westwood+, each offer distinct advantages and disadvantages tailored to different network environments.

TCP Reno remains a foundational protocol, effective in moderately stable networks but limited in its responsiveness to high loss scenarios. TCP CUBIC, on the other hand, excels in high-speed networks, effectively utilizing available bandwidth through aggressive window growth. TCP Vegas provides a proactive approach to congestion management by monitoring round-trip time, though it may underperform in short-lived connections and requires accurate RTT measurements.

BBR represents a significant advancement by optimizing throughput based on bottleneck bandwidth and round-trip time, yet it demands sophisticated implementation and careful resource management. DCTCP is specifically designed for data centers, leveraging ECN to manage congestion proactively and ensure low packet loss, but its effectiveness is limited outside of this environment.

Finally, TCP Westwood+ is particularly suited for variable wireless conditions, where it dynamically estimates available bandwidth to adapt to changing network states. The choice of congestion control algorithm should be informed by the specific requirements of the application and the characteristics of the network environment. By understanding the strengths and limitations of these protocols, network designers and operators can make informed decisions to optimize performance and enhance user experiences across diverse networking scenarios.