Practical Partial Packet Recovery for 802.11: Maranello

COS 598a: Wireless Networking and Sensing Systems

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Context: Coping with wireless bit errors

- **Wired links** are usually all-or-nothing
  - Either the packet arrives correctly or the link is "cut"
- **Wireless links** often deliver packets with errors
  - Bit error rate depends on interference from other links, and multipath fading (recall Roofnet experiments)
  - Packets may have only a few, localized errors
    - Or, packets may have mostly errored bits, but a small piece of salvageable content

Idea: Partial Packet Recovery

- When a frame is received with bit errors:
  - Sender retransmits **just the bits that need correcting**
  - Receiver combines original transmission with retransmissions to form a correct packet

- Increases throughput, because:
  1. The retransmission is **smaller** than the original
  2. Shorter transmissions have **higher delivery probability** than longer transmissions
  3. Consequently, senders select **higher bit rates**

Alternate approach #1: Block checksum

- Divide each packet into blocks
  - Each block has a one-byte sequence number, 8-bit CRC
- Receiver requests retransmit of just blocks that fail checksum by replying with a ***negative acknowledgement (NACK) frame***
  - NACK frame specifies incorrect block sequence numbers
- **Pay block checksum overhead** in the common case (no errors)

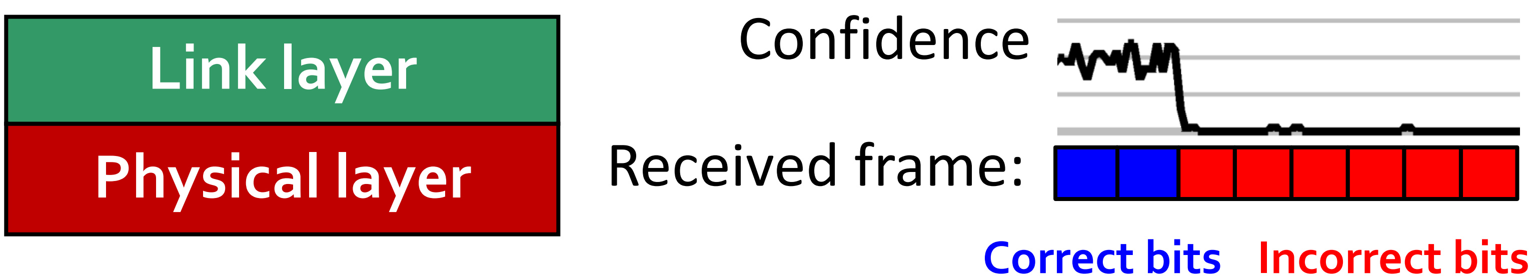
Alternate approach #2: Forward Error Correction

- Don't attempt to identify correct/incorrect bits
  - Instead send parity bits that contain information about **every** bit in the packet
  - Common parity coding scheme: ***Reed-Solomon (R-S)***

- Example: **ZipTx** [MobiCom '08]
  - Two-round forward error correction mechanism
    - In 1st round, transmitter sends a small number of R-S parity bits for a corrupted packet
    - In 2nd round, transmitter sends more R-S parity bits
  - If both rounds fail, the receiver requests a retransmission of the whole packet

Alternate approach #3: Physical-layer hints

- Physical layer "scores" each bit with a numerical confidence in that bit's correctness, passes score up to higher layers
- Receiver's link layer asks for retransmissions of just the bits from low-confidence part of the frame
- Many different ways of combining retransmissions with original transmission
  - Example: SOFT [MobiCom '07] combining information from multiple access points that receive a frame



Maranello

- Block-based checksum design implemented on commodity 802.11 hardware (Broadcom)
- Novel overhead-free link-layer design for the case of no wireless bit errors (common case)
- Maranello protocol implemented in ***firmware*** (software running on a small microprocessor on the Broadcom 802.11 network interface card)

Maranello: Protocol

Incorrect bits

- Receiver computes link-layer frame checksum, compares to the 802.11 frame checksum field, begins recovery if they don't match:

1. **Receiver** breaks errored frame into fixed-size ***blocks***
   - Sender and receiver agree on the block size beforehand

Maranello: Protocol (2)

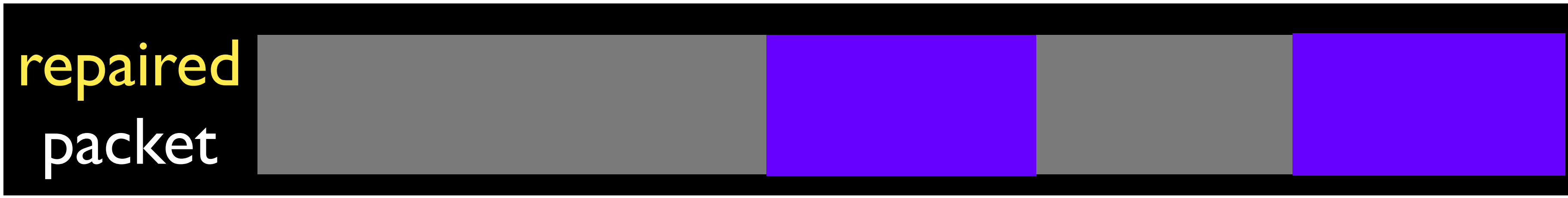
2. **Receiver** computes Fletcher-32 block checksums for each block and includes **all** **block checksums** in a NACK reply
   – If NACK reply lost, transmitter resends entire packet

3. Sender computes block checksums over each block
   – Compares **computed** block checksums to **received** block checksums to determine errored blocks

Maranello: Protocol (3)

4. Sender transmits ***repair blocks*** corresponding to just the blocks received that contain errors (***repair packet***)
   - Sender doubles contention window before repair transmission (recall bounded exponential backoff)
   - If sender's ACK timer expires, it retransmits repair packet
   - If repair packet contains errors, receiver transmits nothing
     - Sender then retransmits the original frame

Maranello: Protocol (4)



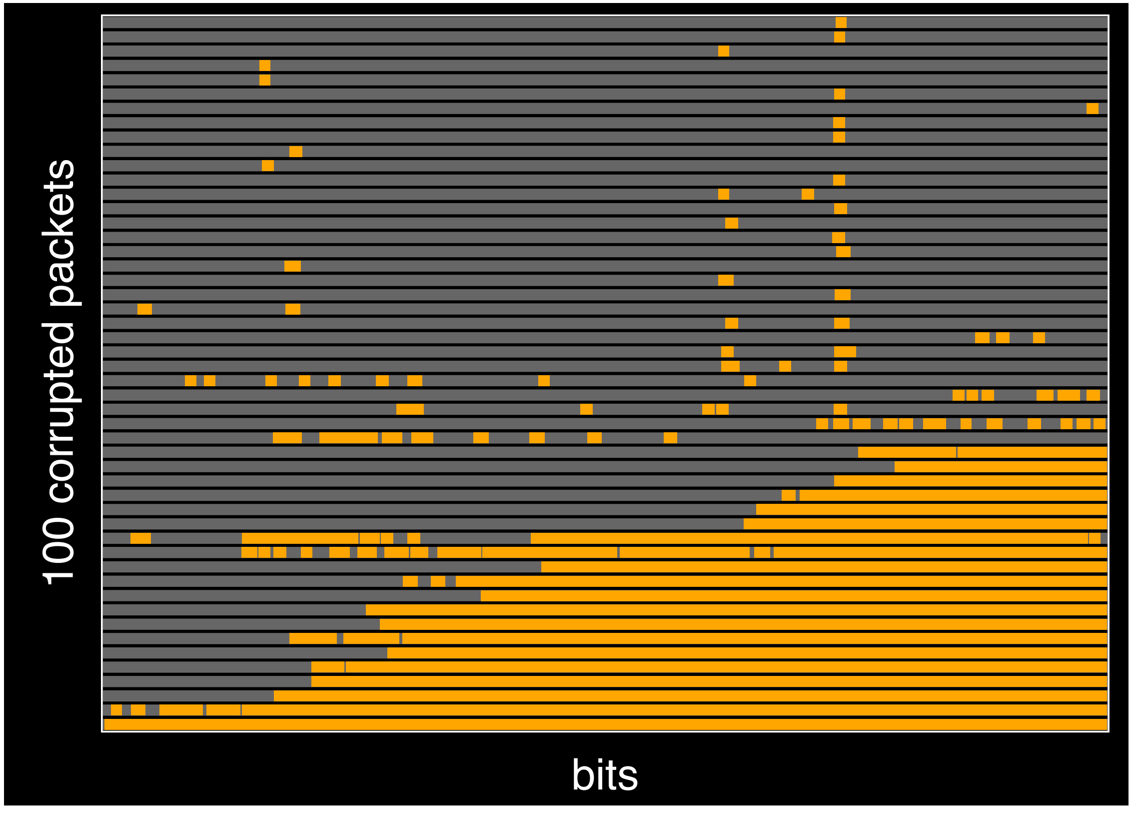
5. Receiver repairs original transmission with repair blocks
   – Re-computes and verifies a CRC-32 ***frame checksum*** (computed over entire frame) to check that the recovered packet is indeed correct

