CS/ECE 439: Wireless Networking

Transport Layer – TCP over Wireless
Wireless Characteristics

- Low bandwidth
- Long or variable latency

Random Errors

- If number of errors is small
  - May be corrected by an error correcting code
- Excessive bit errors
  - Result in a packet being discarded, possibly before it reaches the transport layer
Random Errors

- May cause fast retransmit
  - Example assumes delayed ack - every other packet ack’d

3 duplicate acks trigger fast retransmit at sender
Random Errors

- Fast retransmit results in
  - Retransmission of lost packet
  - Reduction in congestion window
- Reducing congestion window
  - Unnecessary response to errors
  - Reduces the throughput
Random Errors

- Sometimes congestion response is appropriate
  - Interference due to other users
    - Reduce congestion window
  - Bad channel for a long duration
    - Let TCP backoff
    - Do not unnecessarily attempt retransmissions while the channel remains in the bad state

- But what about errors for which reducing congestion window is an inappropriate response?
  - Noise
    - Do not reduce window
Timeouts

- **Burst errors may cause timeouts**
  - If wireless link remains unavailable for extended duration, a window worth of data may be lost
    - Driving through a tunnel
    - Passing a truck
  - **Timeout results in slow start**
    - Slow start reduces congestion window to 1 MSS, reducing throughput
    - Reduction in window in response to burst errors?

- **Random errors may also cause timeouts**
  - Multiple packet losses in a window can result in timeout when using TCP-Reno
    - And to a lesser extent when using SACK
Impact of Transmission Errors

- TCP cannot distinguish between packet losses due to congestion and transmission errors
  - Unnecessarily reduces congestion window
  - Throughput suffers
Impact of Misclassification

2 MB wide-area TCP transfer over 2 Mbps WaveLAN
Ideal Behavior

- **Ideal TCP behavior**
  - Simply retransmit a packet lost due to transmission errors
  - Take no congestion control actions
    - Ideal TCP typically not realizable

- **Ideal network behavior**
  - Transmission errors should be hidden from the sender
  - Errors should be recovered transparently and efficiently

- Proposed schemes attempt to approximate one of the above two ideals
Techniques

- Nature of actions taken to improve performance
  - Hide error losses from the sender
    - Sender is unaware of error-based losses
      - Will not reduce congestion window
  - Let sender know, or determine, cause of packet loss
    - Sender knows about cause of packet loss
      - Will not reduce congestion window
Techniques

- Where modifications are needed
  - At the sender node only
  - At the receiver node only
  - At intermediate node(s) only
  - Combinations of the above
Schemes

- Link level mechanisms
- Split connection approach
- TCP-Aware link layer
- TCP-Unaware approximation of TCP-aware link layer
- Explicit notification
- Receiver-based discrimination
- Sender-based discrimination
Forward Error Correction (FEC) can be used to correct small number of errors

- Correctable errors hidden from the TCP sender
- FEC incurs overhead even when errors do not occur
  - Adaptive FEC schemes can reduce the overhead by choosing appropriate FEC dynamically
Link Layer Mechanisms: Link Level Retransmissions

- Retransmit a packet at the link layer, if errors are detected
- Retransmission overhead incurred only if errors occur
  - Unlike FEC overhead
- In general
  - Use FEC to correct a small number of errors
  - Use link level retransmission when FEC capability is exceeded
Link Level Retransmissions

Link layer state

application
transport
network
link
physical

application
transport
network
link
physical

application
transport
network
link
physical

Link layer state

wireless

© CS 498wn Staff, University of Illinois  Fall 2018
Link Level Retransmissions

- How many retransmissions at the link level before giving up?
  - Finite bound -- semi-reliable link layer
  - No bound -- reliable link layer

- What triggers link level retransmissions?
  - Link layer timeout mechanism
  - Link level acks (negative acks, dupacks, …)
  - Other mechanisms (e.g., Snoop, as discussed later)
Link Level Retransmissions

How much time is required for a link layer retransmission?

