A glimpse into the Linux Wireless Core: From kernel to firmware

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Outline

- Linux Kernel Network Code
  - Modular architecture: follows layering
- Descent to (hell?) layer 2 and below
  - Why hacking layer 2
  - OpenFirmWare for WiFi networks
- OpenFWWF: RX & TX data paths
- OpenFWWF exploitations
  - TCP Piggybacking
  - Partial Packet Recovery

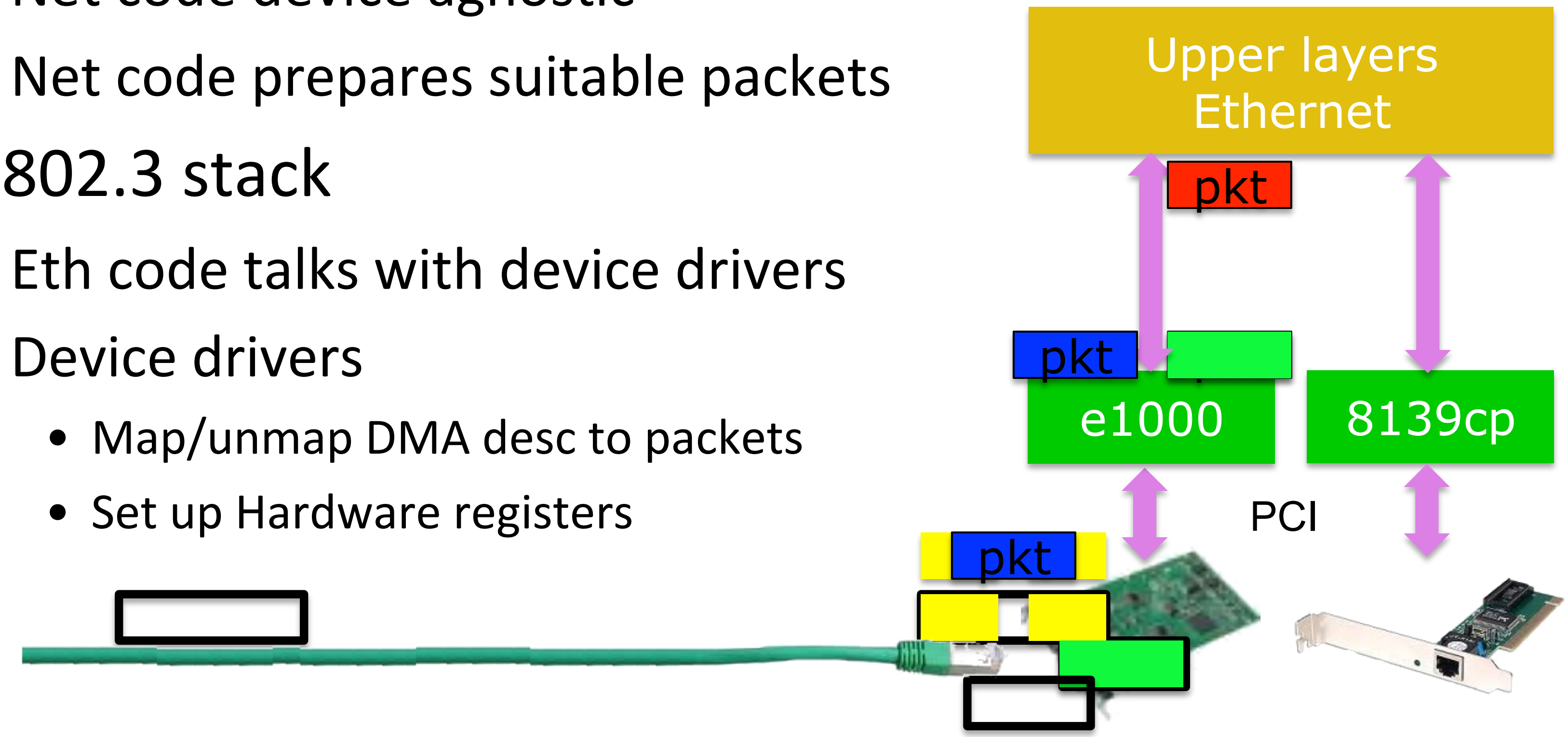
Linux Kernel Network Code

A glimpse into the
Linux Kernel Wireless Code

Part 1

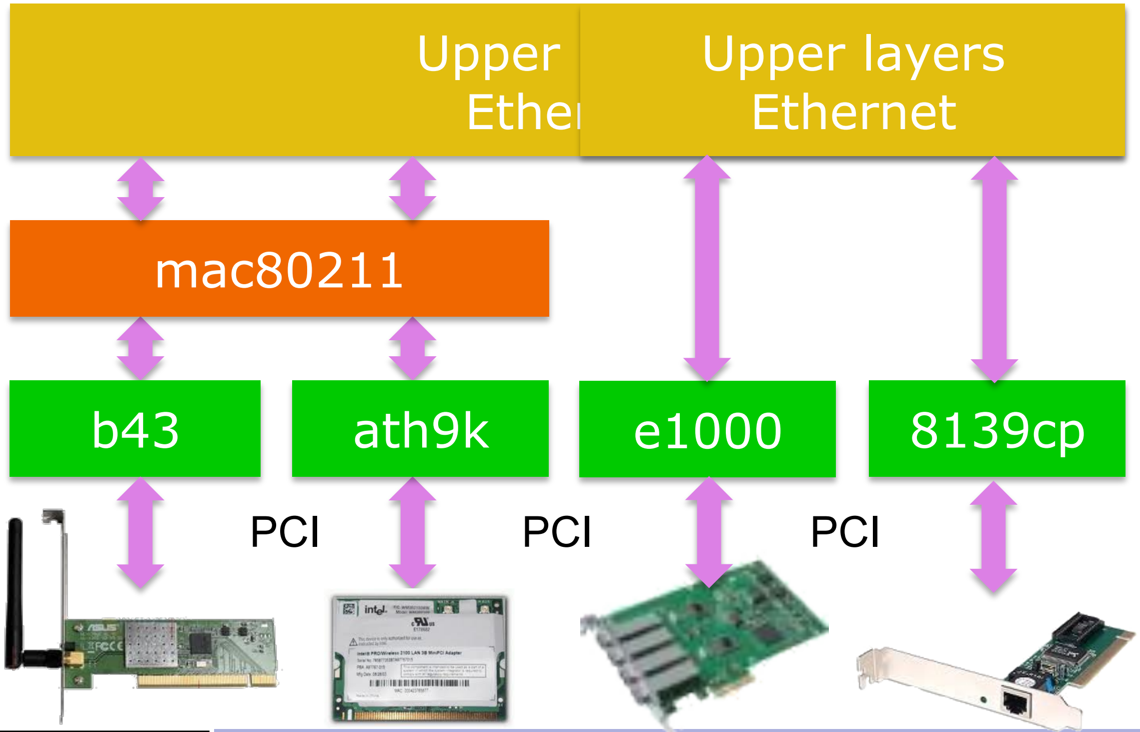
Linux Networking Stack
Modular architecture

- Layers down to MAC (included)
  - All operations above/including layer 2 done by kernel code
  - Net code device agnostic
  - Net code prepares suitable packets
- In 802.3 stack
  - Eth code talks with device drivers
  - Device drivers
    - Map/unmap DMA desc to packets
    - Set up Hardware registers



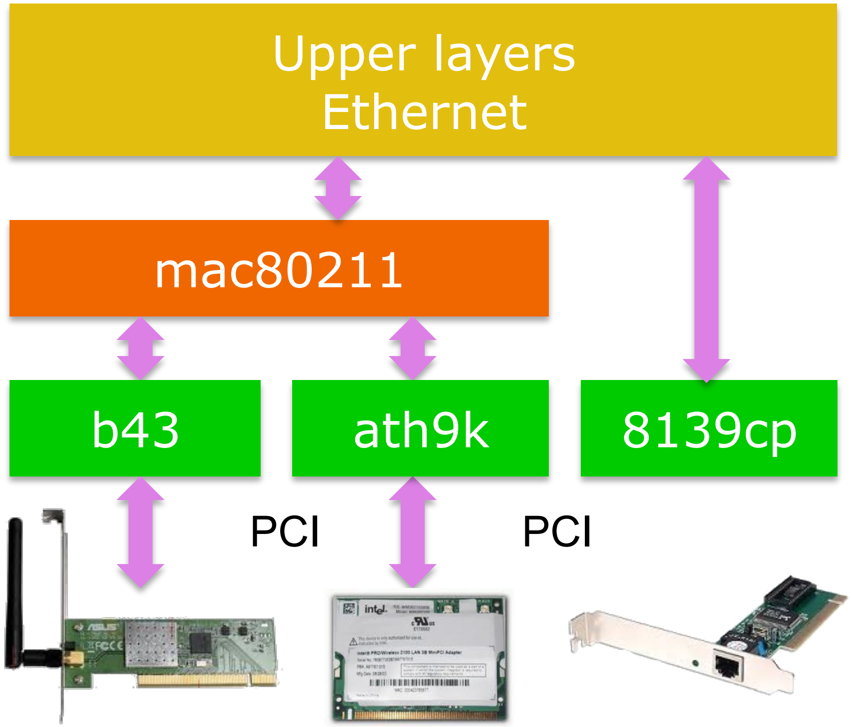
Linux Networking Stack
Modular architecture

- What happens with 802.11?
  - New drivers to handle WiFi HW: how to link to net code?
  - A wrapper "mac80211" module is added



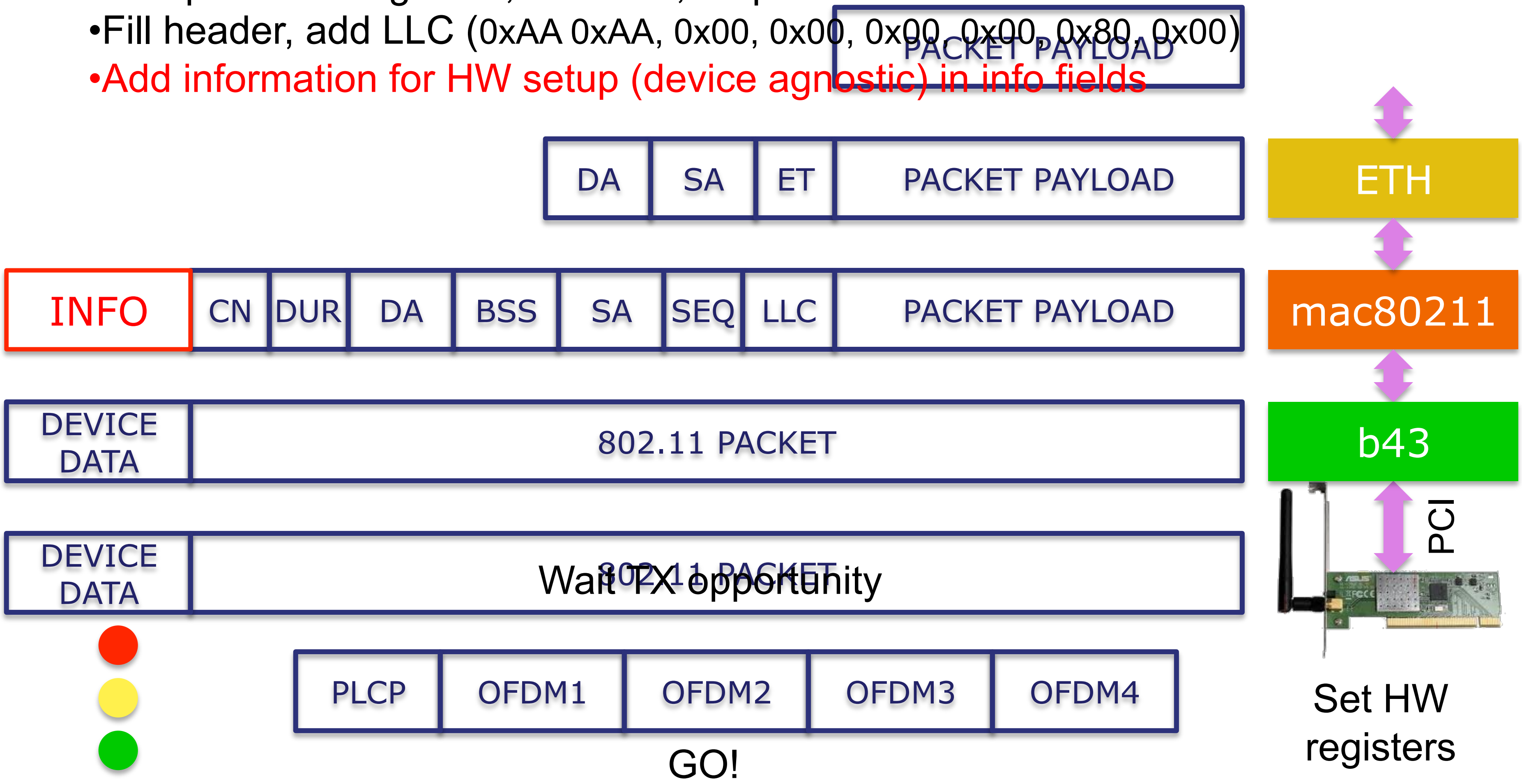
Linux & 802.11
Modular architecture

- Layers down to LLC (~mac) common with 802.3
  – All operations above/including layer 2 done by ETH/UP code
- Packets converted to 802.11 format for rx/tx
  – By wrapper "mac80211"
    - Manage packet conversion
    - Handle AAA operations
- Drivers: packets to devices
  – One dev type/one driver
    - Add data to "drive" the device



Linux & 802.11 Modular architecture/1

- Convert agnostic info into device dependent data
- Fetch from the egress device data the source address
- Compute Control Word, Duration, sequence number
- Fill header, add LLC (0xAA 0xAA, 0x00, 0x00, 0x00, 0x00, 0x80, 0x00)
- Add information for HW setup (device agnostic) in info fields

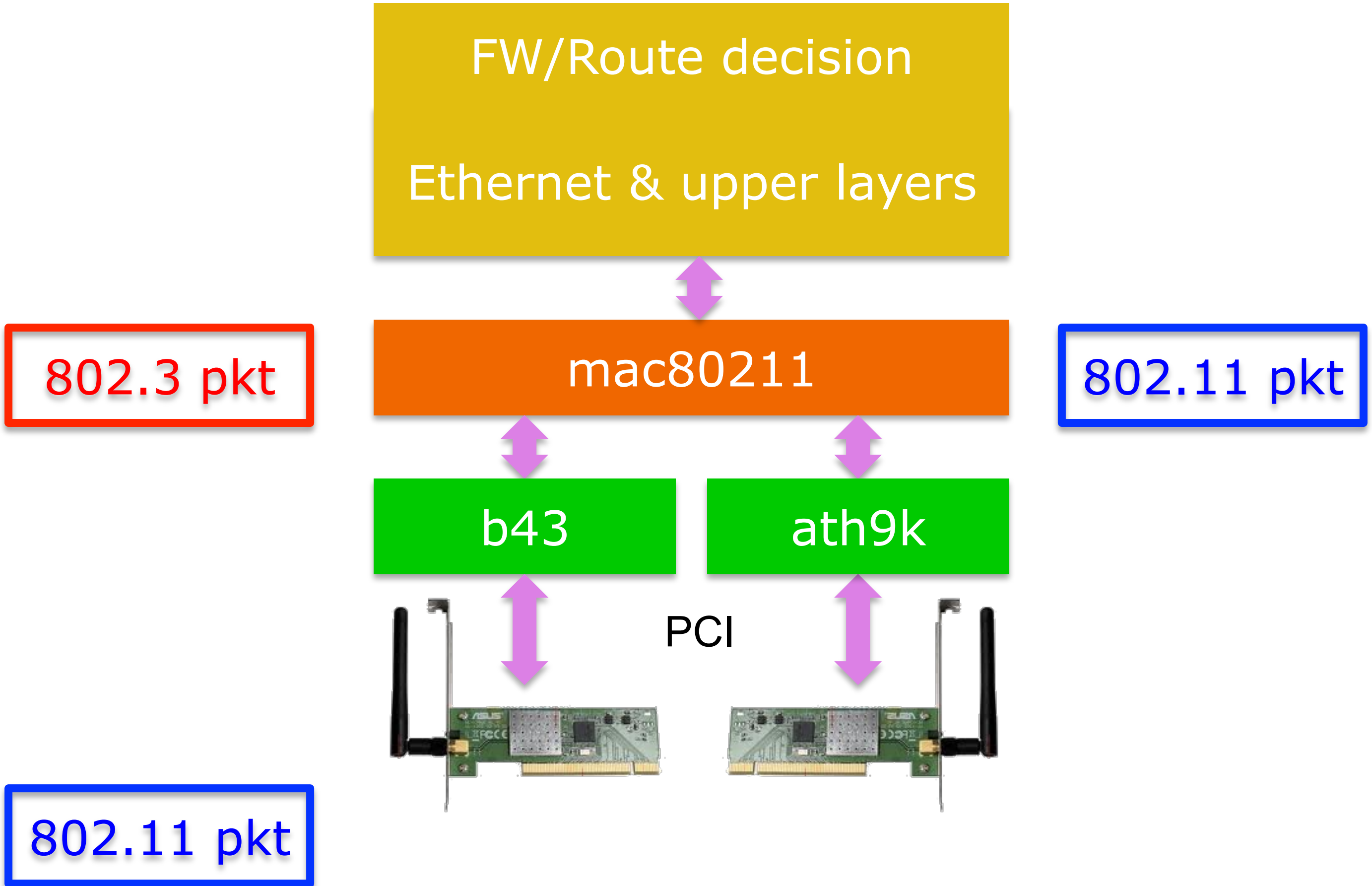


Linux & 802.11

- Opposite path: conversions reversed
- ☹ Several operations involved for each packet
- ☺ Multiple buffer copies (should be) avoided
  - E.g., original packet at layer 4 correctly allocated
    - Before L3 encapsulation output device already known
- ☹ Packets are queued twice
  - Qdisc: before wrapper
  - Device queues: between wrapper and driver
- Bottom line:
  - Clean design but can be resource exhausting

Linux & 802.11
Modular architecture

- Forwarding/routing packet on a double interface box



Linux & 802.11

- On CPU limited platform, fw performance too low
  - Need to accelerate/offload some operations
- Ralink was first to introduce SoC WiFi devices
  - A mini-pci card hosts an ARM CPU
  - Main host attaches a standard ethernet iface
  - The ARM CPU converts ETH packet to 802.11
  - Main host focuses on data forwarding
- Question: where can be profitably used?