Interoperation with legacy 802.11

- **802.11 sender** with Maranello receiver
  - Does not recognize Maranello NACK from receiver
  - So sender retransmits as normal after the (short) "ack timeout" period

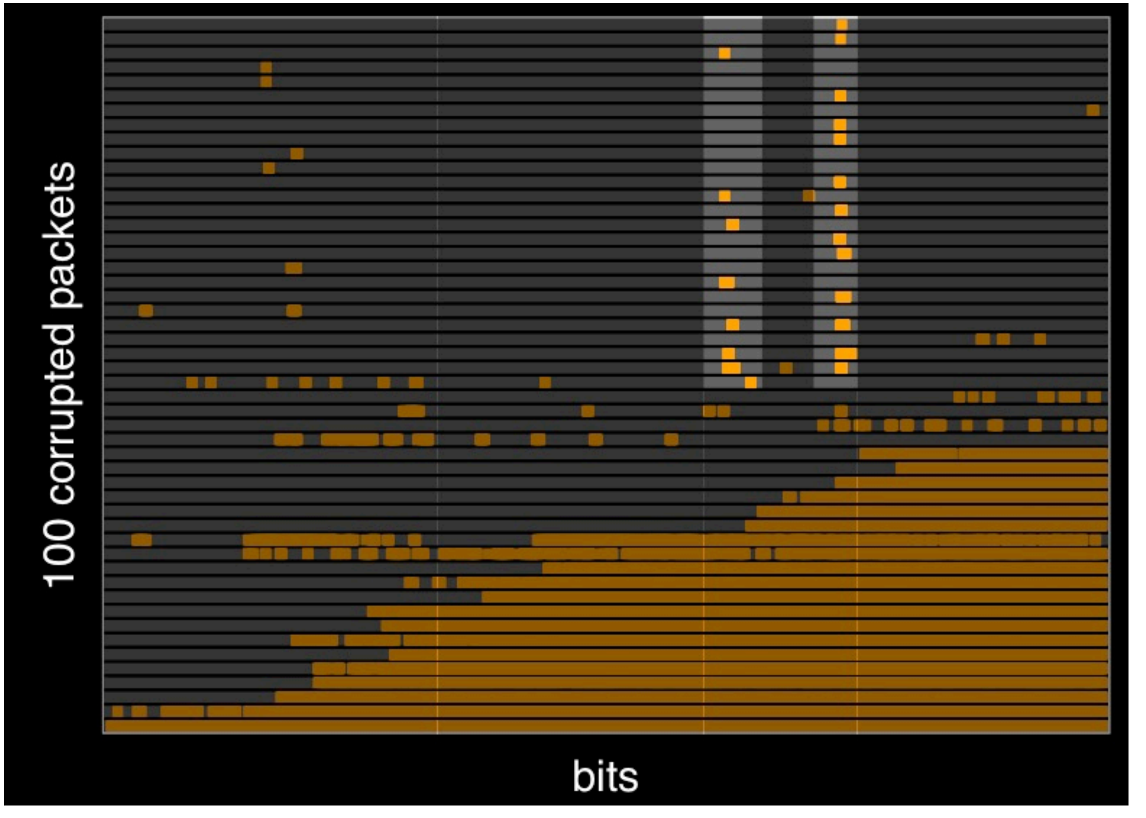
- Maranello sender with **802.11 receiver**
  - Just sends 802.11 ACK if correct, nothing if incorrect
  - Maranello sender will retransmit entire frame to the 802.11 receiver after ack timeout

Errored bit location by packet



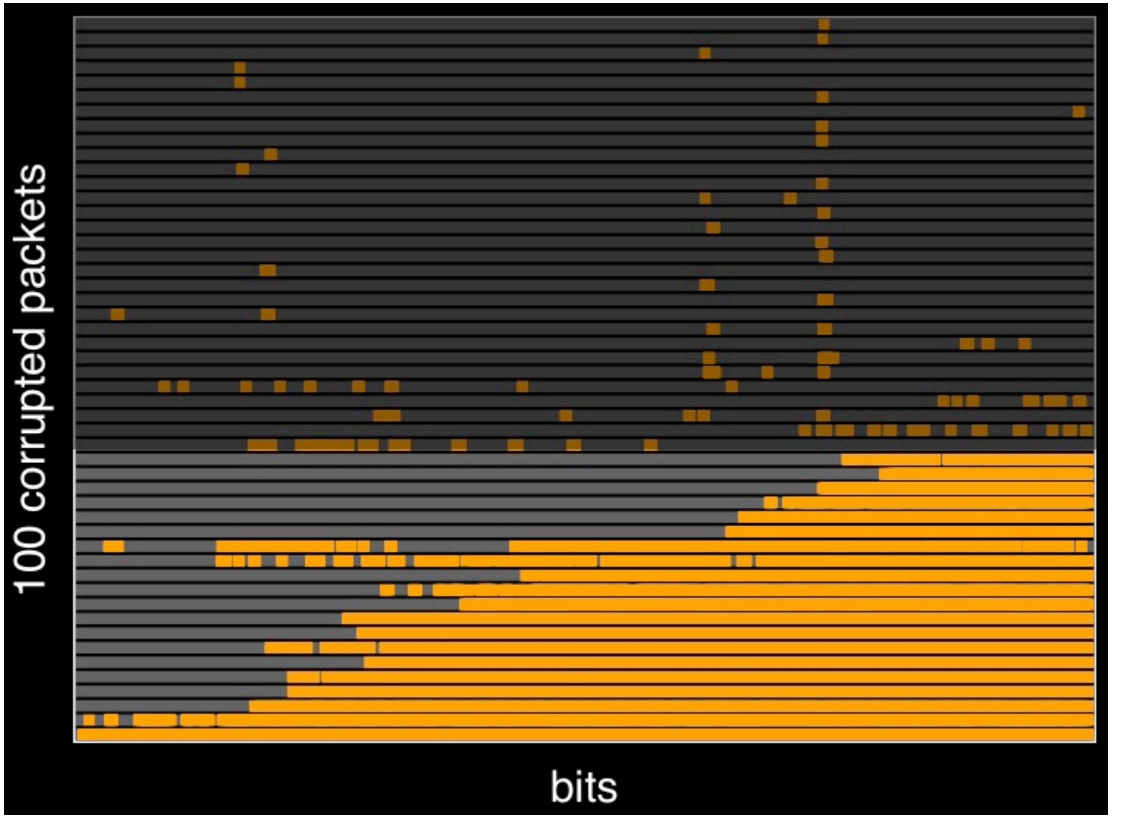
- Orange dot indicates a bit error
  - In **packet** corresponding to vertical axis position
  - At **location in that packet** corresponding to horizontal axis position