- Small fraction of end-to-end TCP RTT
- Large fraction/multiple of end-to-end TCP RTT
Link Level Retransmissions

- Retransmissions can cause
  - Head-of-the-line blocking
  - Congestion losses
Link Level Retransmissions

- The sender’s Retransmission Timeout (RTO)
  - Function of measured RTT (round-trip times)
  - Link level retransmits increase RTT, therefore, RTO

- Infrequent errors
  - RTO will not account for RTT variations due to link level retransmissions

- Frequent errors
  - Increase RTO significantly on slow wireless links
Link Level Retransmissions

- Not all connections benefit from retransmissions
  - Audio

- Need to be able to specify requirements on a per-packet basis
  - Should the packet be retransmitted?
  - How many times?

- Need a standard mechanism to specify the requirements
Link Layer Schemes: Summary

- When is a reliable link layer beneficial to TCP performance?
  - If TCP retransmission timeout is large enough to tolerate additional delays due to link level retransmits
Link Layer Mechanisms: Hiding Losses

- Hide wireless losses from TCP sender
- Link layer modifications needed at both ends of wireless link
  - TCP need not be modified
Split Connection Approach

- End-to-end TCP connection is broken into
  - One connection on the wired part of route
  - One over wireless part of the route
- A single TCP connection split into two TCP connections
  - If wireless link is not last on route
    - More than two TCP connections may be needed
Split Connection Approach

- Connection between wireless host MH and fixed host (FH) goes through base station (BS)
  - \( \text{FH} \rightarrow \text{MH} = \text{FH} \rightarrow \text{BS} + \text{BS} \rightarrow \text{MH} \)
Split Connection Approach

- Split connection results in independent flow control for the two parts
- Flow/error control protocols, packet size, time-outs, may be different for each part
Split Connection Approach

\[ 1 \text{TCP} = \frac{1}{2} \text{TCP} + \frac{1}{2} (\text{TCP or XXX}) \]
Split Connection Approach

- **Indirect TCP**
  - FH -> BS connection: Standard TCP
  - BS -> MH connection: Standard TCP

- **Selective Repeat Protocol (SRP)**
  - FH -> BS connection: standard TCP
  - BS -> FH connection: selective repeat protocol on top of UDP

- Performance better than Indirect-TCP (I-TCP)
  - Wireless portion of connection can be tuned to wireless behavior
Split Connection Approach: Advantages

- BS-MH connection can be optimized independent of FH-BS connection
- Local recovery of errors
- Good performance achievable using appropriate BS-MH protocol
  - Standard TCP on BS-MH performs poorly
  - Selective acks improve performance
Split Connection Approach: Disadvantages

- **End-to-end semantics violated**
  - ack may be delivered to sender, before data delivered to the receiver
  - May not be a problem for applications that do not rely on TCP for the end-to-end semantics
Split Connection Approach: Disadvantages

- **BS retains hard state**
  - BS failure can result in loss of data (unreliability)
    - If BS fails, packet 40 will be lost
    - Because it is ack'd to sender, the sender does not buffer 40
Split Connection Approach: Disadvantages

- BS retains hard state
  - Hand-off latency increases due to state transfer
    - Data that has been ack’d to sender, must be moved to new base station
Split Connection Approach: Disadvantages

- Buffer space needed at BS for each TCP connection
  - BS buffers tend to get full with a slow wireless link slower
    - One window of data on wired connection could be stored at base station for each split connection

- Window on BS-MH connection reduced in response to errors
  - May not be an issue for wireless links with small delay-bw product
Split Connection Approach: Disadvantages

- Extra copying of data at BS
  - Copying from FH-BS socket buffer to BS-MH socket buffer
  - Increases end-to-end latency
- May not be useful if data and acks traverse different paths (both do not go through the base station)
  - Example: data on a satellite wireless hop, acks on a dial-up channel
TCP-Aware Link Layer

- **Snoop Protocol**
  - Retains local recovery of Split Connection approach and link level retransmission schemes
  - Improves on split connection
    - End-to-end semantics retained
    - Soft state at base station, instead of hard state
Snoop Protocol

- Application
- Transport
- Network
- Link
- Physical

TCP connection

- Per TCP-connection state
- rxmt

FH - BS - MH

wireless
Snoop Protocol

- Buffers data packets at the base station BS
  - To allow link layer retransmission
- When dupacks received by BS from MH, retransmit on wireless link, if packet present in buffer
- Prevents fast retransmit at TCP sender FH by dropping the dupacks at BS
Snoop Protocol

Example assumes delayed ack - every other packet ack'd

TCP state maintained at link layer

Duplicate acks are not delayed
dupack

Duplicate acks

Discard dupack

Dupack triggers retransmission of packet 37 from base station

BS needs to be TCP-aware to be able to interpret TCP headers

TCP sender does not fast retransmit
Snoop Protocol: When Beneficial?