Linux & 802.11: setup

- A simple BSS in Linux
  - One station runs hostapd (AP)
  - Others join (STAs): wpa_supplicant keeps joining alive
    - Why? Kernel (STA) periodically checks if AP is alive
    - If management frames lost, kernel (STA) does not retransmit!
    - A supplicant is needed to re-join the BSS
  - In following experiments we fix arp associations

```
$: ip neigh replace to PEERIP lladdr PEERMAC dev wlan0
```

  - Traffic not encrypted
  - QoS disabled

Linux & 802.11: kernel setup

- Check the device type with

```
$: lspci | grep –i net
```

- Load the driver for Broadcom devices

```
$: modprobe b43 qos=0
```

- Check kernel ring buffer with

```
$: dmesg | tail -30
```

- Check which other modules loaded

```
$: lsmod | grep b43
```

- Bring net up and configure an IP address

```
$AP: ifconfig wlan0 192.168.1.1 up
$STA: ifconfig wlan0 192.168.1.10 up
```

Linux & 802.11: hostapd setup

- Configuration of the AP in "hostapd.conf"

```
interface=wlan0
driver=nl80211
dump_file=/tmp/hostapd.dump
ctrl_interface=/var/run/hostapd
ssid=NOISE-B43
hw_mode=g
channel=1
beacon_int=100
auth_algs=3
wpa=0
```

Try to send SIGUSR1

PIPE used by

BSS properties

No encryption/ authentication

- Runs with

```
$: hostapd -B hostapd.conf
```

- Check dmesg!

Linux & 802.11: station setup

- Configuration of STAs in

```
ctrl_interface=/var/run/wpa_supplicant
network={
        ssid="NOISE-B43"
        scan_ssid=1
        key_mgmt=NONE
}
```

BSS to join

- Runs with

```
$: wpa_supplicant -B -i wlan0 -c wpa_supp.conf
```

- Check dmesg!
- **Simple experiment: ping the AP**

```
$: ping 192.168.1.1
```

- **Simple experiment (continued): try capture traffic**

Linux & 802.11: capturing packets

- On both AP and STA run "tcpdump"

```
$: tcpdump -i wlan0 -n
```

- Is exactly what we expect?
  - What is missing?
  - Layer 2 acknowledgment?
- Display captured data

```
$: tcpdump -i wlan0 -n -XXX
```

- What kind of layer 2 header?
- What have we captured?

Linux & 802.11: capturing packets

- Run "tcpdump" on another station set in monitor mode

```
$: ifconfig wlan0 down
$: iwconfig wlan0 mode monitor chan 4(?)
$: ifconfig wlan0 up
$: tcpdump -i wlan0 –n
```

- What's going on? What is that traffic?
  - Beacons (try to analyze the reported channel, what's wrong?)
  - Probe requests/replies
  - Data frames
- Try to dump some packet's payload
  - What kind of header?
  - Collect a trace with tcpdump and display with Wireshark

Linux & 802.11: capturing packets

- Exercise: try to capture only selected packets
- Play with matching expression in tcpdump

```
$: [cut] ether[N] ==|!= 0xAB
```

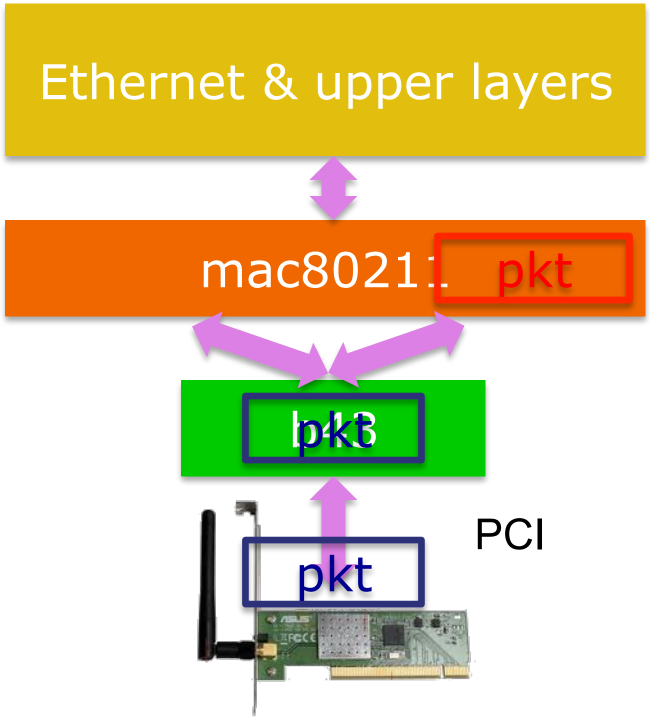
- Discard beacons and probes
- Display acknowledgments
- Display only AP and STA acknowledgments
- Question: is a third host needed?

Virtual Interfaces

- Wrapper/driver "may agree" on virtual packet path
  - Each received packet duplicated by the driver
  - mac80211 creates many interfaces "binded" to same HW
  - In this example
    - Monitor interface attached
    - Blue stream follow upper stack
    - Red stream hooked to pcap

```
$: iw dev wlan0 interface add \
           fish0 type monitor
```

  - Try capturing packets on the AP
    - What's missing?



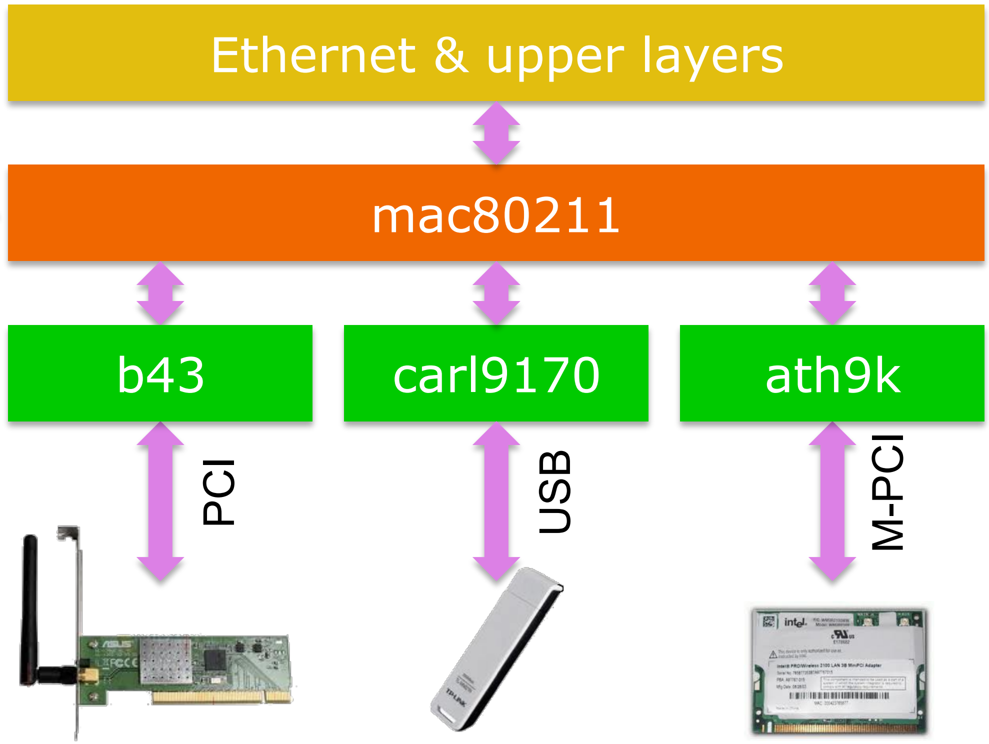
Descent to layer 2 and below
An open firmware

A glimpse into the
Linux Kernel Wireless Code

Part 2

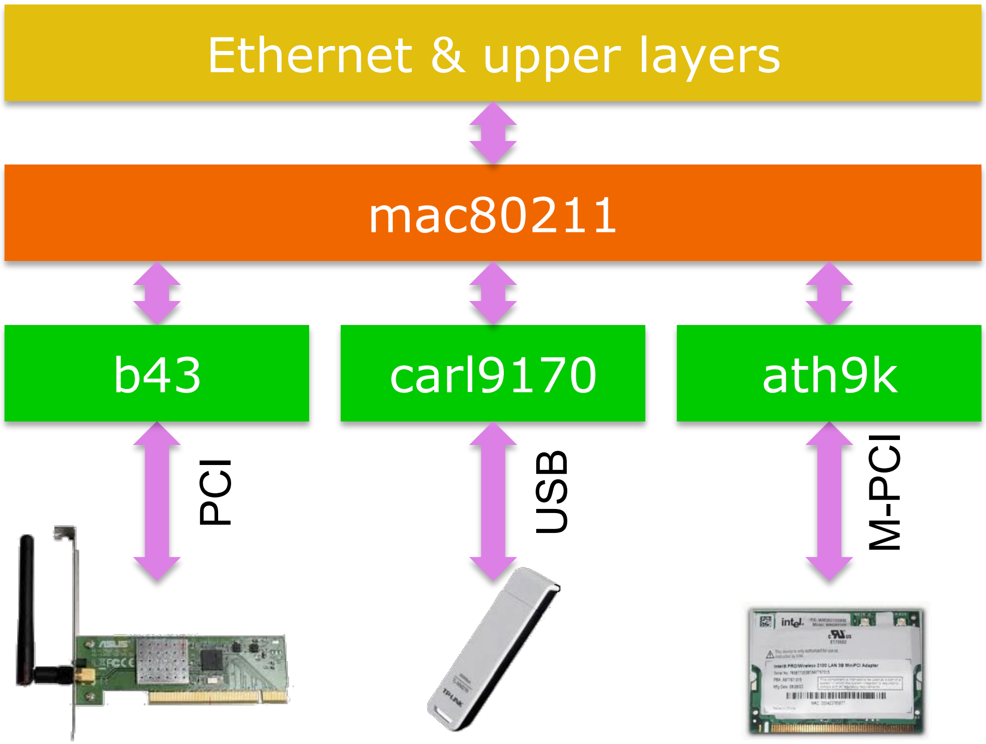
Linux & 802.11
Modular architecture

Wrapper for all hw
Find interface;
remove eth head;
add LLC&dot11 head;
fill (sa;da;ra;seq);
fill(control;duration);
set rate (from RC);
fill (rate;fallback);



Linux & 802.11
Modular architecture/2

Set up hw regs;
Fill hw private fields;
Send frame on DMA;
Get stats;
Reports to mac80211
Several MAC primitives missing!
Who takes care of ack?



Linux & 802.11
Modular architecture/3

Ethernet & upper layers

For sure

We will hack the firmware today but first…
Let's check why we should do that ☺

Firmware does

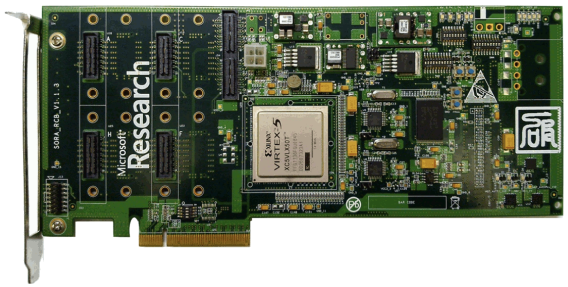


Why/how playing with 802.11

- Radio access protocols: issues
  - Some are unpredictable: noise & intf, competing stations
- Experimenting with simulators (e.g., ns-3)
  - Captures all “known” problems
    - Testing changes to back-off strategy is possible ☺
  - Unknown (not expected)?
    - Testing how noise affects packets not possible ☹
- **In the field testing is mandatory**
  - Problem: one station is not enough!

Programmable Boards

- Complete platforms like
  - WARP: Wireless open-Access Research Platform
  - Based on Virtex-5
  - Everything can be changed
    - PHY (access to OFDM symbols!)
    - MAC
  - Two major drawbacks
    - More than very expensive
    - Complex deployment
  - **If PHY untouched: look for other solutions!**

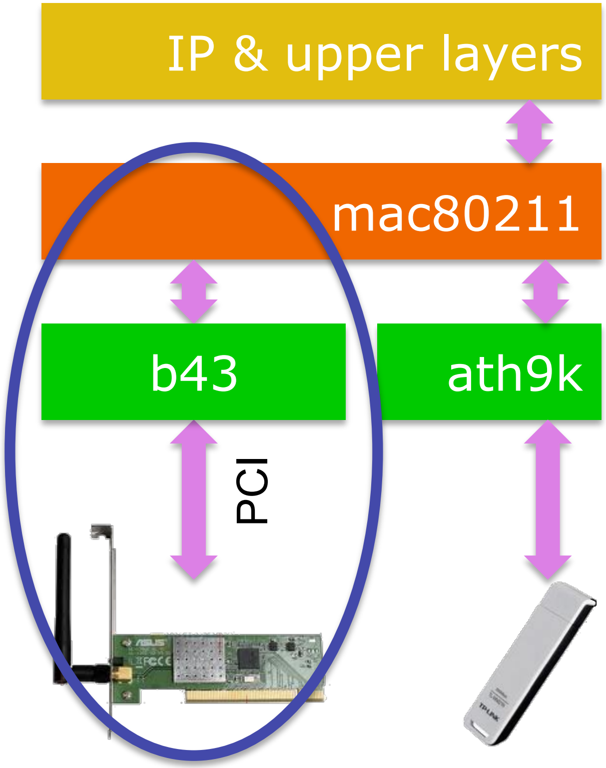


Off-the-shelf hardware

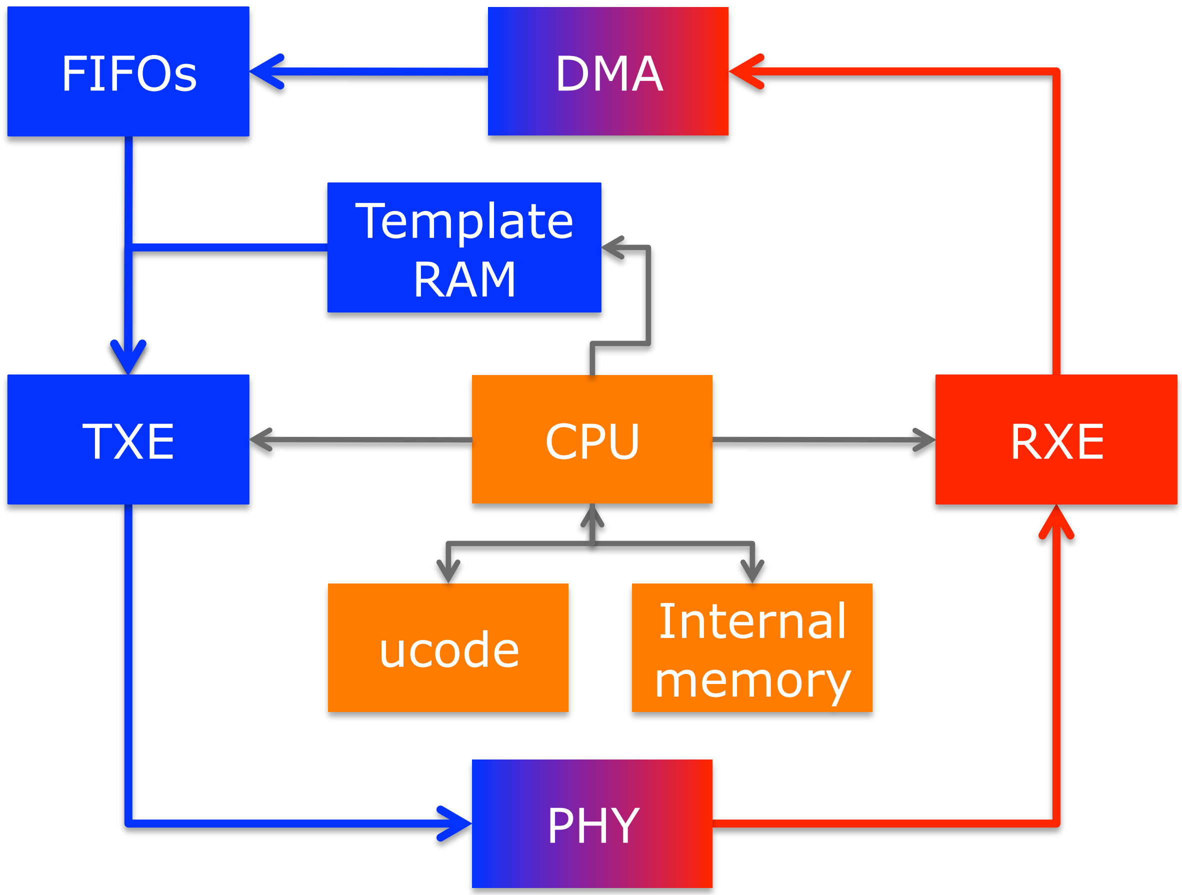
- Five/Six vendors develop cheap WiFi hw
  - Hundreds different boards
  - Almost all boards load a binary firmware
    - MAC primitives driven by a programmable CPU
  - Changing the firmware → Changing the MAC!
- Target platform:
  - Linux & 802.11: modular architecture
  - Official support prefers closed-source drivers ☹
  - Open source drivers && Good documentation
    - Thanks to community! ☺