Wi-Fi bit errors cluster together



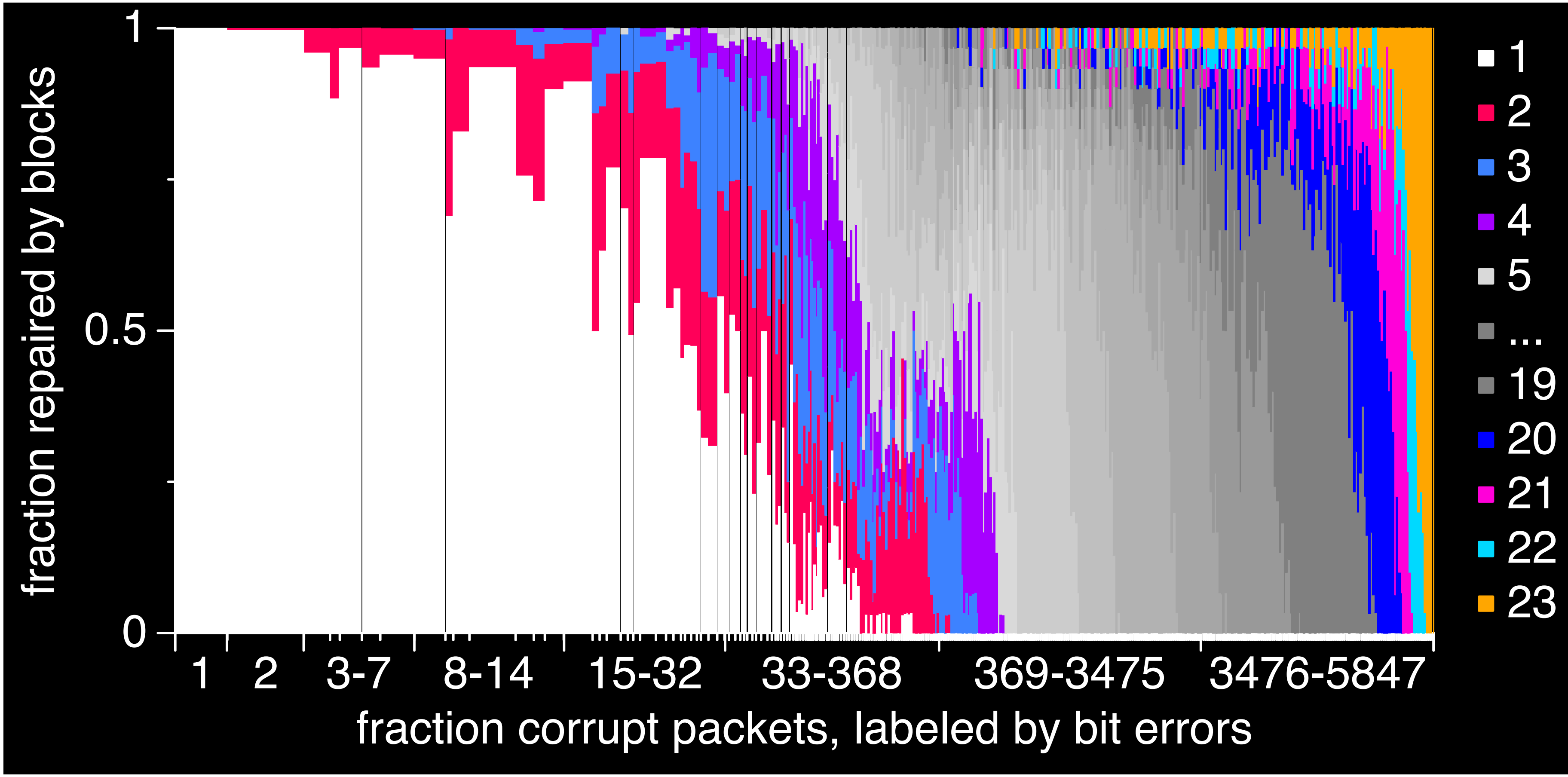
- Some packets have few bit errors (hypothesis: noise burst?)
  - Errors are mostly restricted to certain 64-byte blocks
  - Can be recovered by retransmitting those blocks

Wi-Fi bit errors cluster together



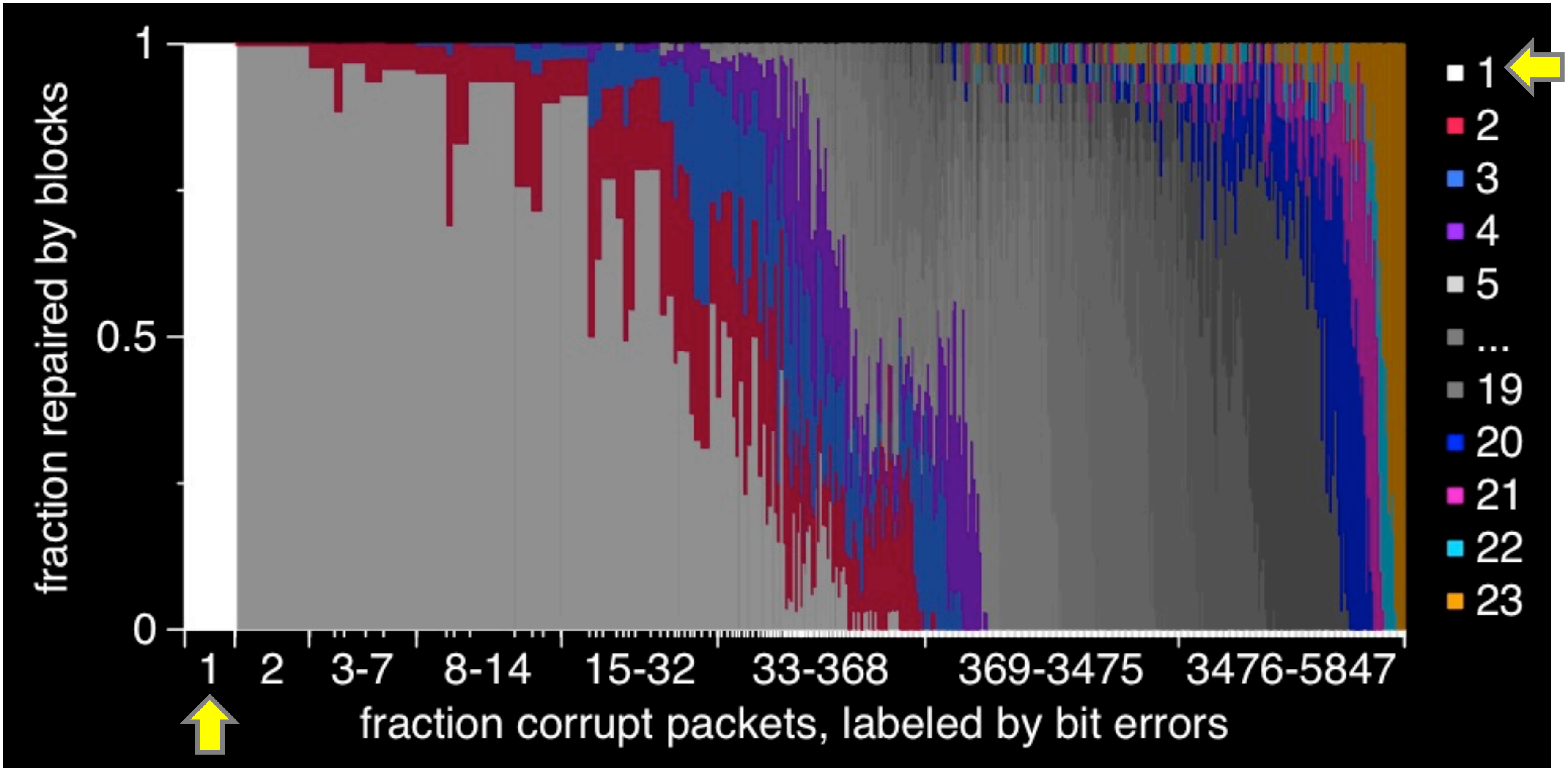
- Some packets have many bit errors (hypothesis: interference or loss of synchronization)
  - Similarly, can be recovered by retransmitting errored blocks

How many blocks are needed to repair?