- **Snoop**
  - Prevents fast retransmit despite transmission errors on the wireless link

- **If wireless link level delay-bandwidth product is less than 4 packets**
  - Simple (TCP-unaware) link level retransmission scheme can suffice
  - Since delay-bandwidth product is small
    - Retransmission scheme can deliver the lost packet without resulting in 3 dupacks from the TCP receiver
Snoop Protocol: Advantages

- High throughput
  - Performance further improved using selective acks
- Local recovery from wireless losses
- Fast retransmit not triggered at sender
- End-to-end semantics retained
- Soft state at base station
  - Loss of the soft state affects performance, but not correctness
Snoop Protocol: Disadvantages

- Link layer at base station needs to be TCP-aware.
- Not useful if TCP headers are encrypted (IPsec).
- Cannot be used if TCP data and TCP acks traverse different paths (both do not go through the base station).
WTCP Protocol

- Snoop hides wireless losses from the sender
  - But sender’s RTT estimates may be larger in presence of errors
  - Larger RTO results in slower response for congestion losses
WTCP Protocol

- Local recovery
- Timestamp option to estimate RTT
- The base station
  - Adds base station residence time to the timestamp when processing an ack received from the wireless host
- Sender’s RTT estimate
  - Not affected by retransmissions on wireless link
WTCP Protocol

Numbers in this figure are timestamps

Base station residence time is 1 unit
WTCP: Disadvantages

- Requires use of the timestamp option
- May be useful only if retransmission times are large
  - Link stays in bad state for a long time
  - Link frequently enters a bad state
  - Link delay large
- WTCP does not account for congestion on wireless hop
  - Assumes that all delay at base station is due to queuing and retransmissions
  - Will not work for shared wireless LAN, where delays also incurred due to contention with other transmitters
TCP-Unaware Approximation of TCP-Aware Link Layer

- **Delayed Dupacks Protocol**
  - Attempts to imitate Snoop, without making the base station TCP-aware
  - **Snoop implements two features at the base station**
    - Link layer retransmission
    - Reducing interference between TCP and link layer retransmissions (by dropping dupacks)
  - **Delayed Dupacks implements the same two features**
    - At BS: link layer retransmission
    - At MH: reducing interference between TCP and link layer retransmissions (by delaying dupacks)
Delayed Dupacks Protocol
Delayed Dupacks Protocol

- Delayed dupacks released after interval D, if missing packet not received by then
- Link layer maintains state to allow retransmission
- Link layer state is not TCP-specific
Delayed Dupacks Protocol

TCP sender does not fast retransmit

Delayed dupacks are discarded if lost packet received before delay D expires

Base station forwards delayed dupacks

TCP sender does not fast retransmit

Delayed dupacks are discarded if lost packet received before delay D expires

Base station forwards delayed dupacks
Delayed Dupacks Scheme: Advantages

- Link layer need not be TCP-aware
- Can be used even if TCP headers are encrypted
- Works well for relatively small wireless RTT (compared to end-to-end RTT)
  - Relatively small delay $D$ sufficient in such cases
Delayed Dupacks Scheme: Disadvantages

- Right value of dupack delay $D$ dependent on the wireless link properties
- Mechanisms to automatically choose $D$ needed
- Delays dupacks for congestion losses too, delaying congestion loss recovery
Explicit Notification Schemes

- **General Philosophy**
  - **Approximate Ideal TCP behavior**
    - TCP sender should simply retransmit a packet lost due to transmission errors
    - No congestion control actions
  - **Wireless node**
    - Determines that packets are lost due to errors
    - Informs sender using an explicit notification
  - **Sender - on notification**
    - Does not reduce congestion window
    - Retransmits lost packet
Explicit Notification Schemes