Linux & 802.11 Broadcom AirForce54g

- Architecture chosen because
  - Existing asm/dasm tools
    - A new firmware can be written!
  - Some info about hw regs
- We analyzed hw behavior
  - Internal state machine decoded
  - Got more details about hw regs
  - Found timers, tx&rx commands
  - Open source firmware for DCF possible
- We released OpenFWWF!
  - OpenFirmWare for WiFi networks



Broadcom AirForce54g
Basic HW blocks



Description of the HW

- CPU/MAC processor capabilities
  - 8MHz CPU, 64 general purpose registers
- Data memory is 4KB, direct and indirect access
  - From here on it's called Shared Memory (SHM)
- Separate template memory (arrangeable > 2KB)
  - Where packets can be composed, e.g., ACKs & beacons
- Separate code memory is 32KB (4096 lines of code)
- Access to HW registers, e.g.:
  - Channel frequency and tx power
  - Access to channel transmission within N slots, etc…

TX side

- Interface from host/kernel
  - Six independent TX FIFOs
  - DMA transfers @ 32 or 64 bits
  - HOL packet from each FIFO
    - can be copied in data memory
      - Analysis of packet data before transmission
      - Kernel appends a header at head with rate, power etc
    - can be transmitted “as is”
    - can be modified and txed, direct access to first 64 bytes

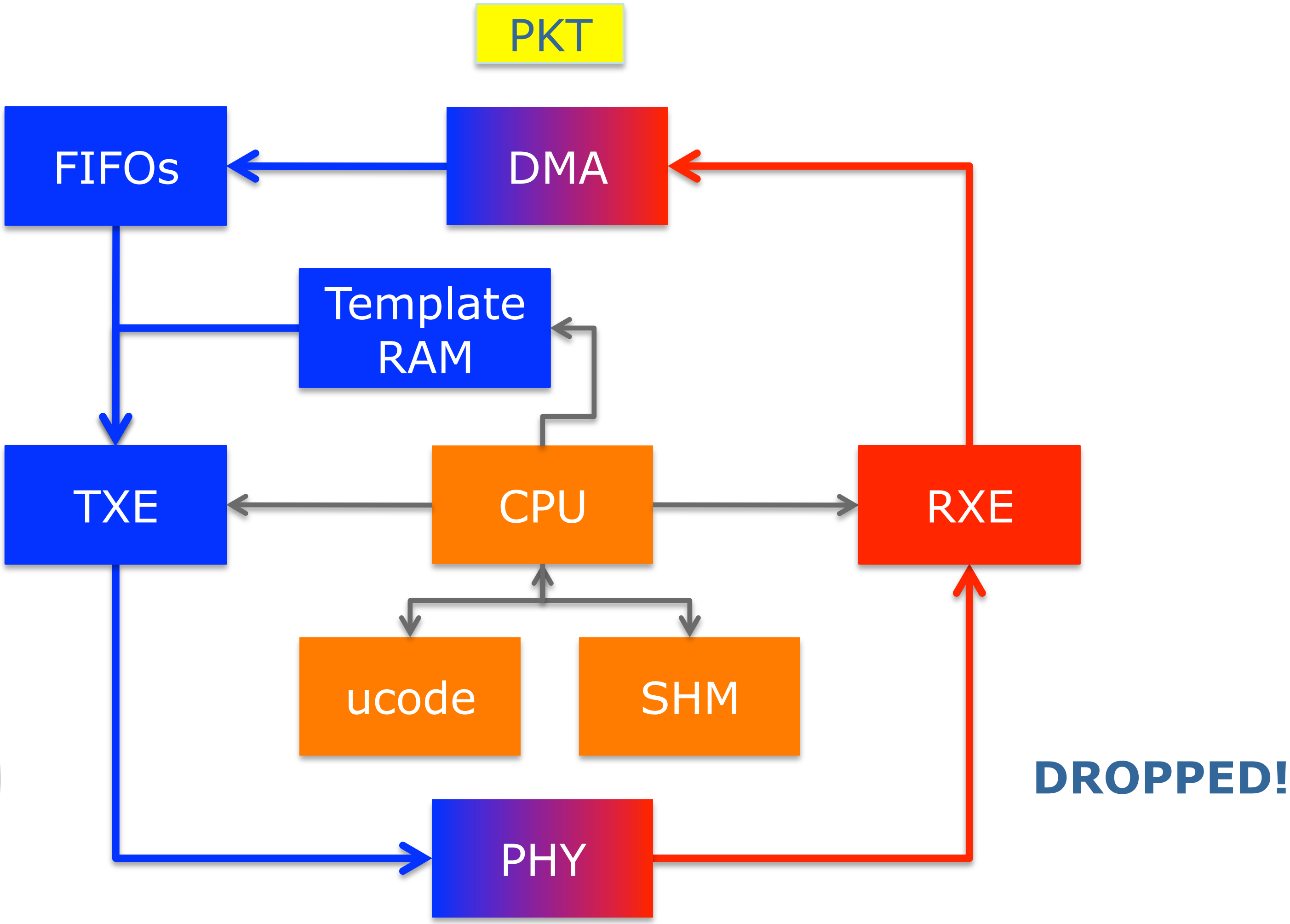
TX side/2

- Interface to air
  - Only 802.11 b/g supported, soon n
  - Full MTU packets can be transmitted (~2300bytes)
    - If full packet analysis is needed, analyze block-by-block
  - All 802.11 timings supported
    - Minimum distance between Txed frames is 0us
      - Note: channel can be completely captured!!
  - Backoff implemented in software (fw)
    - Simply count slots and ask the HW to transmit

RX side

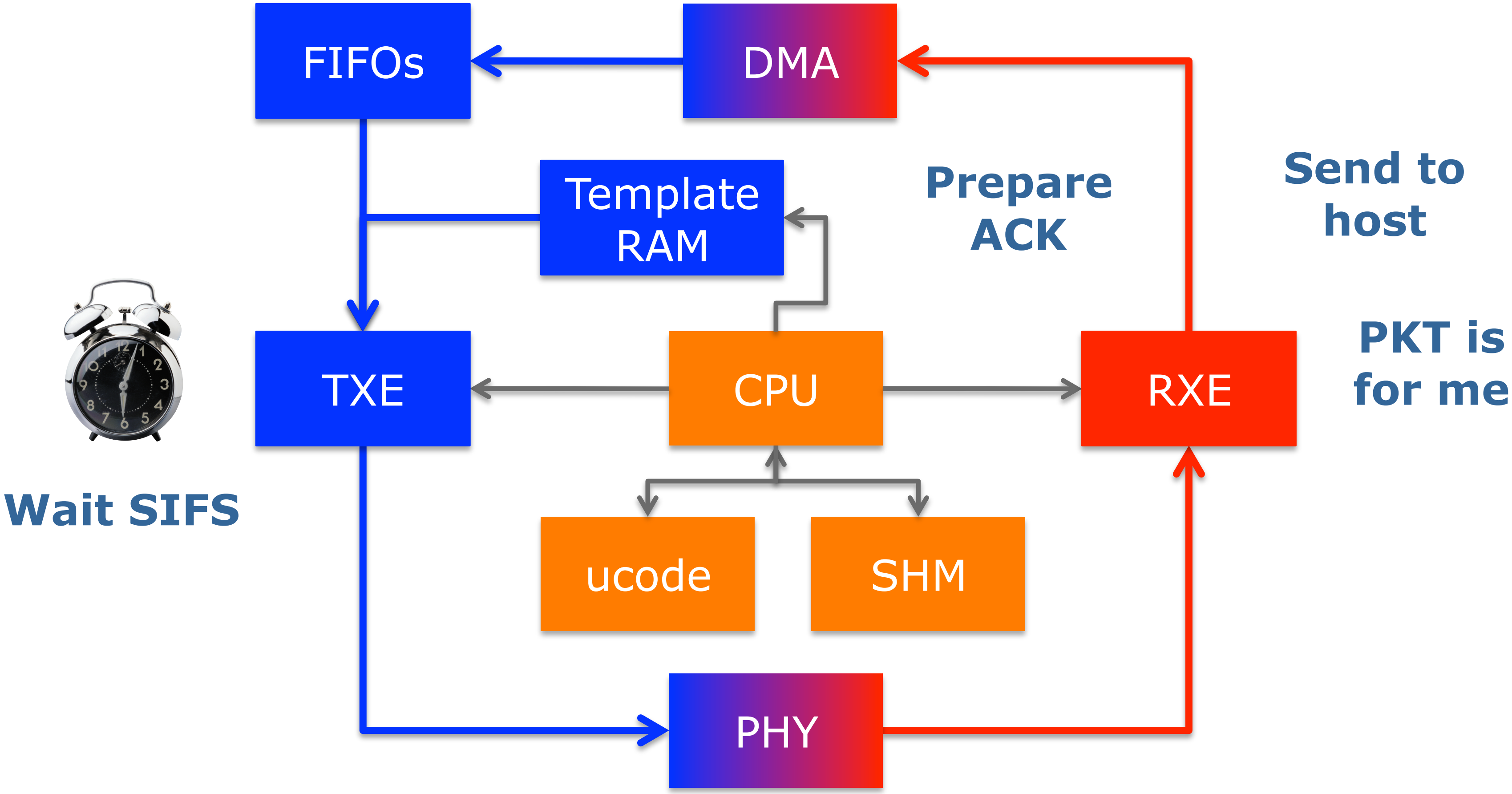
- Interface from AIR
  - HW acceleration for
    - PLCP and global packet FCS - Destination address matching
  - Packet can be copied to internal memory for analysis
    - Bytes buffered as soon as symbols is decoded
  - During reception and copying CPU is idle!
    - Can be used to offload other operations
  - Packets are pushed to host/kernel
    - If FW decides to go and through one FIFO ONLY
    - May drop! (e.g., corrupt packets, control…)

Example:
TX a packet, wait for the ACK



ACK

Example: RX a packet, transmit an ACK



What lesson we learned

- From the previous slides
  - Time to wait ack (success/no success)
  - Dropping ack (rcvd data not dropped, goes up)
  - And much more
    - When to send beacon
    - Backoff exponential procedure and rate choice
  - Decided by MAC processor (by the firmware)
- Bottom line:

Hardware is (almost) general purpose

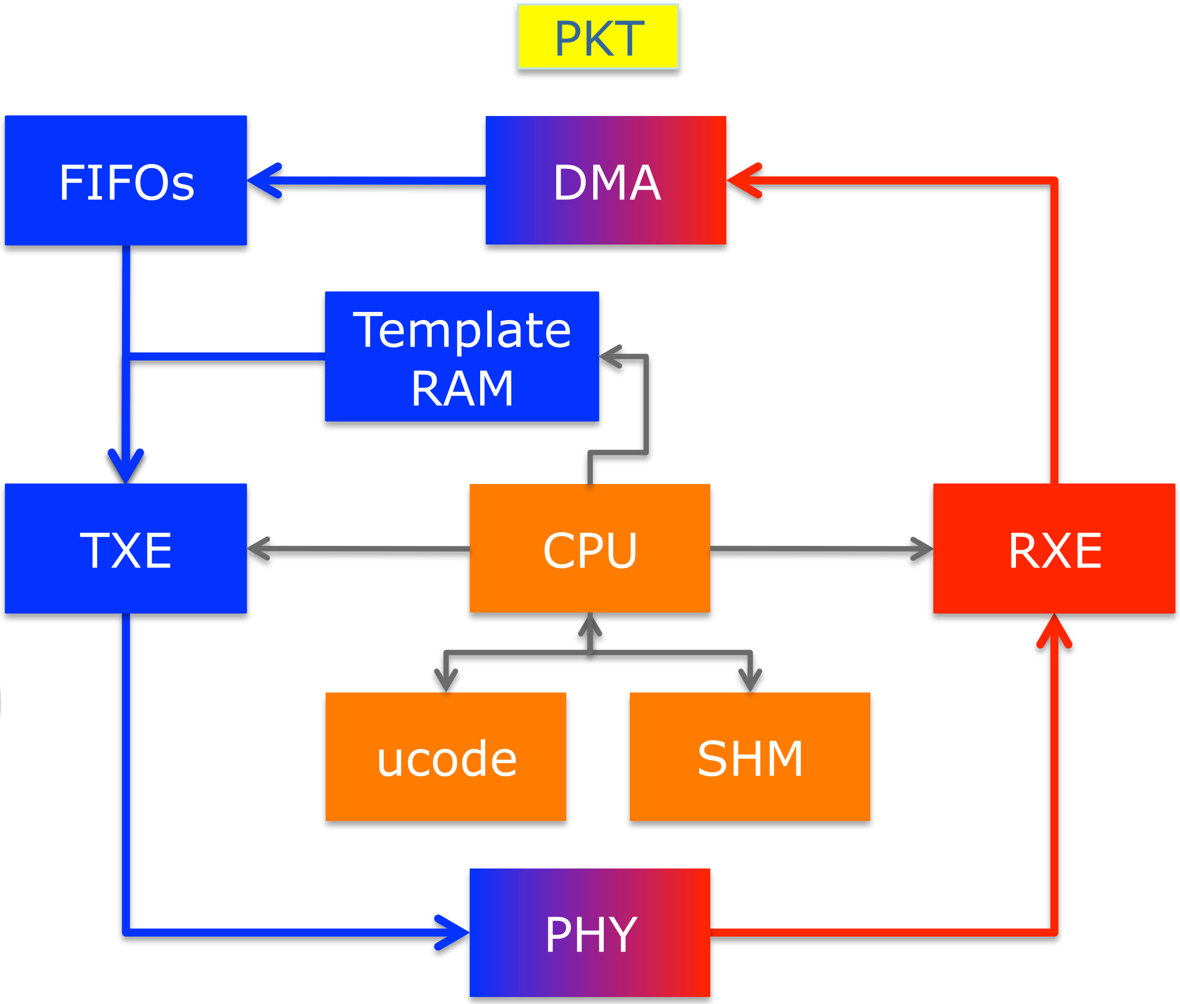
From lesson to OpenFWWF Description of the FW

- OpenFWWF
  - It's not a production firmware
  - It supports basic DCF
    - No RTS/CTS yet, No QoS, only one queue from Kernel
  - Full support for capturing broken frames
  - It takes 9KB for code, it uses < 200byte for data
    - **We have lot of space to add several features**
- Works with 4306, 4311, 4318 hw
  - Linksys Routers supported (e.g., WRT54GL)