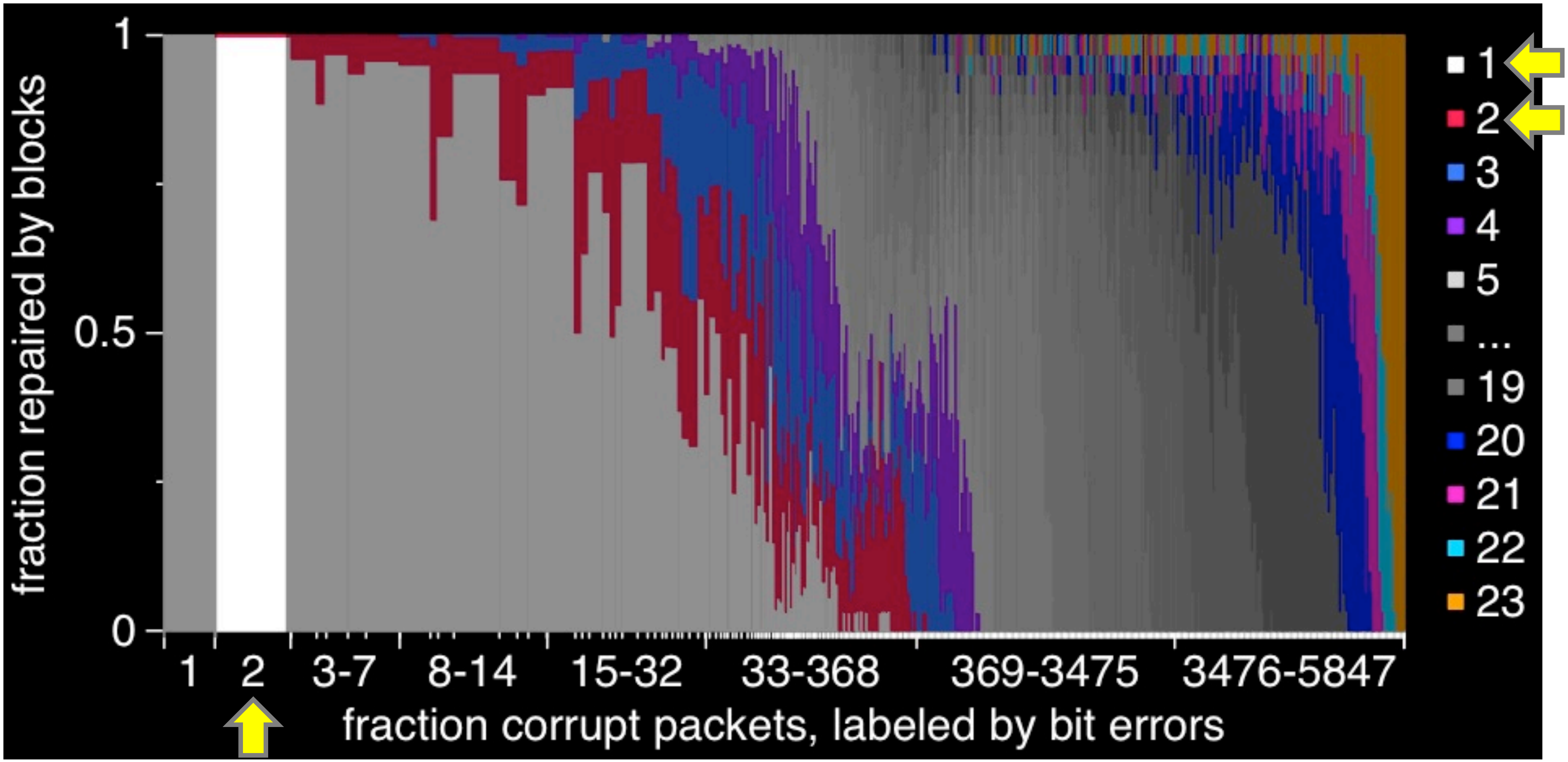
- Horizontal axis: number of bit errors in packets
- Vertical axis: Stacked bar graph (# 64-byte blocks required to repair)

One block fixes a one-bit error



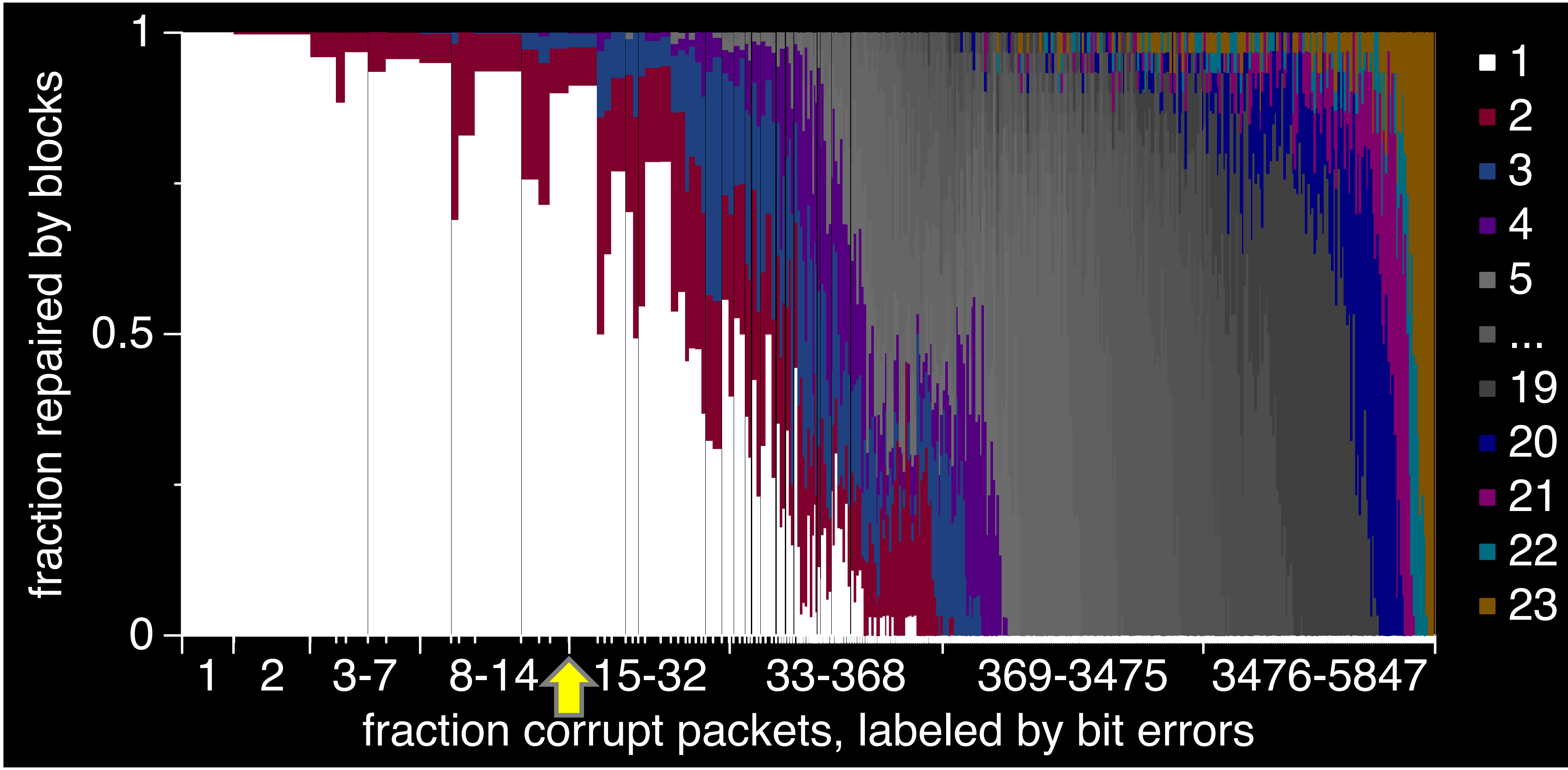
- For packets with **1** bit error, **one** 64-byte block always repairs the packet