- Motivated by the Explicit Congestion Notification (ECN) proposals
- Variations proposed in literature differ in
  - Who sends explicit notification
  - How they know to send the explicit notification
  - What the sender does on receiving the notification
Explicit Loss Notification – MH as TCP Sender

- Wireless link first on the path from sender to receiver
- Base station
  - Keeps track of holes in the packet sequence
  - Dupack from receiver
    - Base station compares the dupack sequence number with recorded holes
    - If there is a match, an ELN bit is set in the dupack
- Sender - Dupack with ELN set
  - Retransmit packet
  - Do not reduce congestion window

Record hole at 2

MH 4 3 2 1 1
wireless

BS

FH 4 3 1 1

Dupack with ELN set
Explicit Loss Notification – MH as TCP Sender

- **Base station**
  - Attempts to deliver packets to the MH using a link layer retransmission scheme
  - If packet cannot be delivered using a small number of retransmissions
    - BS sends a Explicit Bad State Notification (EBSN) message to TCP sender
- **When TCP sender receives EBSN, it resets its timer**
  - Timeout delayed, when wireless channel in bad state
Partial Ack Protocols

- Send two types of acknowledgements
  - A partial acknowledgement informs the sender that a packet was received by an intermediate host (typically, base station)
  - Normal TCP cumulative ack needed by the sender for reliability purposes
Partial Ack Protocols

- When a packet for which a partial ack is received is detected to be lost, the sender does not reduce its congestion window.
- Loss assumed to be due to wireless errors.
Explicit Loss Notification - MH as TCP receiver

- **Approximate hypothetical ELN**
- **Base station**
  - Caches TCP sequence numbers
  - Does not cache data packets
- If sequence number for lost packet is cached at the base station
  - Duplicate acks are tagged with ELN bit before being forwarded to sender
- Sender takes appropriate action on receiving ELN
Explicit Loss Notification - MH as TCP receiver

Sequence numbers cached at base station

Dupack with ELN
Receiver-Based Discrimination Scheme

- MH is TCP receiver
  - Use heuristics to guess cause of packet loss
  - If packet loss is “due” to errors
    - Send a notification to the TCP sender

- TCP sender - on notification
  - Retransmit lost packet
  - Do not reduce congestion window
Receiver-Based Scheme

Congestion loss
Receiver-Based Scheme

```
FH   BS   MH
12 11 10

FH   BS   MH
12 11 10
```

2T

Error loss
Receiver-Based Scheme

- Receiver uses the inter-arrival time between consecutively received packets to guess the cause of a packet loss

- On determining a packet loss as being due to errors, the receiver may
  - Tag corresponding dupacks with an ELN bit, or
  - Send an explicit notification to sender
Receiver-Based Scheme: Disadvantages

- Limited applicability
- The slowest link on the path must be the last wireless hop
  - To ensure some queuing will occur at the base station
- The queueing delays for all packets (at the base station) should be somewhat uniform
  - Multiple connections on the link will make inter-packet delays variable
Receiver-Based Scheme: Advantages

- Can be implemented without modifying the base station (an “end-to-end” scheme)
- May be used despite encryption, or if data & acks traverse different paths
Sender-Based Discrimination Scheme

- Sender can attempt to determine cause of a packet loss
- If packet loss determined to be due to errors, do not reduce congestion window
- Sender can only use statistics based on round-trip times, window sizes, and loss pattern
  - Unless network provides more information (example: explicit loss notification)
Sender-Based Heuristics: Disadvantage

- Does not work quite well enough as yet!!

Reason

- Statistics collected by the sender garbled by other traffic on the network
- Not much correlation between observed short-term statistics, and onset of congestion
Sender-Based Heuristics: Advantages

- Only sender needs to be modified
- Needs further investigation to develop better heuristics
  - Investigate longer-term heuristics
TCP in Presence of Transmission Errors: Summary

- Many techniques have been proposed, and several approaches perform well in many environments.
- **Recommendation:** Prefer end-to-end techniques.
  - End-to-end techniques are those which do not require TCP-Specific help from lower layers.
  - Lower layers may help improve TCP performance without taking TCP-specific actions.
- **Examples:**
  - Semi-reliable link level retransmission schemes
  - Explicit notification