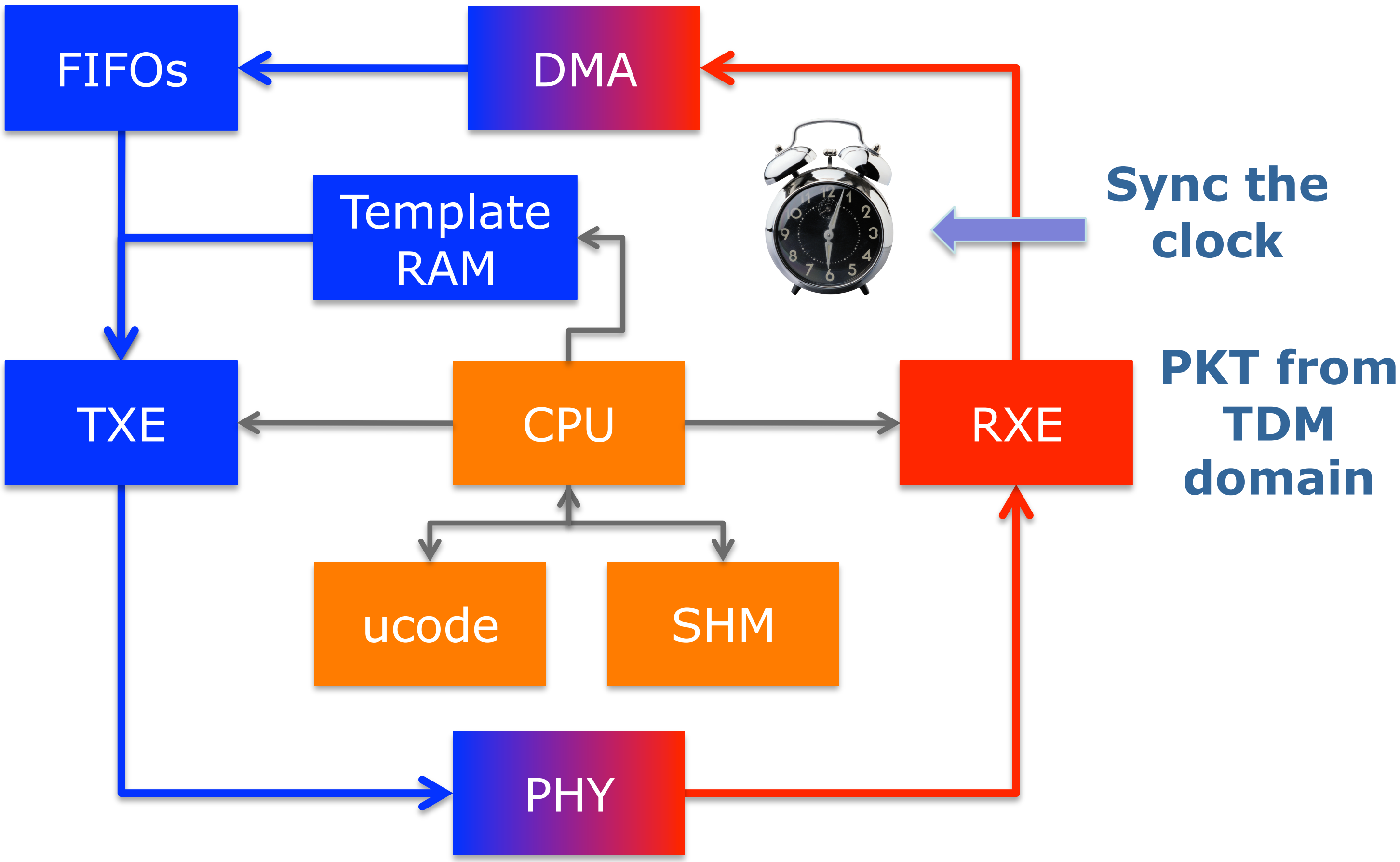
Broadcom AirForce54g
Simple TDM

TDM needed! Waiting turn

GO!



Broadcom AirForce54g
Simple TDM/2



OpenFWWF
RX & TX data paths

A glimpse into the
Linux Kernel Wireless Code

Part 3

Firmware in brief

- Firmware is really complex to understand ☹
  - Assembly language
    - CPU registers: 64 registers [r0, r1, …, r63]
    - SHM memory: 4KB of 16bits words addressable as [0x000] -> [0x7FF]
    - HW registers: spr000, spr001, …, spr1FF
  - Use `#define` macro to ease understanding
    - `#define CUR_CONTENTION_WIN r8`
    - `#define SPR_RXE_FRAMELEN spr00c`
    - `#define SHM_RXHDR SHM(0xA88)`
      - `SHM(.)` is a macro as well that divides by 2
  - Assignments:
    - Immediate mov 0xABBA, r0; // load 0xABBA in r0
    - Memory direct mov [0x0013], r0; // load 16bit @ 0x0026 (LE!)

Firmware in brief/2

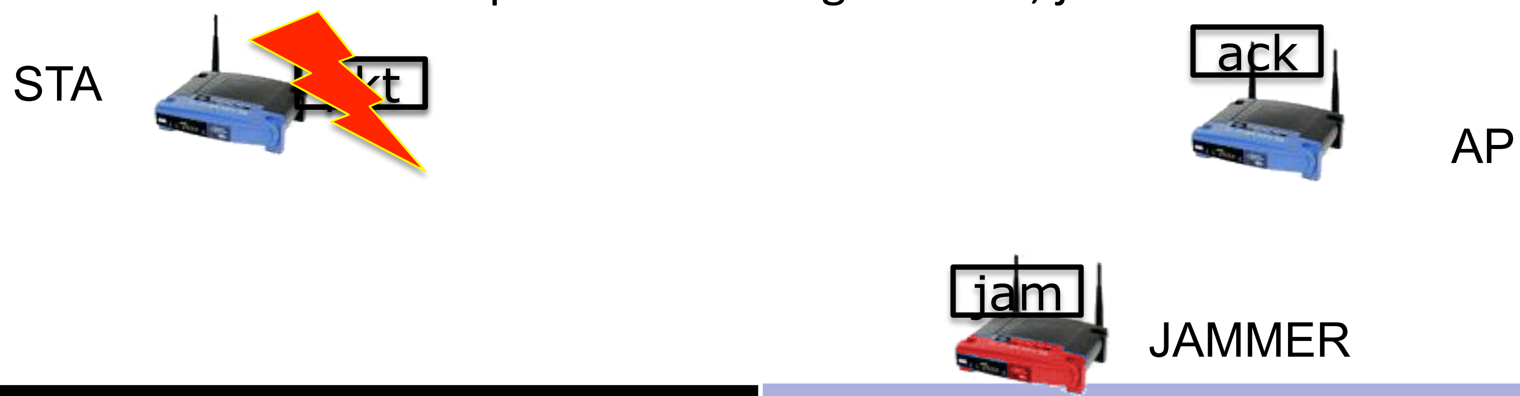
- Value manipulation:
  - Arithmetic:
    - Sum: `add r1, r2, r3;` // r3 = r1 + r2
    - Subtraction: `sub r2, r1, r3;` // r3 = r2 - r1
  - Logical:
    - Xor: `xor r1, r2, r3;` // r3 = r1 ^ r2
  - Shift:
    - Shift left: `sl r1, 0x3, r3;` // r3 = r1 << 3
- Pay attention:
  - In 3 operands instruction, immediate value in range [0..0x7FF]
  - Value is sign extended to 16bits

Firmware in brief/3

- Code flow execution controlled by using jumps
  - Simple jumps, comparisons
    - Jump if equal: `je r2, r5, loop;` // jump if r2 == r5
    - Jump if less: `jl r2, r5, exit;` // jump if r2 < r5 (unsigned)
  - Condition register jumps: jump on selected CR (condition registers)
    - on plcp end: `jext COND_RX_PLCP, rx_plcp;`
    - on rx end: `jext COND_RX_COMPLETE, rx_complete;`
    - on good frame: `jext COND_RX_FCS_GOOD, frame_ok;`
    - unconditionally: `jext COND_TRUE, loop;`
  - A check can also clean a condition, e.g.,
    - `jext EOI(COND_RX_PLCP), rx_plcp;` // clean CR bit before jump
  - Call a code subsection, save return value in link-registers (lr):
    - `call lr0, push_frame;` // return with `ret lr0, lr0;`

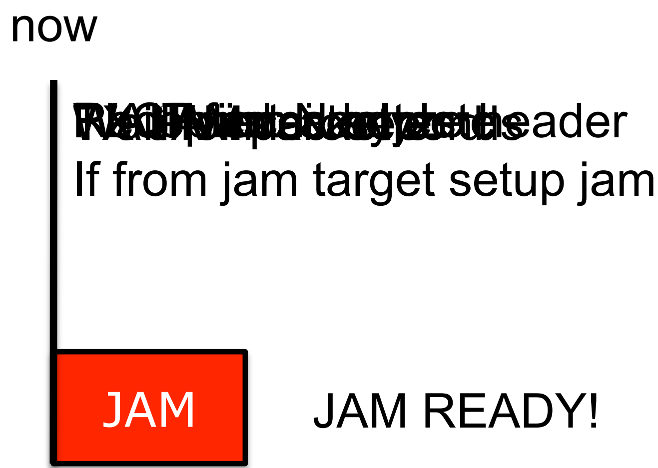
Firmware in brief/4

- OpenFWWF is today ~ 1000 lines of code
  - Not possible to analyze in a single lesson
  - We will analyze only some parts
- A simple exercise:
  - Analyze quickly the receiver section
  - Propose changes to implement a jammer
    - When receives packets from a given STA, jams noise!

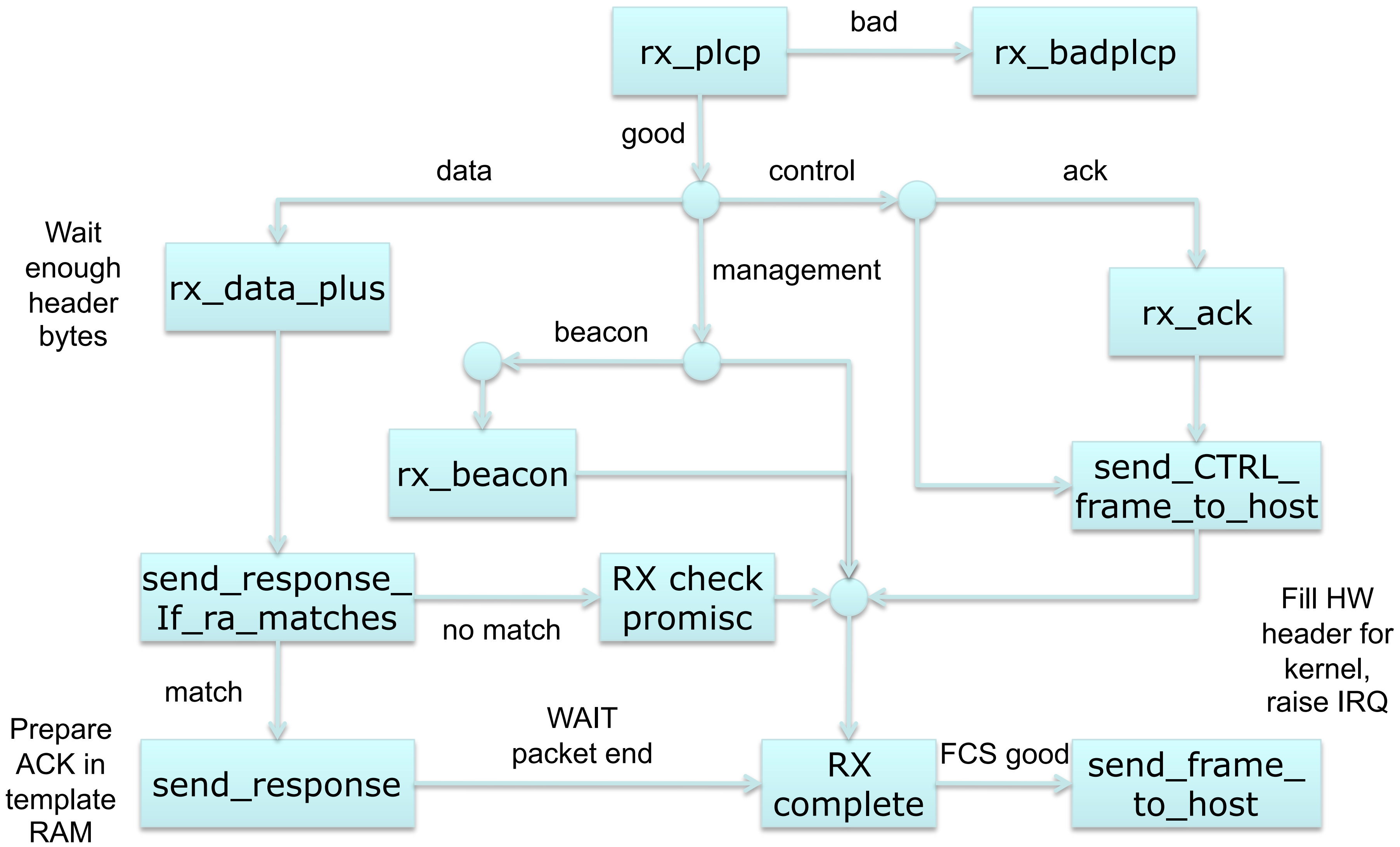


RX code made easy

- During reception CPU keeps on running
  - Detect end of PLCP
  - May wait for a given number of bytes received
  - May prepare a response frame (ACK)
  - Wait for end of reception
  - May schedule response frame transmission after a while



RX code made easy/2



RX code made easy/3

- During reception
  - CR RX_PLCP set when PLCP is completely received
  - CR COND_RX_BADPLCP set if PLCP CRC went bad
  - SPR_RXE_FRAMELEN hold the number of already received bytes
  - First 64B of packet are copied starting at `SHM_RXHEADER = SHM(0x908)`
    - First 6B hold the PLCP
  - CR COND_RX_COMPLETE set when packet is ready
- We can have a look at the code flow for a data packet
  - rx_plcp: checks it's a data packet
  - rx_data_plus: checks packet is longer than 0x1C = 6(PLCP)B + 22(MAC)B
  - send_response: copy src mac address to ACK addr1, set state to TX_ACK
  - rx_complete: schedule ACK transmission

RX code made easy/4

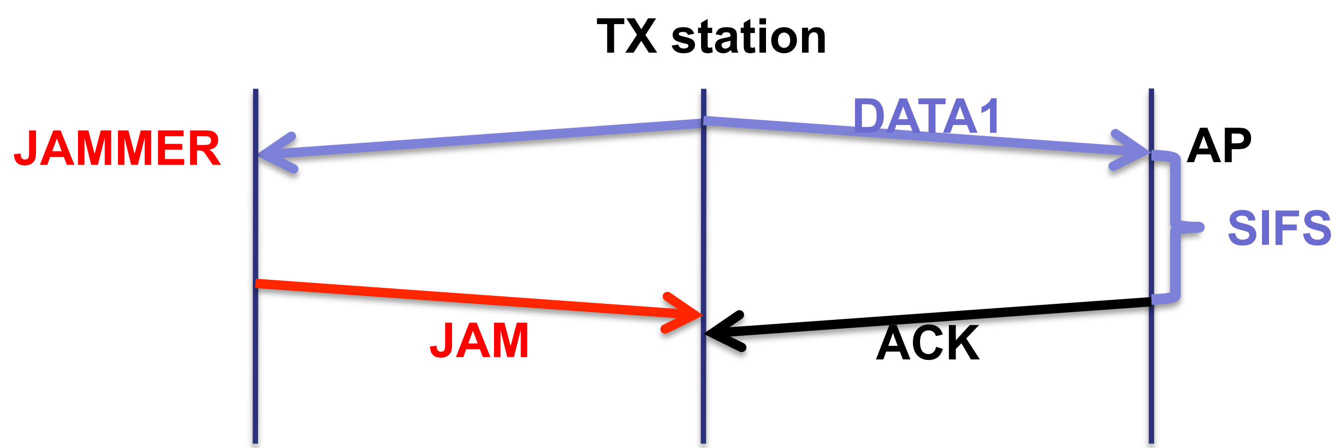
- If first byte of a packet are copied to SHM
- If we have ways of displaying SHM
  - Could we find evidence of received packets?
- Useful tool
  - $: b43-fwdump [-s]
  - Display r0..r63 registers
  - Switch “-s” dump content of SHM
- Run this experiment: Ping the AP very fast from the STA

```
$: ping -i 0.1 192.168.1.1 -b size
```

  - On AP dump the SHM: locate the ICMP packet
  - Fix the rate on STA: how do the first 6 bytes change?
  - Try for different ICMP size.

Back to jammer

- Disturbing a station when sending data
  - Jammer recognizes tx'ed data and sends fake ACK packet
    - Starts little before the SIFS
    - Send a slightly longer packet
- Maybe (for testing) jamming all packets is too much
  - Selected packets?