One block usually fixes two bit errors



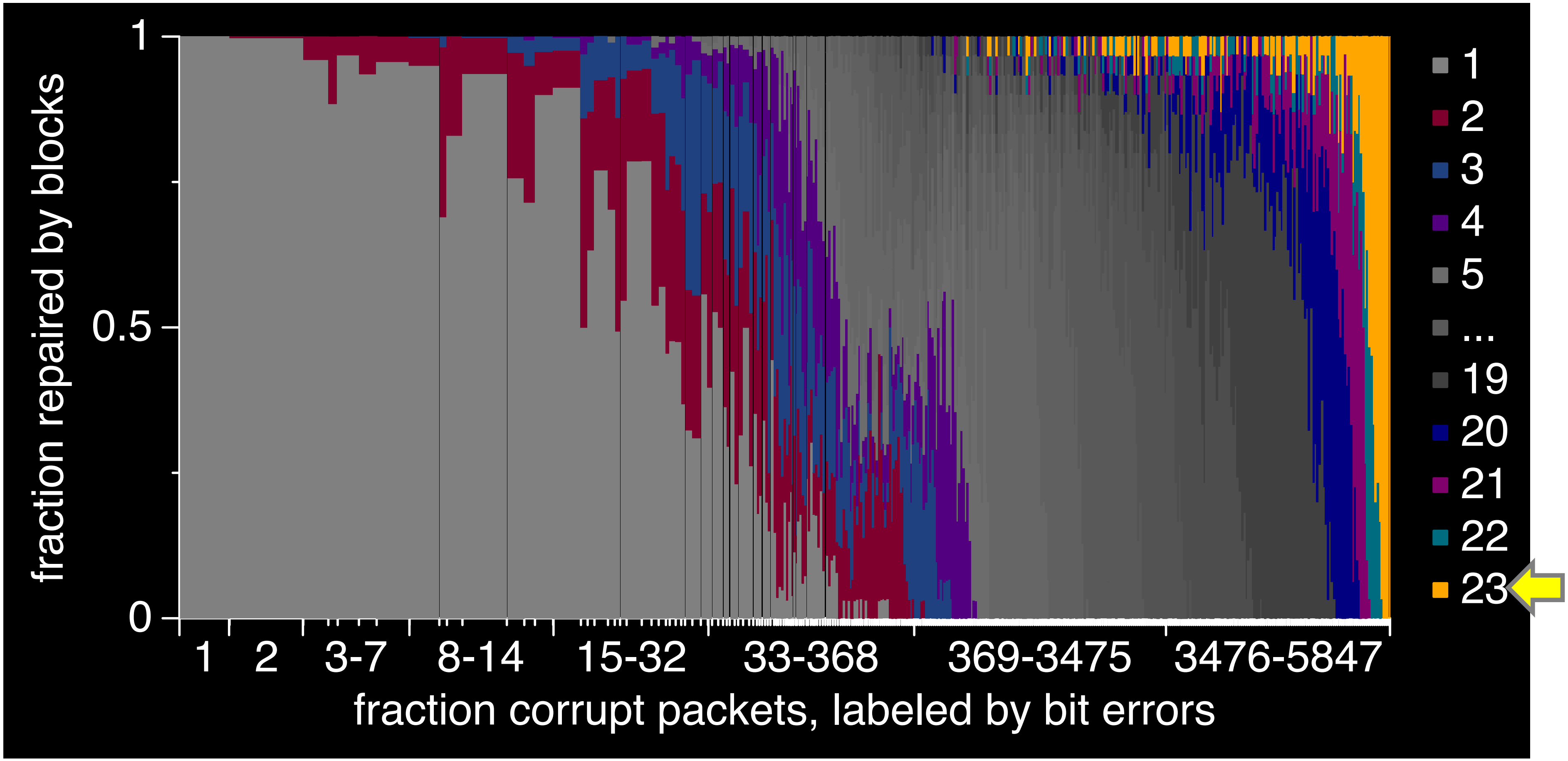
- Among packets with **two** bit errors:
  - **One** 64-byte block repairs the packet 99.7% of the time
  - **Two** 64-byte blocks repair the packet 0.3% of the time

How many bit errors can one block fix?



- Fraction of packets repaired by **one** 64-byte block, by number of errored bits
  - Under 15 errored bits, **≈ 90% packets can be fixed with one block**
  - Packet size 1,500 bytes, so one block is ≈ **4%** of the packet's size

How many blocks are needed to repair?



- There are 23 blocks per packet, so orange area represents packets that need a **complete retransmission** (**very few**)

Summary: How many repair blocks?

- So far, we have seen the following:
  - The overhead of one block is 4% of a packet
  - For 1–2 errored bits, one block fixes most packets
  - Under 15 errored bits, one block fixes ≈ 90% packets
  - Very few packets require a complete retransmission

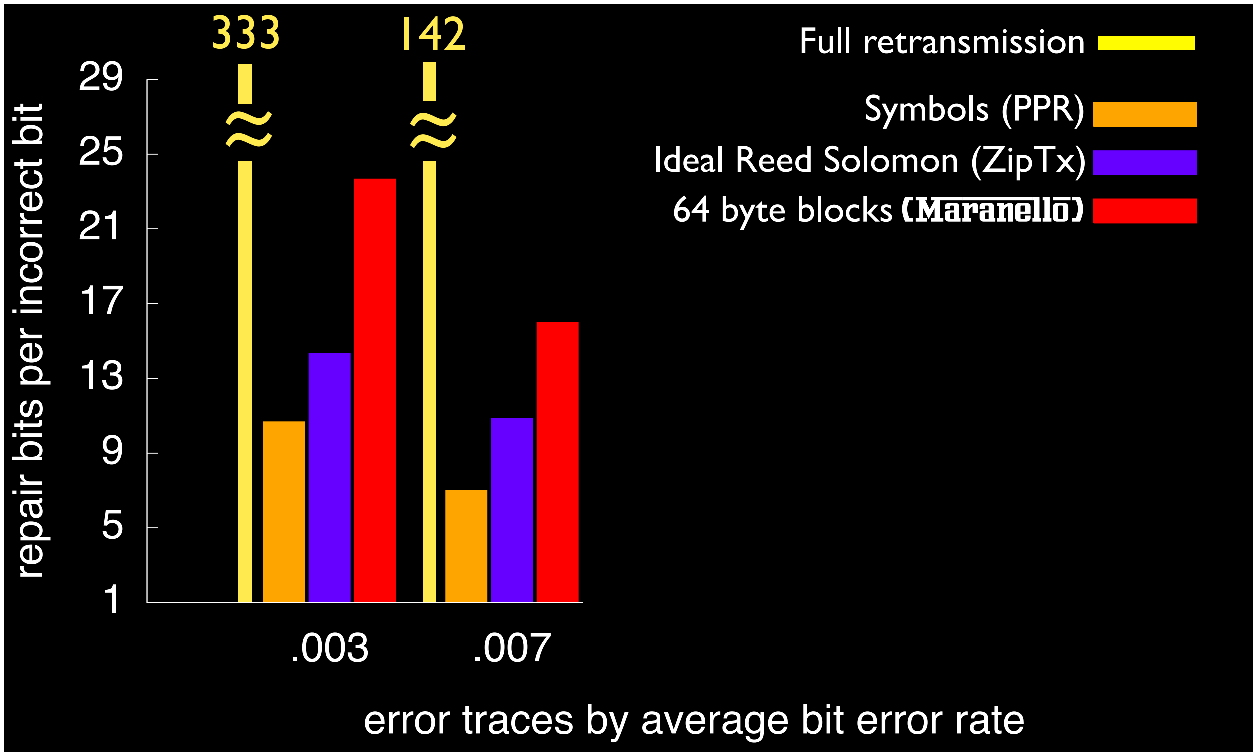
- **But is number of repair blocks required the right question?**
  - We are looking for evidence that partial packet recovery will in fact increase performance, *i.e.*, throughput
  - This data doesn't tell us anything about how often how many bit errors occur (*i.e.*, where on the x-axis are we most of the time)