Back to jammer/2

- Propose changes to code flow for a selected data packet
- Exercise: only for UDP packets to port 43962
  - rx_plcp: checks it's a data packet
  - rx_data_plus: checks packet is longer than 0x1C = 6(PLCP)B + 22(MAC)B
  - send_response: copy src mac address to ACK addr1, set state to TX_ACK
  - rx_complete: schedule ACK transmission

JAM code

- To switch to a different firmware
  - Look at /lib/firmware
  - Link the desired firmware release as “b43”
  - Remove b43 module, reload and bring back the network up

```
$: rmmod b43 . . .
```

- How to test JAM code? “iperf” performance tool
- On AP run in server mode (receiver)

```
$: iperf -s -u -p 10000 -i 1
```

- On STA run in client mode (transmit)

```
$: iperf –c 192.168.1.1 –u –p 10000 –i 1 –t 10
```

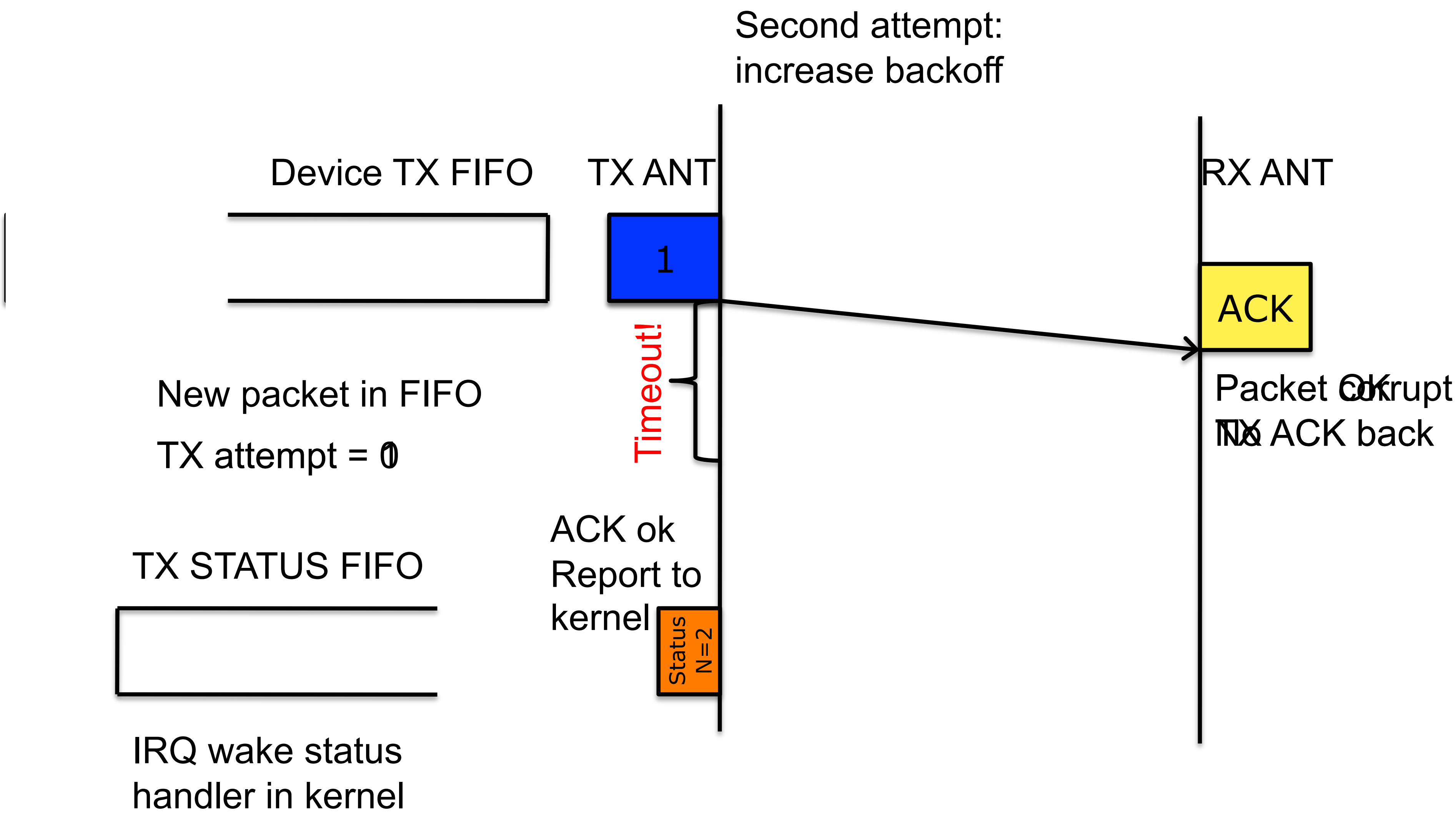
TX made easy

- Packets are prepared by the kernel
  - Fill all packet bytes (e.g., 802.11 header)
  - Choose hw agnostic device properties
    - Tx power to avoid energy wasting
    - Packet rate: rate control algorithm (minstrel)
  - A driver translates everything into hw specific
    - b43: rate encoded in PLCP (first 6B)
    - b43: append a fw-header at packet head
      - Firmware will setup hw according to these values

TX made easy/2

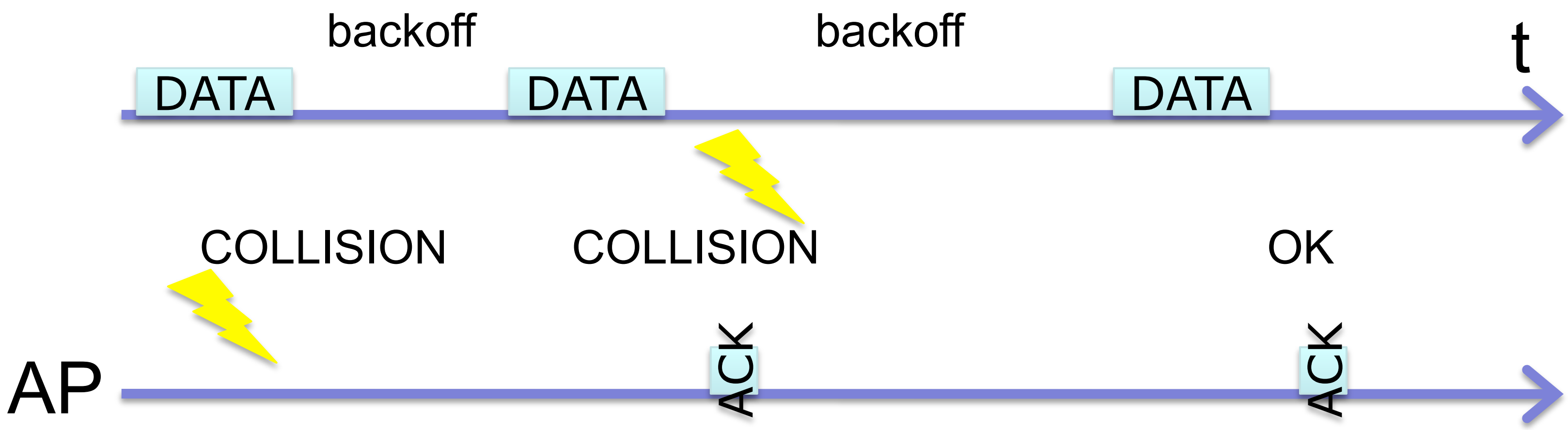
- Kernel (follows)
  - b43: send packet data (+hw info) through DMA
- firmware:
  - Continuous loop, when no receiving
    - If IDLE, check if packet in FIFO (comes from DMA)
    - If packet does not need ACK, TX,report and exit
    - If packet needs ACK, wait ACK timeout
    - If ACK timeout expired:
      - if ACK RXed, report to kernel, exit
      - If ACK not RXed, setup backoff, try again
      - If too much TX attempt, remove packet from FIFO, report to kernel, exit

TX made easy/3



TX made easy/4

- Summary



- FW reports to kernel the number of attemps
  - Kernel feeds the rate control algo
  - A rate for the next packet is chosen

TX made easy/5

- Currently “minstrel” is the default RC algo
  - At random intervals tries all rates
  - Builds a tables with success “rate” for each “rate”
  - In the short term it selects the best rate
  - How to checks this table from userspace?
    - DEBUGFS ☺
    - Take a look at folder

      `sys/kernel/debug/ieee80211`

TX made easy: exercise

- Firmware: backoff entered if ack is not rx
  - Simple experiment
    - Two STAs joined to the same BSS
    - iperf on both STAs to the AP
    - They should share the channel
  - What happen if we hack one station fw?
  - Let's try…
    - TX path really complex, skip
    - But at source top we have a few "_CW" values

OpenFWWF Exploitation: Two concrete MACs released

A glimpse into the
Linux Kernel Wireless Code

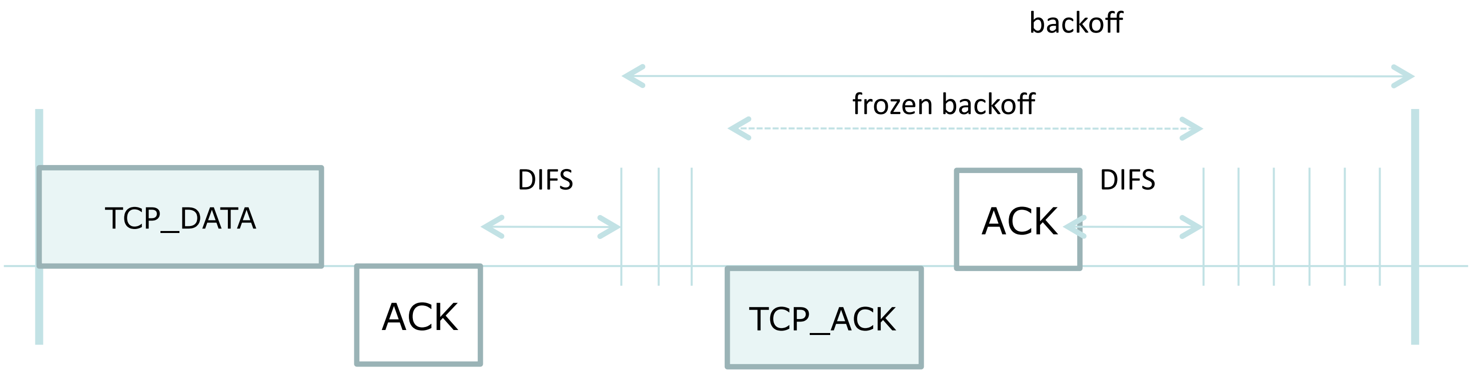
Part 4

OpenFWWF Exploitation: TCP-PIGGYB-ACK

In collaboration with
Ilenia Tinnirello & Pierluigi Gallo
University of Palermo

TCP flow over WiFi

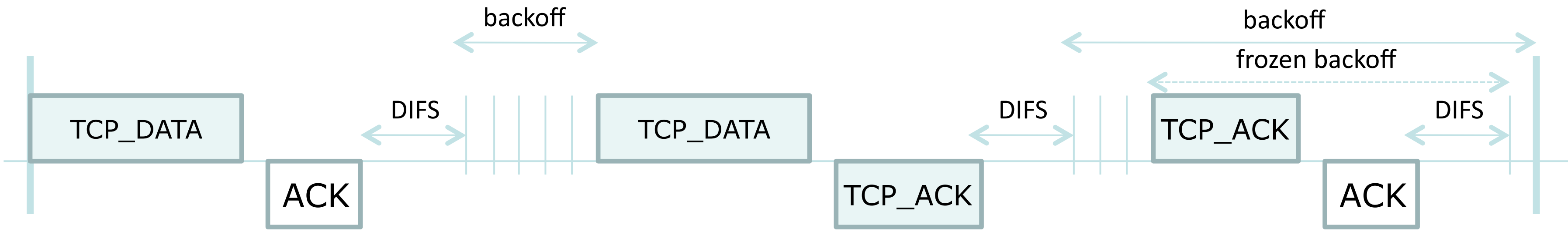
- AP: sends data segments to STA (e.g., from remote)
- STA: sends TCP ACK to AP (that forwards them)
  - Two separate channel accesses
- Idea: TCP ACK is short
  - Why not replacing L2 ACK with a mixed L2+L4 ACK?



T_a=TCP_DATA+SIFS+ACK+DIFS+TCP_ACK+ACK+DIFS+E[backoff]

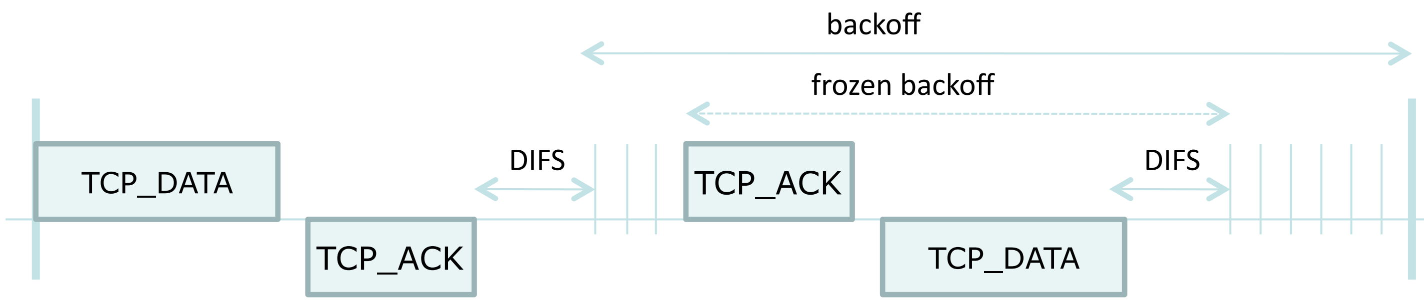
TCP flow over WiFi/2

- Expected behavior: TCP-PIGGYB-ACK!



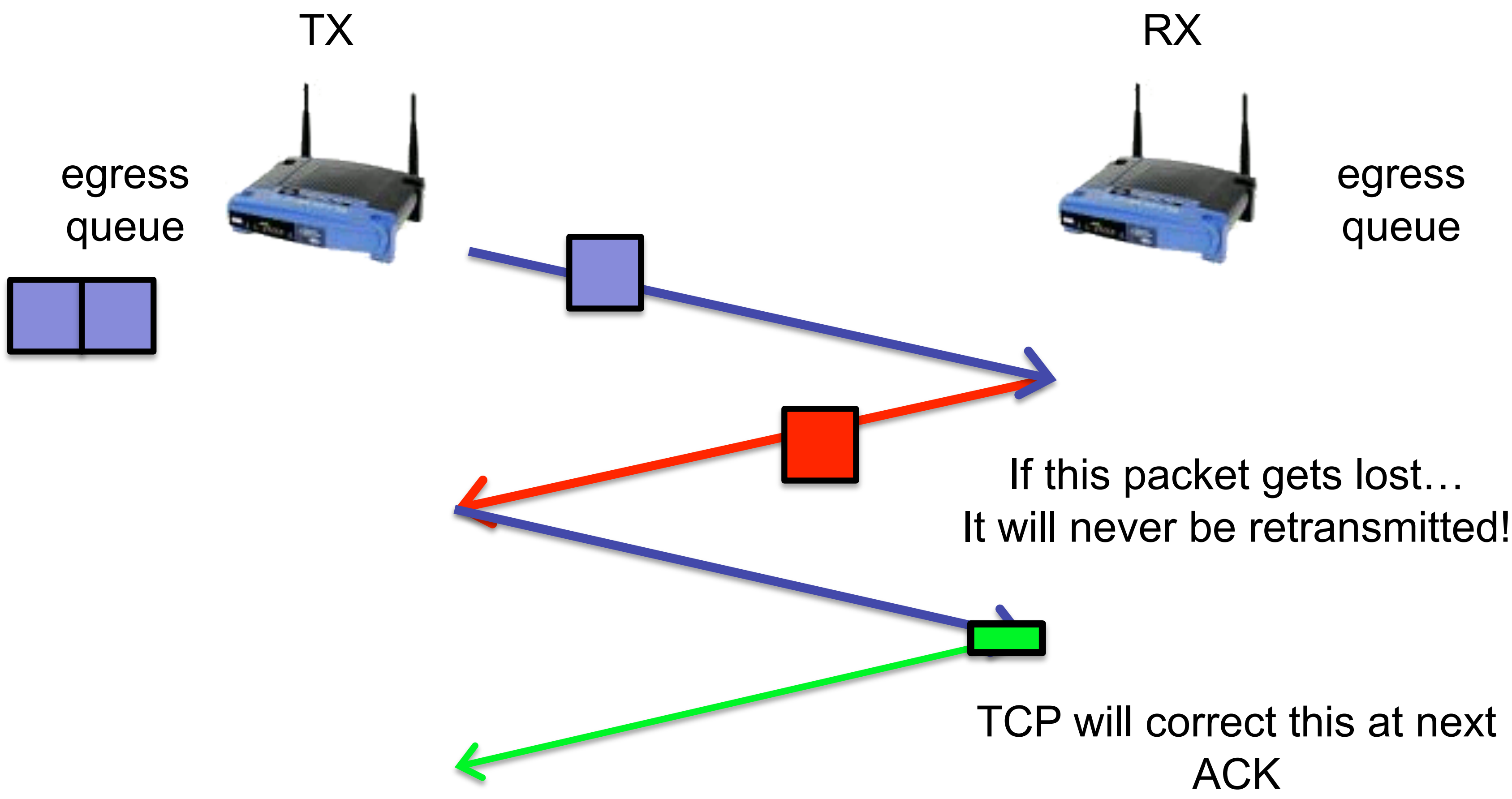
T_c=2 TCP_DATA+3 SIFS+3 DIFS+2 TCP_ACK+2 ACK+2 E[backoff]

- Enhanced behavior, work in progress.



T_b=2 TCP_DATA+2 SIFS+2 DIFS+2 TCP_ACK+ACK+E[backoff]

TCP-PIGGYB-ACK: scenario



TCP-PIGGYB-ACK: changes

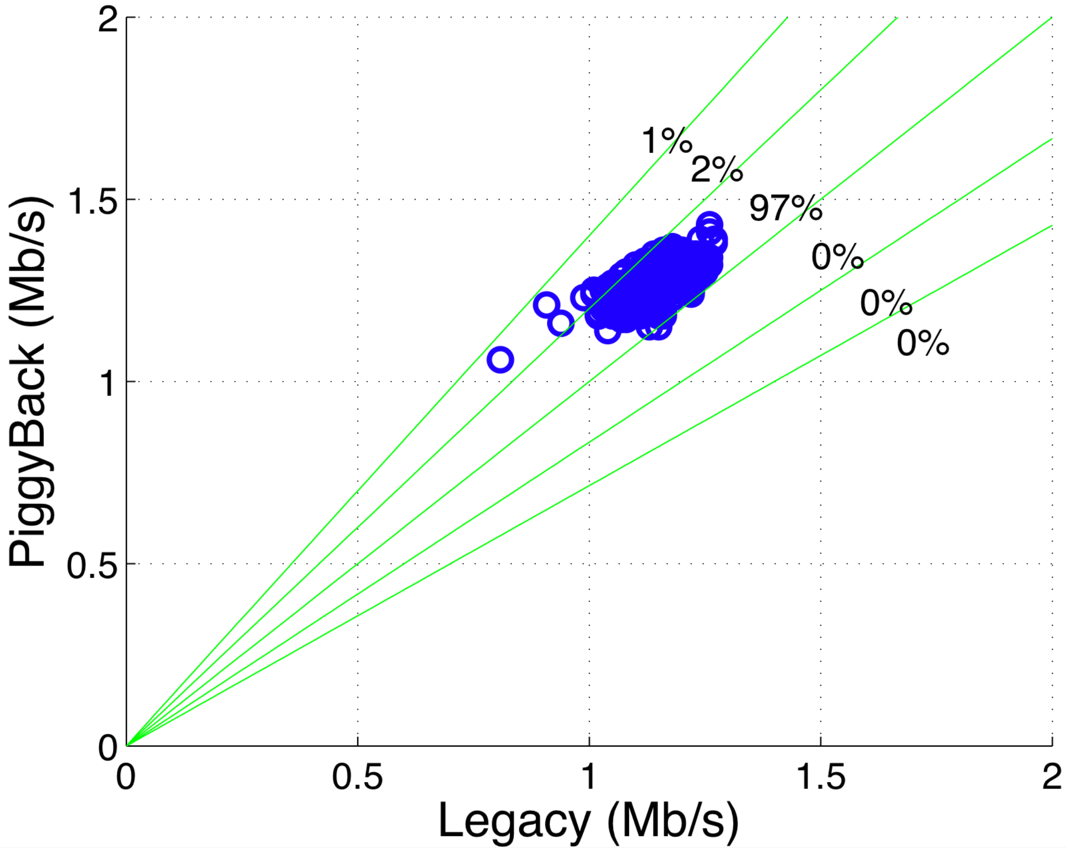
- FW @ rx
  - Piggyback: only if a TCP DATA is received
    - Avoid Ping-Pong
  - Piggyback: only if a TCP ACK is in queue
    - If not, send L2 ACK
  - Piggyback: header is L2ACK, longer!
- Kernel @ tx
  - If L2ACK long (=>TCP ACK) received
    - Forge and inject a recovered TCP ACK in the stack

TCP-PIGGYB-ACK Performance Evaluation

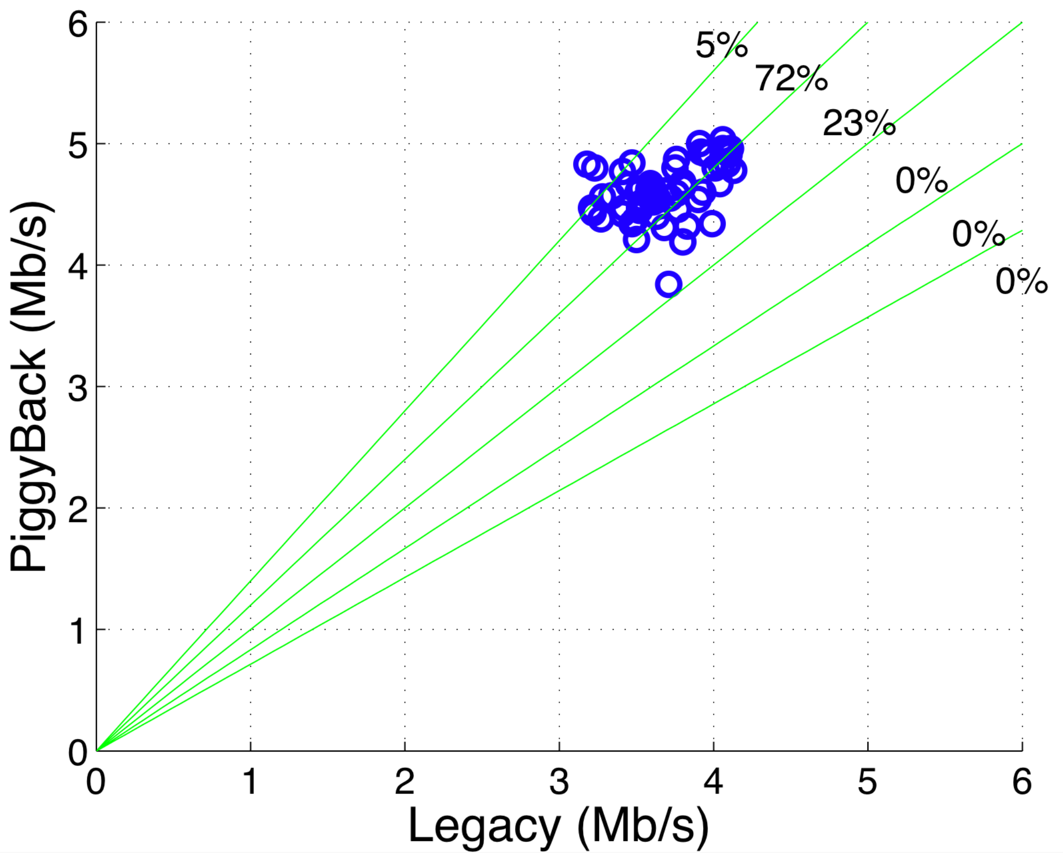
- Testbed & measurement
  - Two peers, several other BSS
  - One peer is the Access Point

```
while(1) {
    For 60 sec: exchange traffic with no PIGGYBACK
    Measure throughput T1 at rx
    For 60 sec: exchange traffic with PIGGYBACK
    Measure throughput T2 at rx
    Plot(T1, T2)
}
```

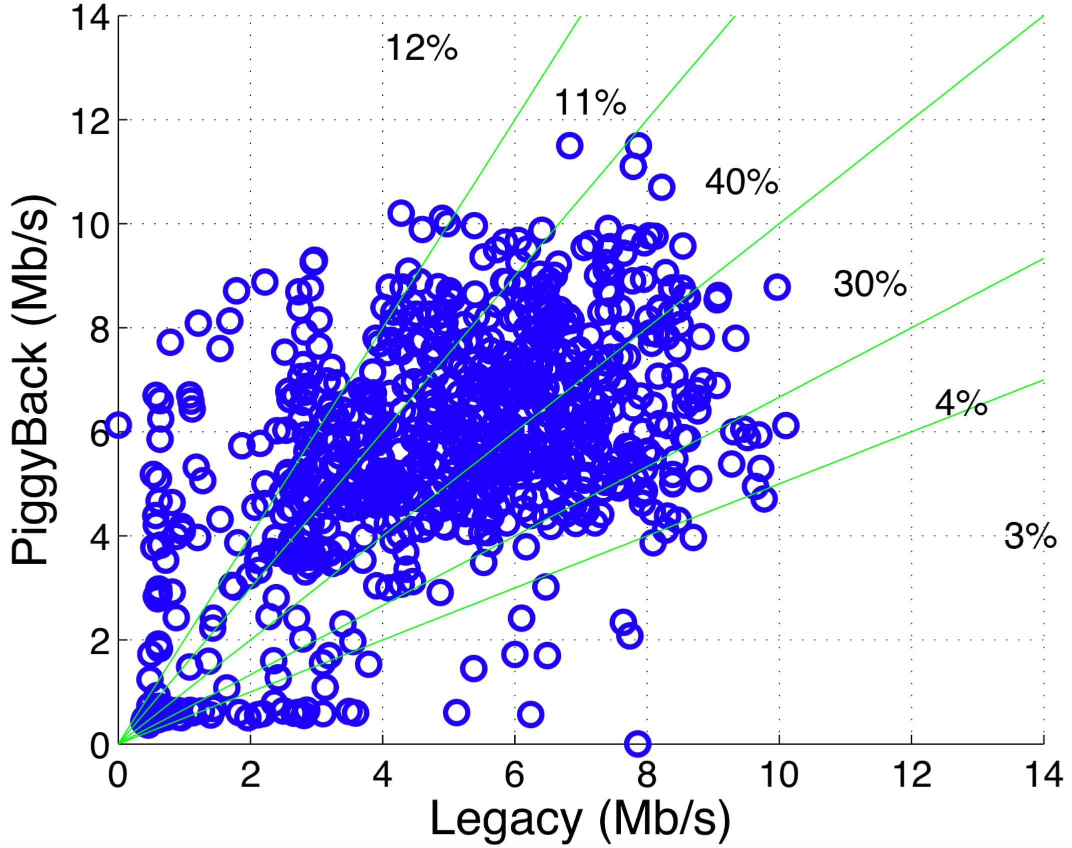
Performance Evaluation
Data rate fixed to 2Mb/s



Performance Evaluation
Data rate fixed to 11Mb/s



Performance Evaluation
Data rate free



TCP-PIGGYB-ACK: Comments

- Lost TCP-ACK in piggybacking
  - Not retransmitted
- Problems with rate control algorithm?
- Not all TCP segment are piggybacked with TCP-ACK
  - E.g., when the queue is empty

TCP-PIGGYB-ACK: exercise

- Switch module and firmware
  - We have a single kernel module for rx/tx
  - Still two separated FW – Not production!
- Keep in mind: for debug purposes
  - Experiments "legacy" to port 12346
  - Experiments "piggy" to port 12345
  - AP should receive TCP data, generate L2+L4 ACK
  - STA should transmit TCP data
- Play with `/sys/kernel/debug/b43/phyN/specack`

TCP-PIGGYB-ACK: exercise/2

- Use iperf/tcp
  - AP(rx) `$: iperf -s -p 12345|12346 -i 1`
  - STA(tx) `$: iperf -c 192.168.1.1 -p 12345 -i 1 -t 10`
- At the end on both, issue
  - `$: sudo cat /sys/kernel/debug/b43/phyN/specack`
- To reset statistics
  - `$: echo 0 | tee /sys/kernel/debug/b43/phyN/specack`

OpenFWWF Exploitation: Partial Packet Recovery

In collaboration with

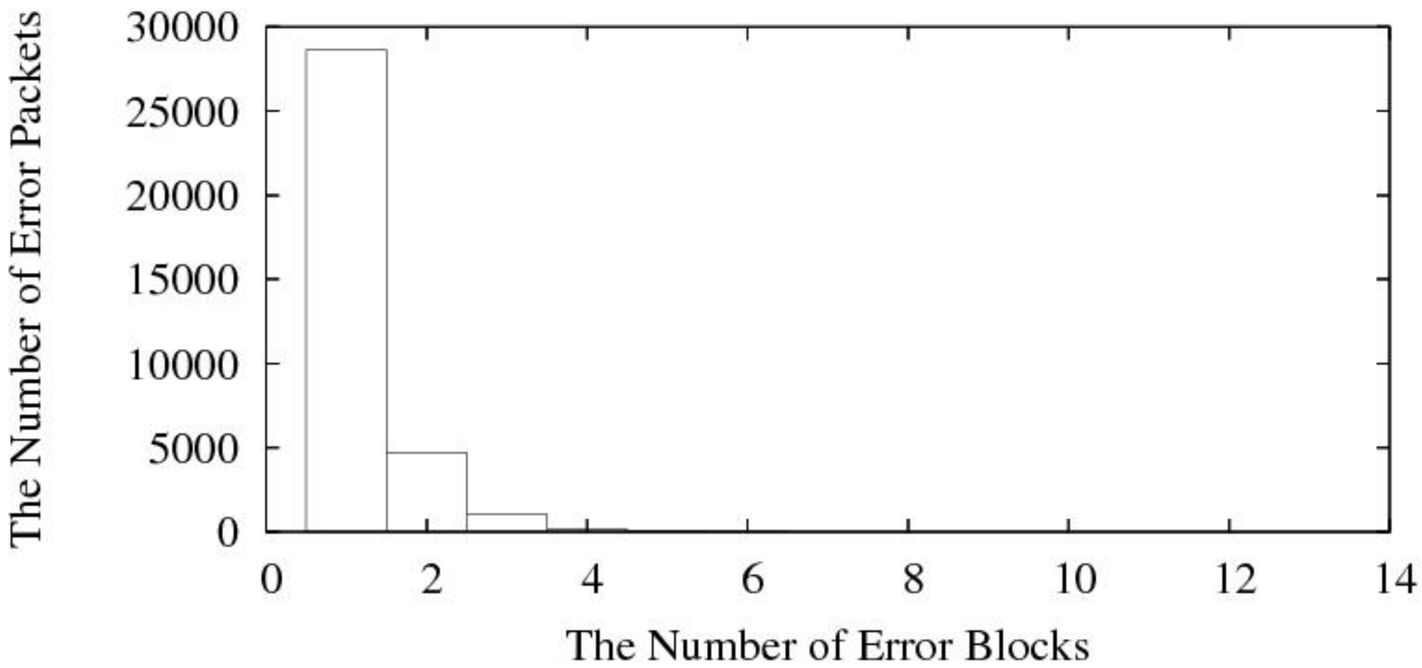
Errors & noise in WiFi

- Packet Error Rate of 802.11 networks is high[1]
  - Random noise can affect only a few bits
    - One or multiple blocks of corrupted bits inside a packet
  - Corrupted frames are discarded
    - Even if only 1 bit is wrong!
  - 802.11 retransmits after ACK timeout
  - Correctly received bits are completely wasted

[1] Bo Han, Lusheng Ji, Seungjoon Lee, Bobby Bhattacharjee, and Robert R. Miller. All Bits Are Not Equal. A Study of IEEE 802.11 Communication Bit Errors. INFOCOM 2009, pp. 1602-1610, Apr. 2009.

Errors & noise in WiFi/2

- Suppose we divide packets into 64bytes block
  - Typical packet trace of a managed station



Recent Approaches

- Forward Error Correction (FEC) based
  - ZipTx [2] sends RS redundant bits for recovery
  - Two-round coding scheme
  - Educated guess of BER and high recovery delay
    - Implemented(?) in kernel-space on Atheros devices
    - Evaluated in 11a, outdoor tests (low interference)

[2] K. C.-J. Lin, N. Kushman, and D. Katabi. ZipTx: Harnessing Partial Packets in 802.11 Networks. ACM MOBICOM 2008, pag. 351–362, Sept. 2008.

Recent Approaches

- Based on Automatic Repeat reQuest (ARQ)
  - PPR [3] relies on the confidence of each bit's correctness
  - Retransmit only corrupted bits
  - Not available in commercial hardware
    - implemented and evaluated on 802.15.4 protocol stack

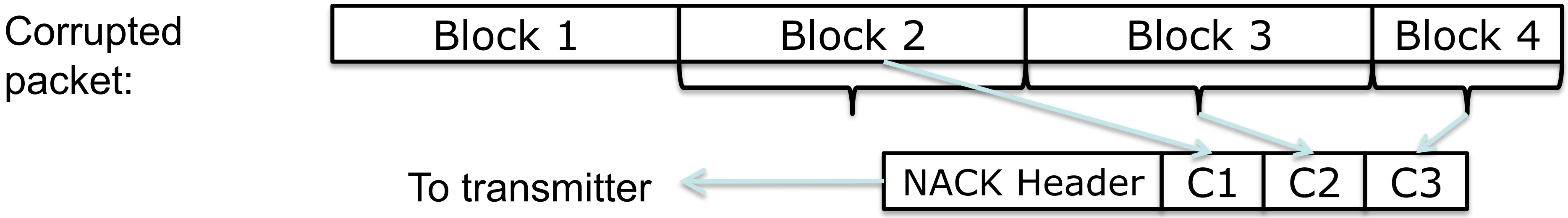
[3] K. Jamieson and H. Balakrishnan. PPR: Partial Packet Recovery for Wireless Networks. ACM SIGCOMM 2007, pag. 409–420, Aug. 2007

Our approach

- Similar to PPR
  - No access to confidence information
- Use checksum coefficient embedded in packets
- We implemented everything from scratch
  - Changes to Linux kernel
  - Changes to OpenFWWF
- We designed MARANELLO and BOLOGNA
  - AKAS Practical Partial Packet Recovery P^3R!