Repair size

- Measure how many repair bits (on average) a particular protocol needs to fix one incorrect bit

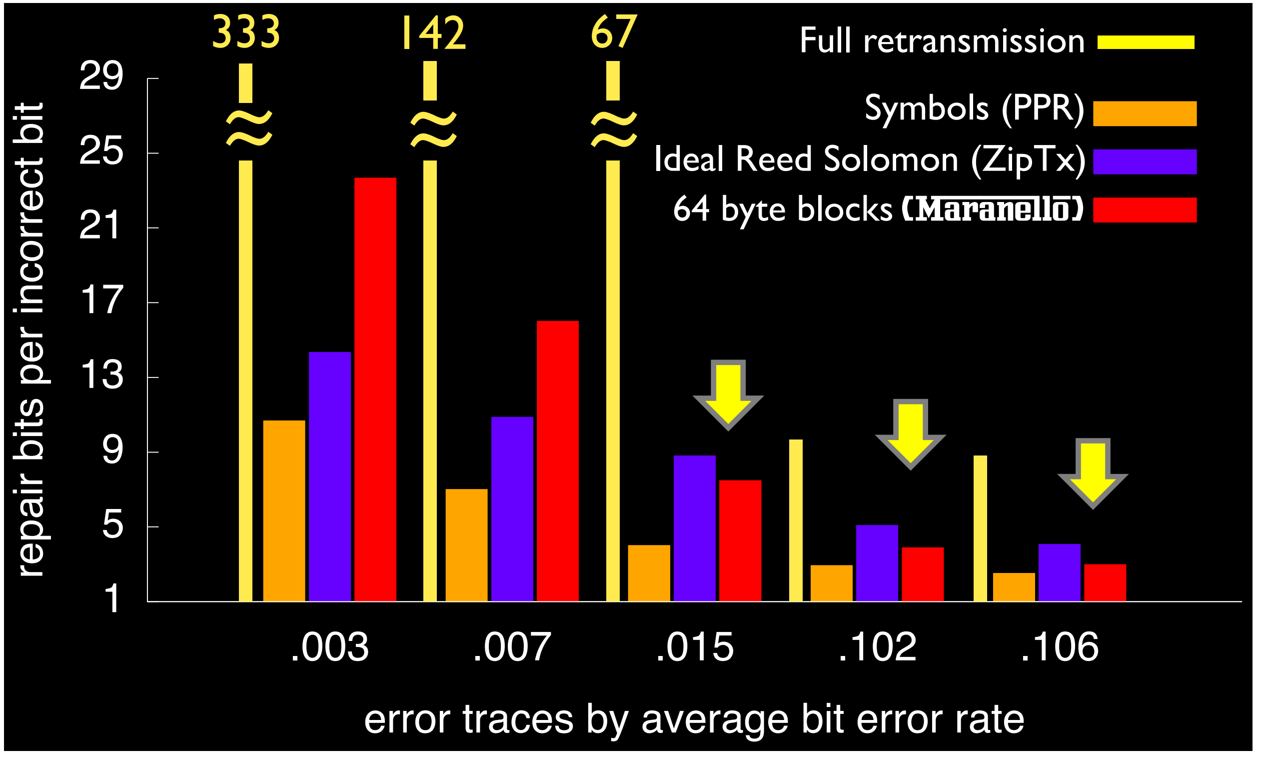
- Trace-driven simulation
  - Use Broadcom cards to send and receive packets with known payloads over the air
  - Record ***traces*** of the received frames and mark each received bit as correct or incorrect
  - Software simulator runs the protocol to be evaluated, in simulation, using trace data for received frames

Repair size: Maranello competitive at low BER



- At **low BER:** Maranello requires only marginally more repair bits than Reed-Solomon ZipTx approach
- Parity bits fix a small number of errors efficiently (simulated "ideal" ZipTx that knows the number of errors needing repair)

Repair size: Maranello outperforms ZipTx at high BER



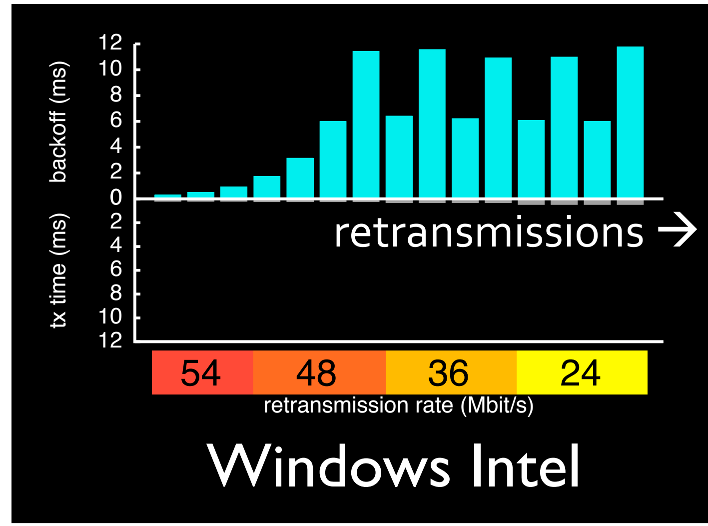
- At **high BER:** Maranello outperforms Reed-Solomon based approach
- Additional Reed-Solomon parity bits contain information about the **entire packet, inefficient** if errors are localized to a single block(s)

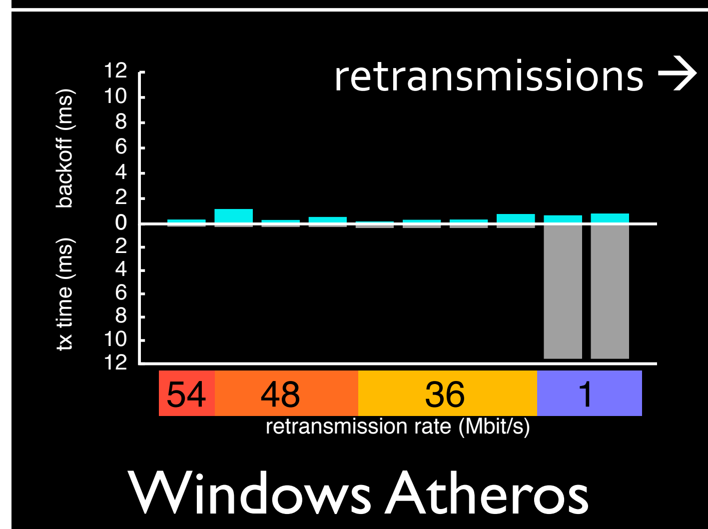
Retransmission behavior varies across hardware

- **Backoff** and **bit rate selection** impact Maranello's performance
  - 802.11 standard **specifies backoff** (but chipsets do not always respect the standard)
  - Recall: Standard **doesn't specify bit rate selection**

- **Maranello helps Intel** because it increases delivery rate at high bitrates, avoiding backoff

- **Maranello helps Atheros** because it reduces the chance of falling back to 1 Mbit/s





Implementation: Alternatives

- Implementation in the OS kernel driver software
  - Microbenchmark shows > 70 μs ($\gg$ 10 μs SIFS time) delay between receipt of packet and triggered response, so **unsuitable**
    - CPU interrupt latency and NIC-RAM bus transfer delay
- Software-defined radio platforms (*e.g.* GNU radio)
  - **High-latency (ms)** Ethernet or USB bus makes unsuitable
- Sora software defined radio [NSDI '08]
  - Software-defined radio on PCI express bus
  - Open question as to whether Sora would work for partial packet recovery (ACKs cached in current version of Sora)

Implementation

- ***OpenFWWF*** open firmware for Broadcom 802.11 NIC
  - Publically-downloadable firmware assembly code that runs on Broadcom NIC microprocessor

- Broadcom 802.11 NIC system components:

  1. **Tx/Rx FIFO queues:** buffers frames to/from the physical layer (transmission over the air)

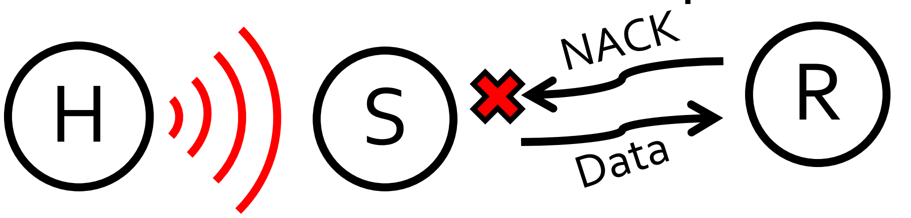
  2. **Internal shared memory:** State variables that can be read/written from the kernel driver

  3. **Template RAM:** "Scratch" memory for composing an arbitrary frame and transmitting over the air

  4. **Internal registers and external conditions:** Interface with the physical layer and timers (for, *e.g.*, backoff)

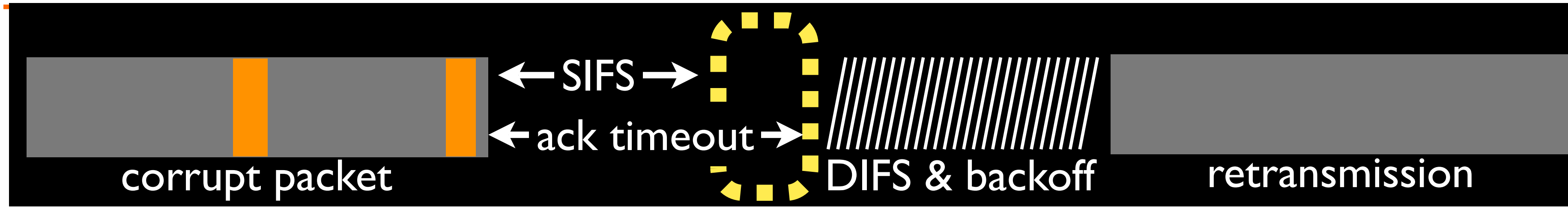
Implementation: NACK generation

- Receiver computes block checksums in firmware
- Problem: For some transmission rates, Maranello NACK airtime is greater than 802.11 ACK
  - May cause problems if hidden terminals present. *Why?*



- Data contains network allocation vector (NAV) but with a duration shorter than Maranello needs for NACK
- Solution: **No solution;** just let the collisions happen. Claim that preliminary experiments show improved overall throughput

Implementation: NACK generation



- Problem: 802.11 NIC microprocessor is **not fast enough** to compute block checksums during SIFS interval (10 μs)
  - Each block checksum takes up to 4 μs
  - But running 802.11, the microprocessor is normally **idle** during a frame reception
- Solution: Modify firmware to **copy partially-received packets into memory the microprocessor can access**
  - **Overlap** one block's block checksum computation with reception of the next block

Implementation: Sender-side

- Before the first transmission, sender pre-computes block checksums in the OS kernel driver, on the main CPU
  - Then sends block checksums to the firmware with the packet's contents
  - Why? Main CPU is more powerful, can spare the time, and block checksum computation on the sender is not time-critical (why?)

Performance evaluation

- 802.11 channels 1, 6, 11 (span the 2.4 GHz unlicensed frequency band) in **environments with background traffic**
  - **Advantage:** Characterizes performance of Maranello *in situ*
    - Evaluate in three different environments (research lab, home, university), so can claim some generality
  - **Disadvantage:** Lose repeatability of the experiment, so more difficult for the experimenters to isolate experimental factors that impact performance
- Enable Minstrel **bit rate adaptation**
  - So compare Maranello and 802.11 at or close to the best bit rate for a particular link
- Evaluate throughput, latency gains, and then drill-down for causes

Link throughput experiment

- *By how much does Maranello increase link* ***throughput****?*

- Methodology
  - Use the ***Iperf*** network measurement tool in UDP mode to saturate a wireless link in the testbed
  - A one-minute run for 802.11, then immediately afterwards, a one-minute run for Maranello
    - < 15 second gap implies wireless conditions **unlikely** to have changed
  - Repeat the experiment ten times with sender and receiver in the same locations
  - Change locations of sender and receiver, in the same testbed

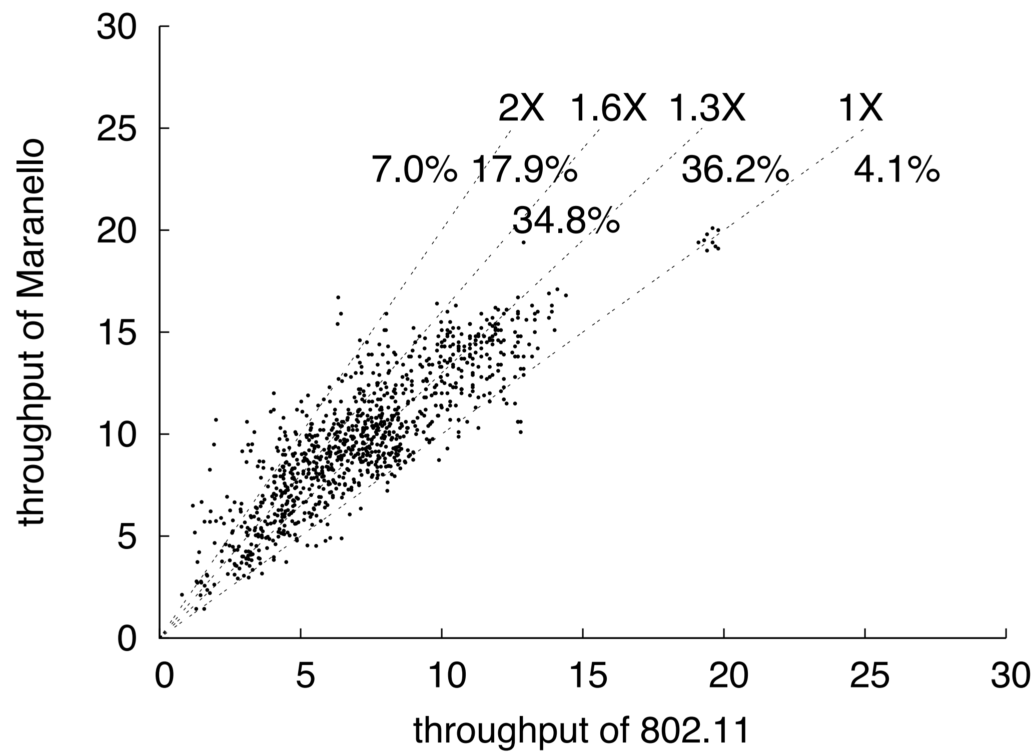
Maranello increases link throughput

- University building results
  - Best results (high channel contention)
  - Other environments qualitatively similar
  - Each point in the scatter plot represents an Iperf run