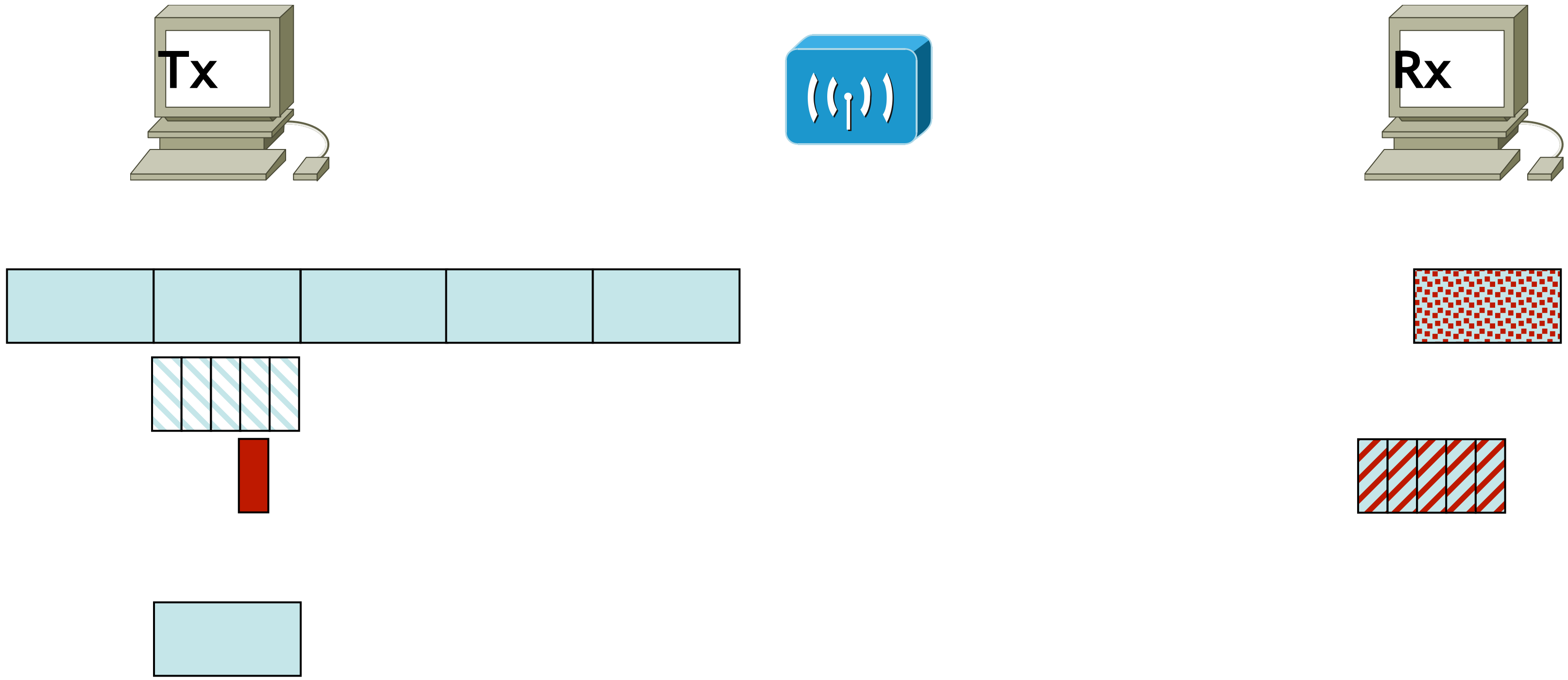
Maranello: P³R

- At rx corrupted packet is divided into blocks
  - Blocks are equally sized (apart the last one)
  - For each block apart the first compute a checksum
  - Checksums sent back to the transmitter in a N-ACK



  - Transmitter retransmits only corrupted blocks
  - First block can't be protected
    - It must always be retransmitted, contains the header!

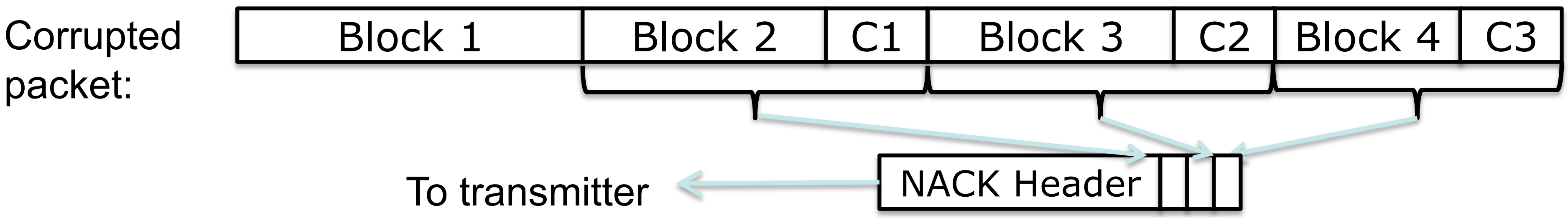
Maranello: handling retransmission



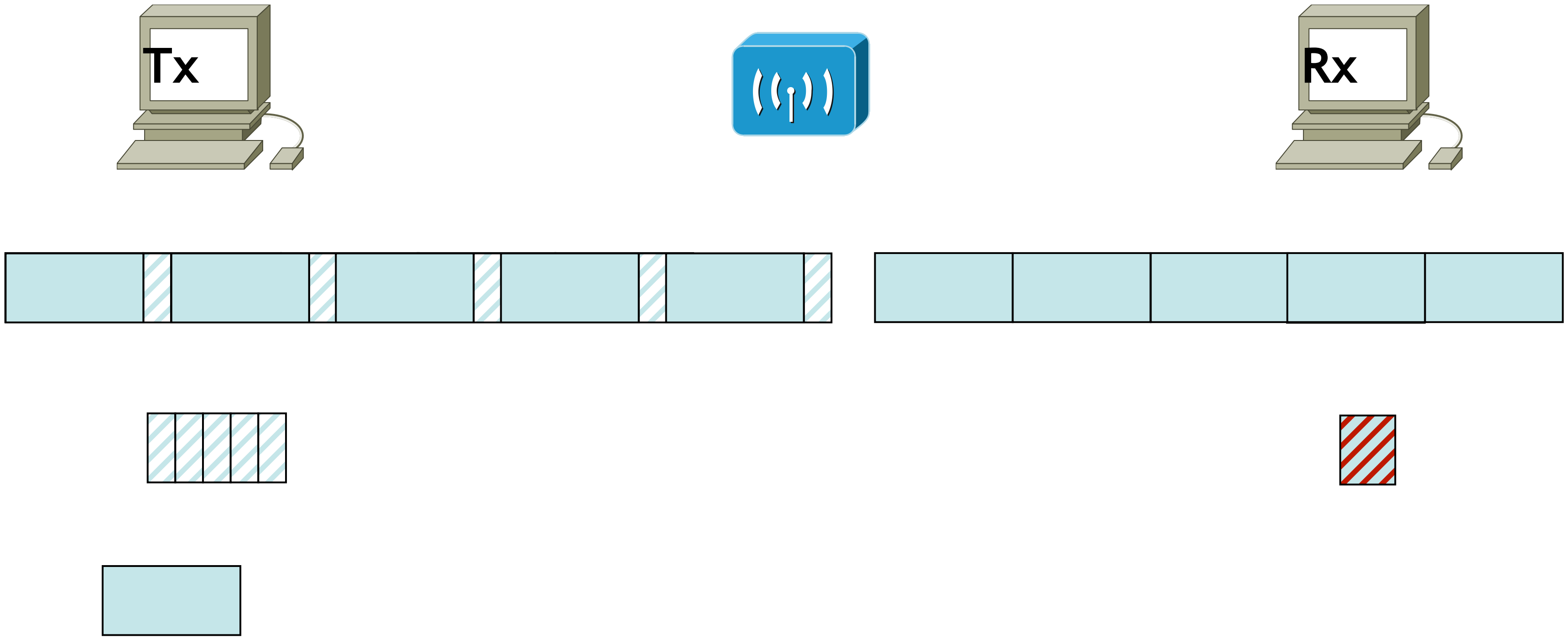
FCS checking, Block Checksums computation (Fletcher-32), NACK, packet retransmission

Bologna: P^3R

- Like Maranello but…
- At tx packet is expanded
  - In each block a checksum is embedded
- Rx checks all blocks:
  - If packet fails, send back a NACK
  - NACK is the bitmap of corrupt blocks



Bologna: handling retransmission



Generation and transmission of repair packet

Advantages of P^3R

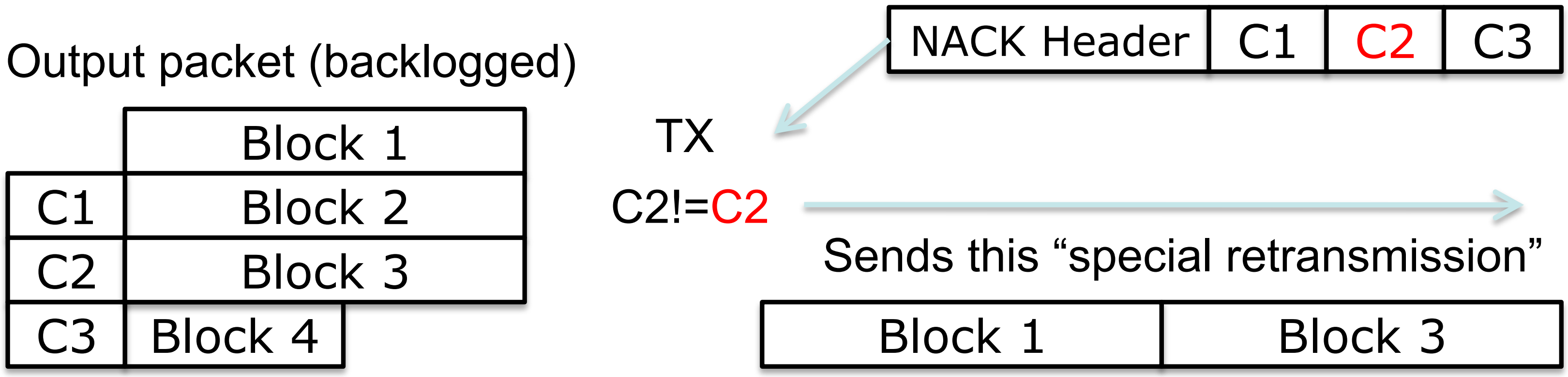
- Receiver-controlled recovery
- Utilizing the airtime reserved for ACKs
  - No additional overhead for correct packets
- Faster packet recovery
  - Recovery immediately after a transmission fails
  - Shorter recovery frames

Implementation Architecture

- Time-critical operations should be implemented in firmware space
  - RX: block checksum calculation, NACK generation
  - TX: block checksum calc., block retransmissions
- Why not in driver space
  - High bus transfer delay + interrupt latency (>70 us)
- ACK, and NACK:
  - must start within 10us after receiving a frame

Implementation: Transmitter

- Kernel=>Maranello operations:
  - precompute checksums for each output packet
  - send packet and checksums to the firmware
- Firmware=>Maranello operations:
  - receive NACK: compares checksums to those precomputed
  - rebuild “special retransmission” putting pieces together



Implementation: receiver

- Firmware=>Maranello operations:
  - compute checksums on packet reception
  - if frame is corrupted
    - send NACK instead of ACK, same timings
    - send corrupted packet up to kernel
- Kernel=>Maranello operations:
  - stores corrupted packet
  - when receives a special retransmission
    - rebuild the original packet

Other details

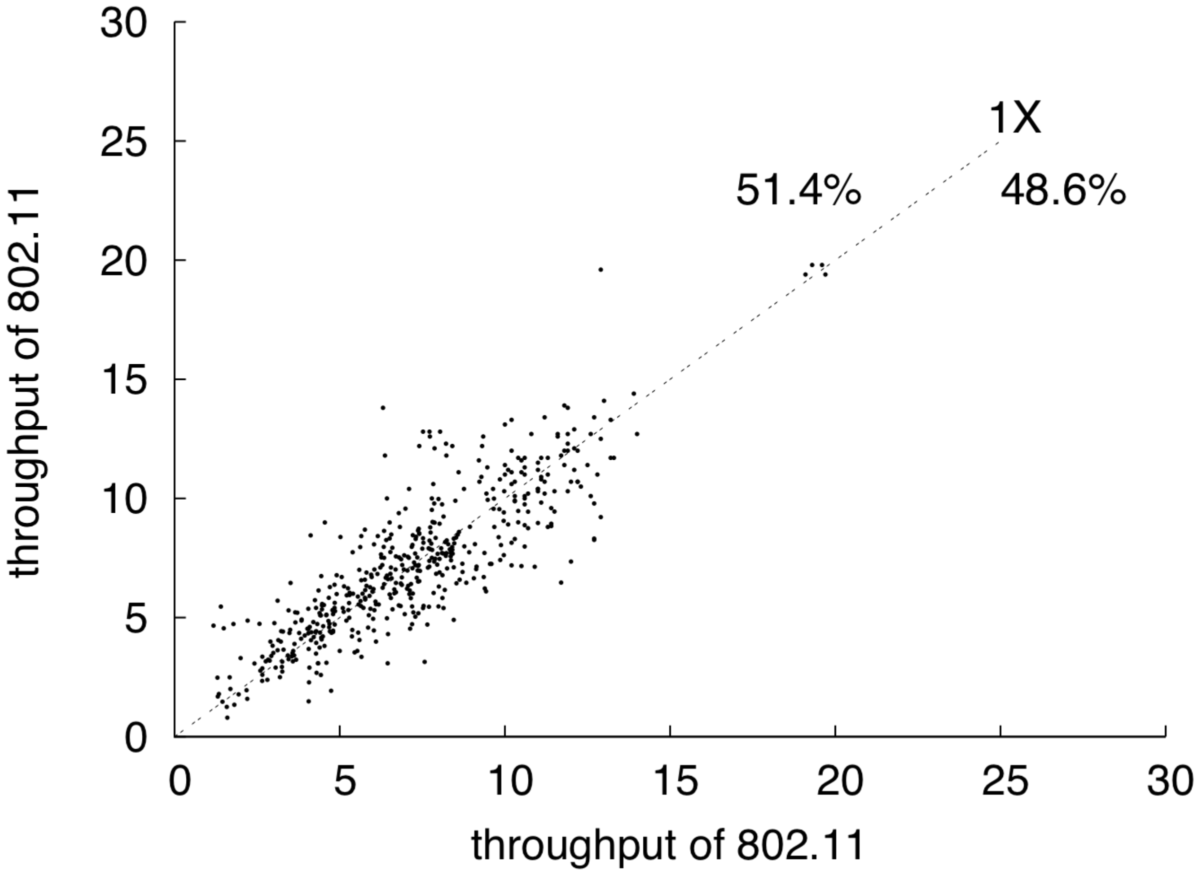
- Maranello & Bologna
  - We used 64-byte blocks
  - Checksum:
    - CRC16 is desiderata
    - OpenFWWF has not access to CRC engine
    - We used Fletcher-16/32, computing checksums on the fly
  - Recovered packets protected by an additional CRC32 checksum

Throughput tests

- Repeat this experiment
  - 60s UDP traffic, sta to AP (iperf), legacy => ϑ_1
  - 60s UDP traffic, sta to AP (iperf), Maranello => ϑ_2
  - Plot (ϑ_1, ϑ_2)
- Each run follows sta initialization
- Three environments
  - ATT lab
  - Maryland campus
  - Bo's home
- Linux sta
  - Fixed channels (1, 6, 11)
  - Minstrel as RC