- Slanted lines delineate constant-factor gains

- Results:
  - About **one-third** of the time **little to no gain**

  - About **one-third** of the time **almost 2× gain**



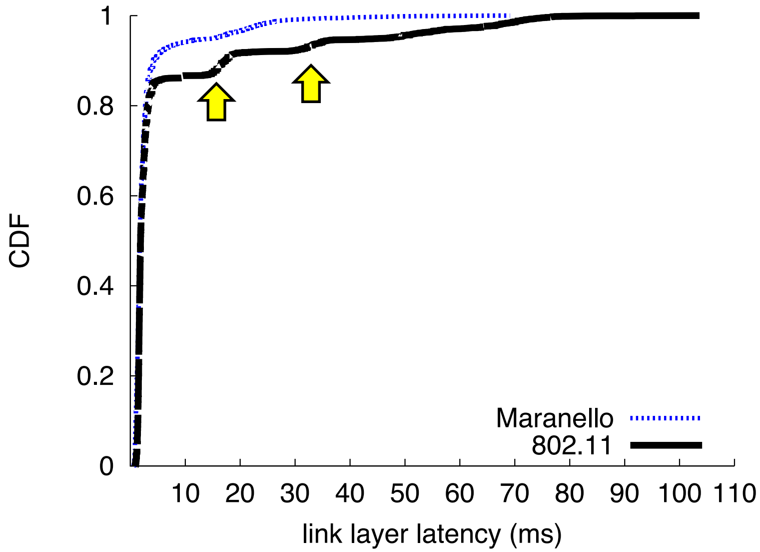
Transmission latency experiment

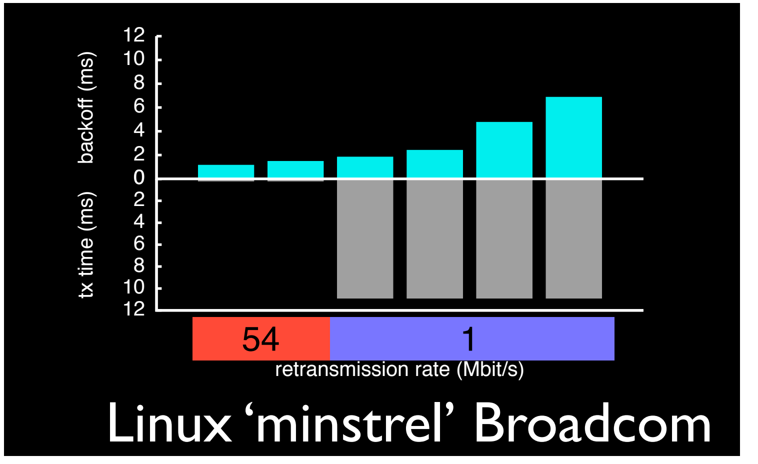
- *Does Maranello decrease the **time it takes to correctly deliver one packet** across a link?*

- Methodology
  - Measure time from the firmware **fetching a packet** from the head of the Tx FIFO queue, to **receipt of an ACK**
  - Includes retransmissions (in the case of 802.11), repair transmissions (in the case of Maranello), backoff, *etc.*
  - Firmware's microsecond timestamp counter measures this time precisely

  - **Desired:** Measure time from **fetching a packet** from the head of the Tx FIFO queue to **packet's correct reception**
    - In most cases, this would be a fixed time interval less than proposed measurement (time to deliver the ACK to sender)

Maranello decreases transmission latency

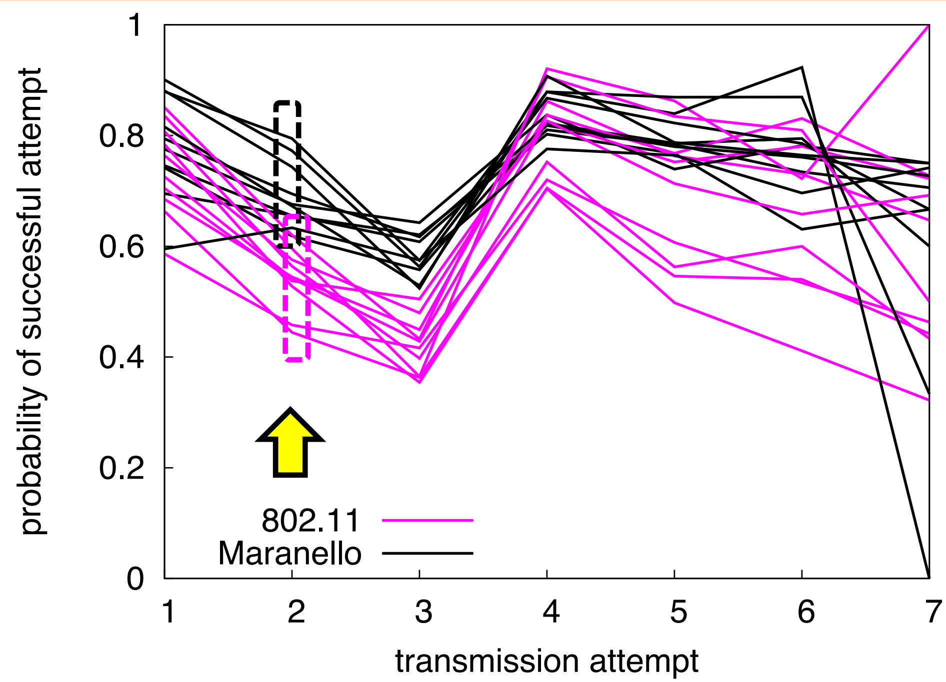




- Latency for packets that need one or more retransmissions
- One pair of sender, receiver locations
- 802.11 modes at 16 and 32 ms represent **Minstrel 1 Mbit/s fallback**
- A log scale on the x-axis would show more detail at lower latencies
  - Possibly showing the high-rate retransmissions

Source of Maranello's improvements

- Measure **delivery probability of each transmission attempt**
  - **Higher** delivery probability → **higher** throughput, **lower** latency
- Note: this graph counts **transmissions** (including first transmission)
- Attempt #1: Roughly equal between 802.11, Maranello (both just send the original packet)



- Attempts #2, #3: Both 802.11 and Maranello maintain bit rate
  - But, Maranello sends a **shorter repair packet**
  - Shorter packet has a **lesser chance of being lost**
- Minstrel **fallback to 1 Mbit/s** on attempt #4 increases delivery probability
  - Maranello still sending shorter repair packets

Frame aggregation and optimal block size

- 802.11 **frame aggregation**
  - As bit rates increase, relative overhead of DIFS, backoff, headers, and ACK increases
  - 802.11n, 802.11ac **aggregate** many frames together
    - Each frame gets own checksum (like "block checksum" approach)
  - Aggregation **increases latency**
  - Maranello is **complementary with aggregation:** can repair corrupted aggregates

- Optimal Maranello **block size**
  - Larger block size would be less efficient on wireless channel but more computationally efficient
  - Can dynamically vary the block size based on BER

Further reading

- ZipTx: Harnessing Partial Packets in 802.11 Networks. Kate Ching-Ju Lin, Nate Kushman, Dina Katabi. Proceedings of MobiCom 2008
  - A practical implementation and evaluation of the forward error correction approach to the problem of partially-received packets
- Beyond the Bits: Cooperative Packet Recovery using Physical Layer Information (SOFT). Grace Woo, Pouya Kheradpour, Dawei Shen, Dina Katabi. Proceedings of MobiCom 2007.
- Datalink Streaming in Wireless Sensor Networks (Seda). Raghu Ganti, Praveen Jayachandran, Haiyun Luo, and Tarek Abdelzaher. Proceedings of Sensys 2006.
- Fast Resilient Jumbo Frames in Wireless LANs. Iyer et al., Proceedings of IWQoS 2009.
- Sora: High Performance Software Radio using General Purpose Multi-core Processors. Tan et al., Proceedings of USENIX NSDI 2009.