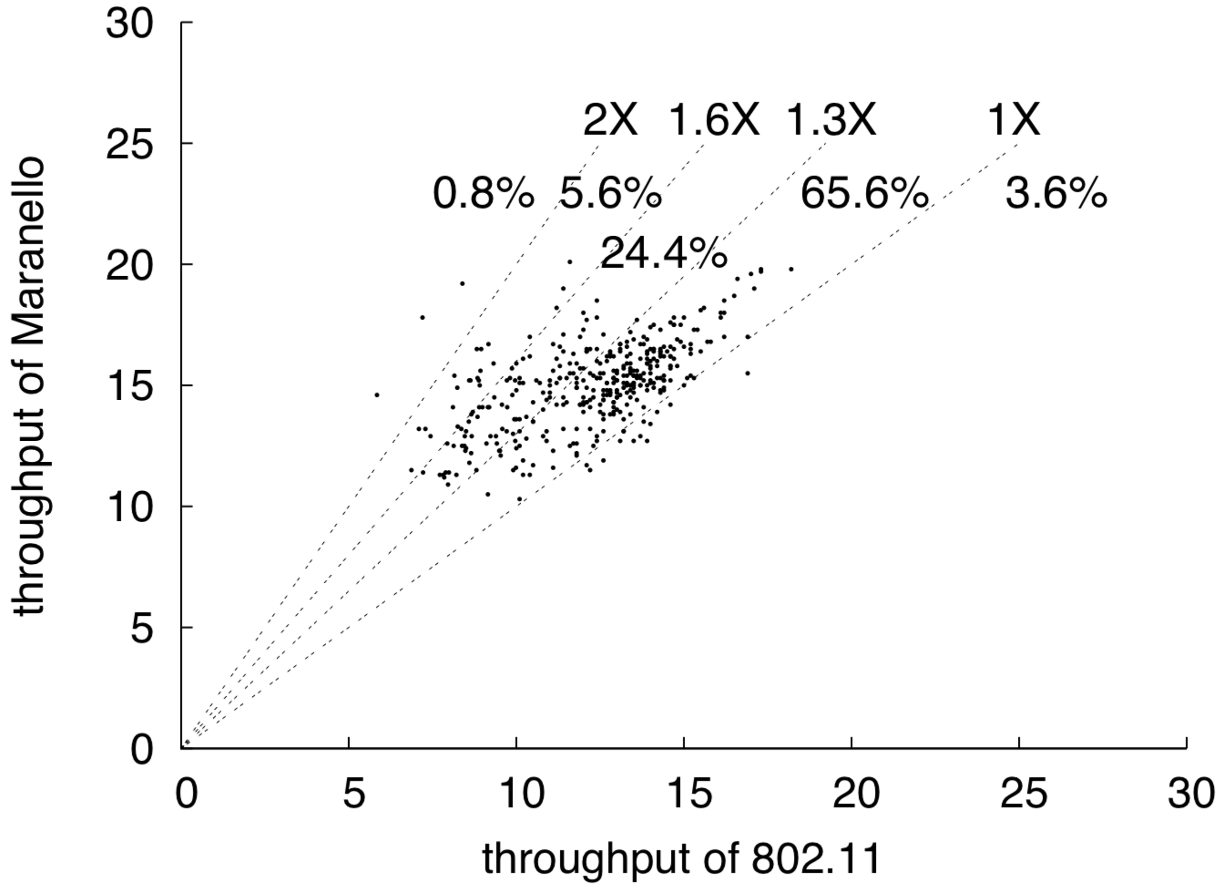
Throughput tests

- Reliable test?



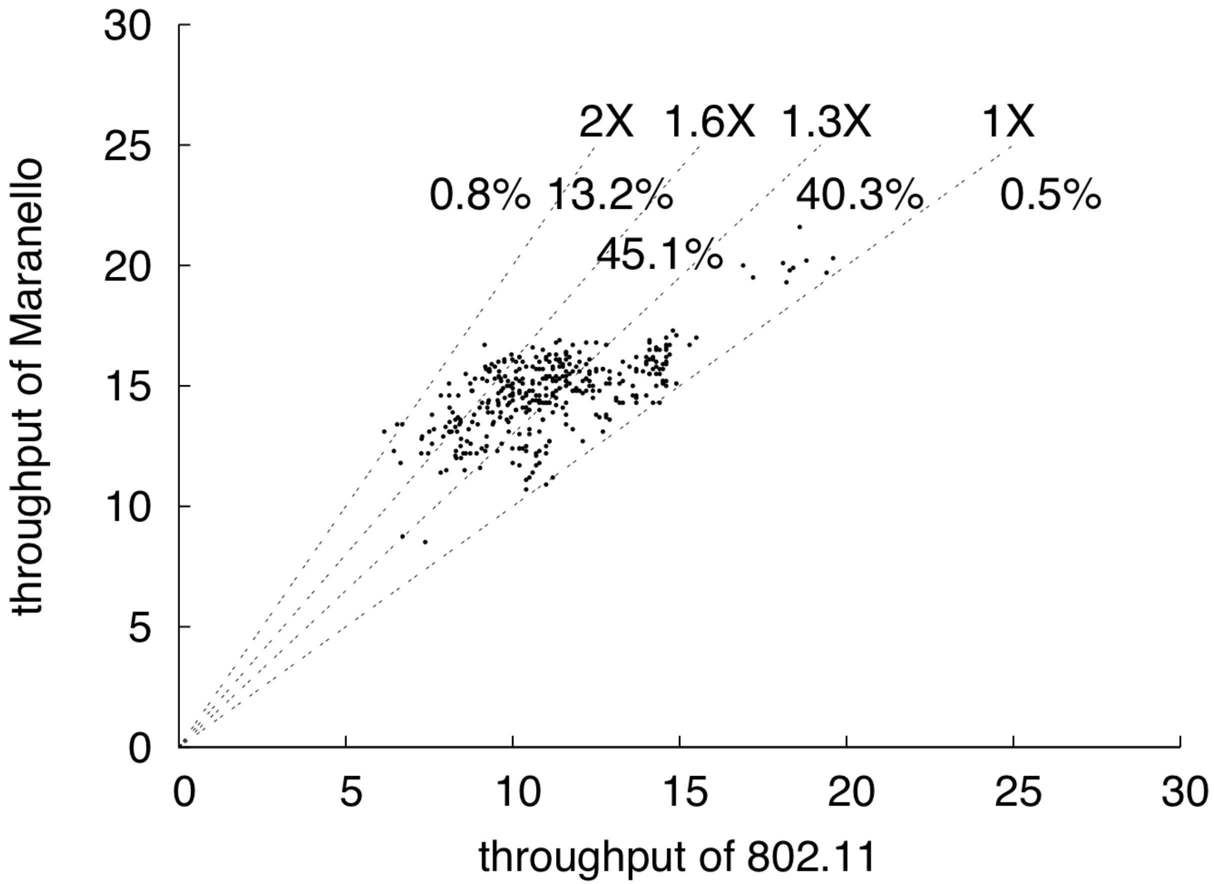
Throughput tests

- Bo's home



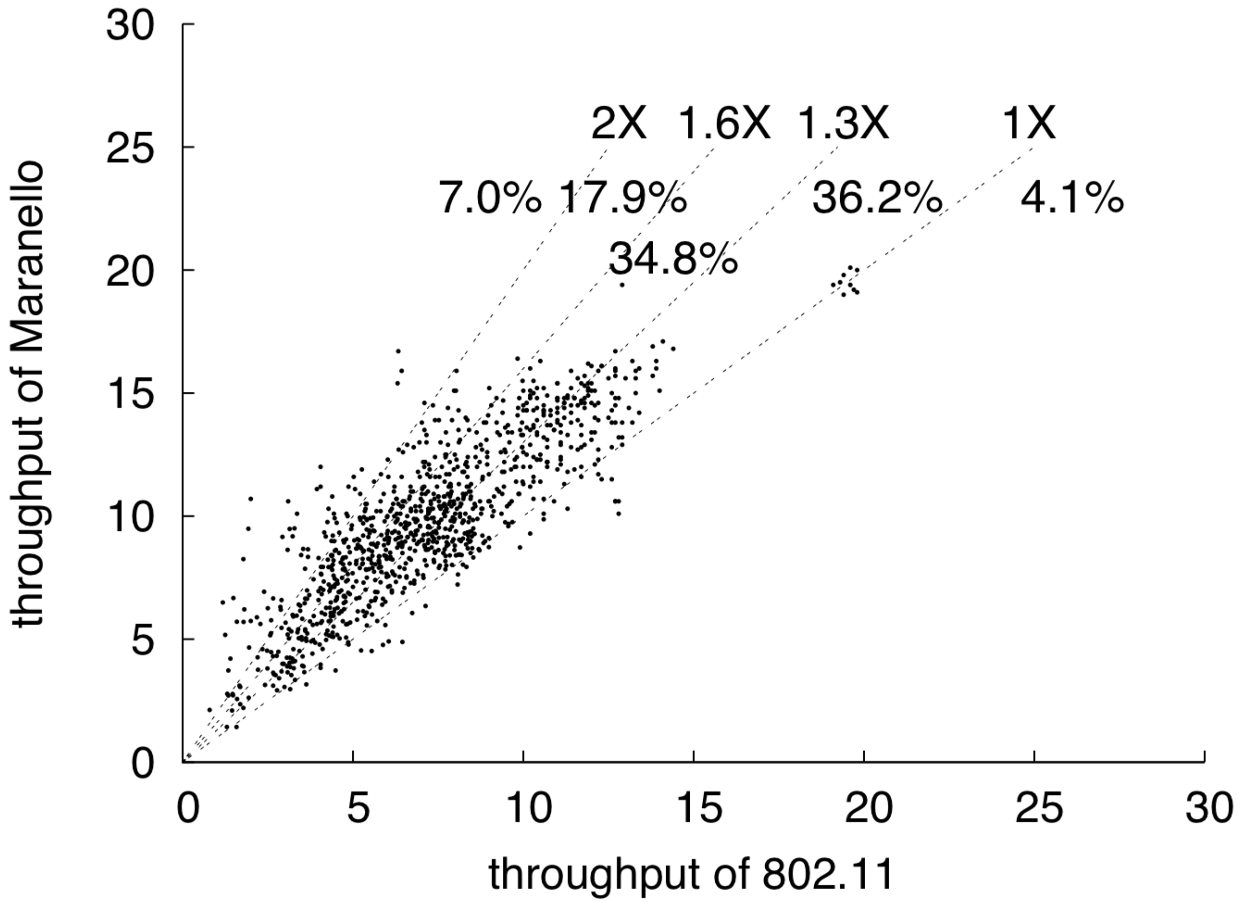
Throughput tests

- ATT lab



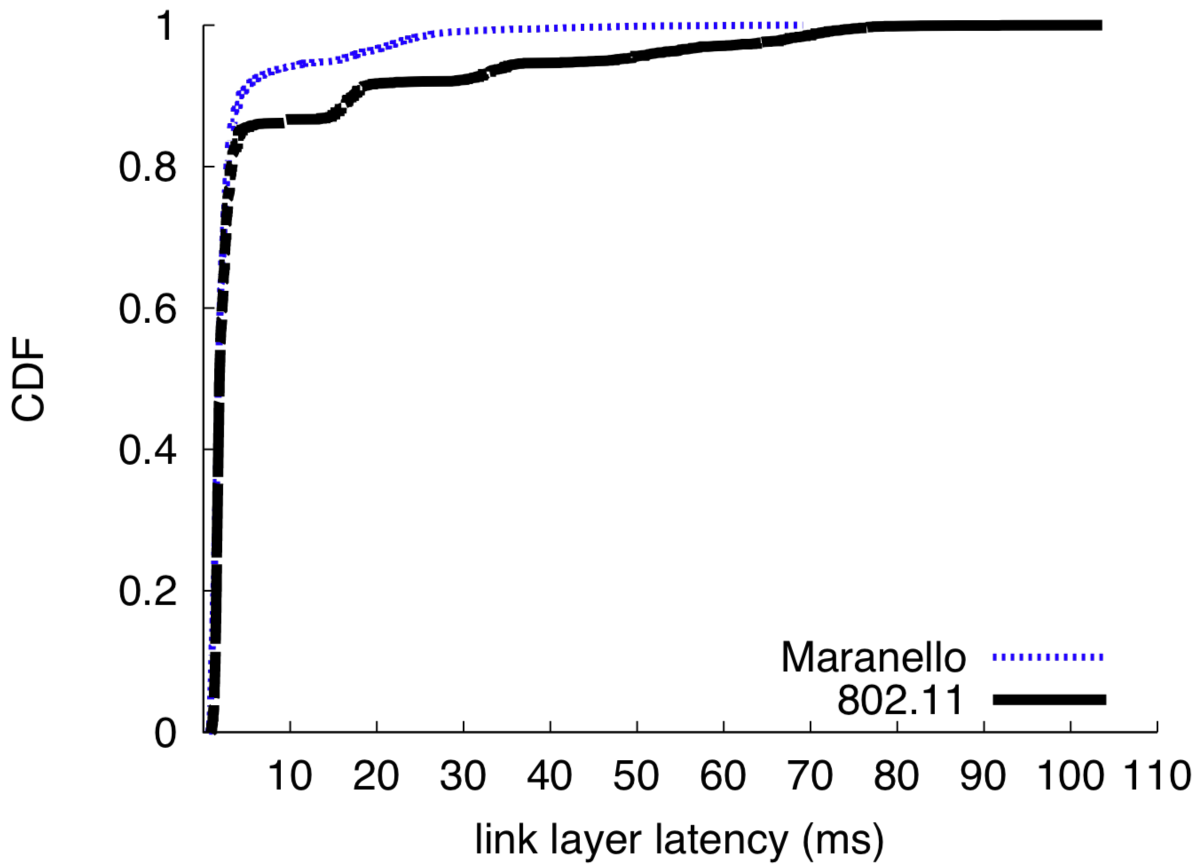
Throughput tests

- Maryland campus



Throughput tests

- Link layer latency is reduced (shorter retr)



MARANELLO vs BOLOGNA

Maranello

PRO

- *Partial Packet Recovery*
- Backward comp. 802.11
- Link latency--
- No extra-bits in reg. packets

ISSUES

- NACK very long

BBR

PRO

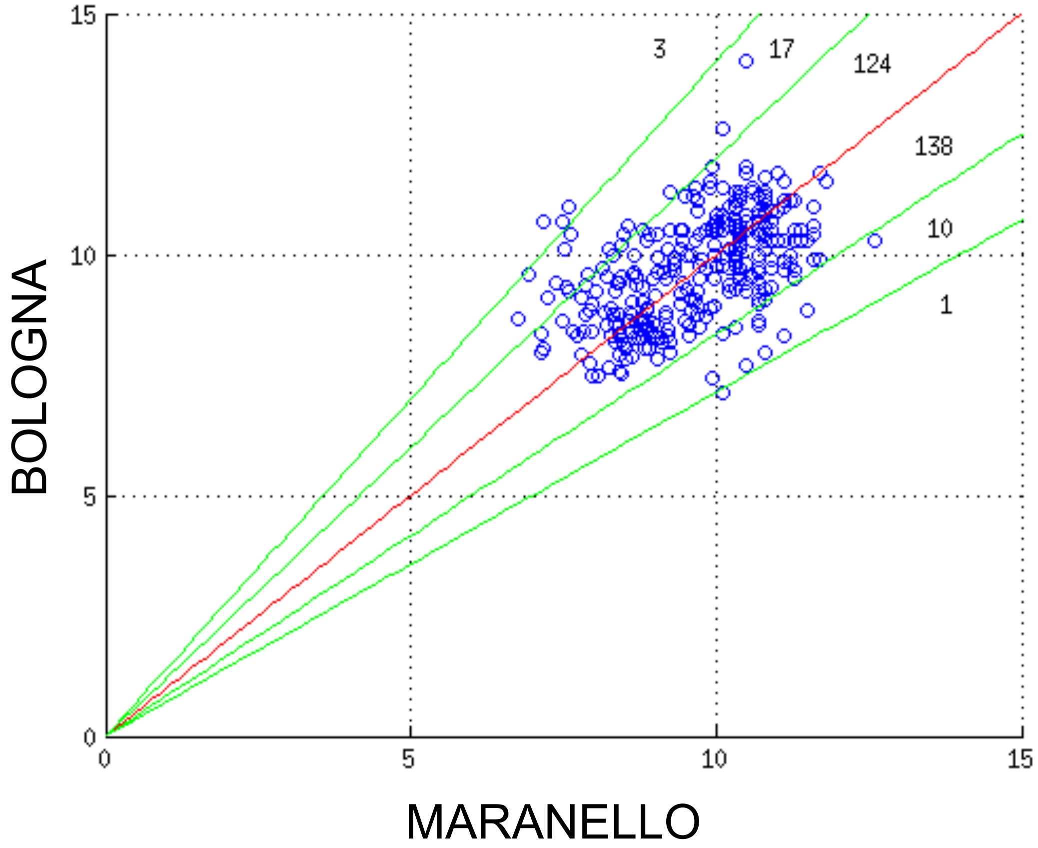
- *Partial Packet Recovery*
- Backward comp. 802.11
- Link latency--
- NACK minimized

ISSUES

- Packet expansion

MARANELLO vs BOLOGNA

- Same comparison (preliminary results)

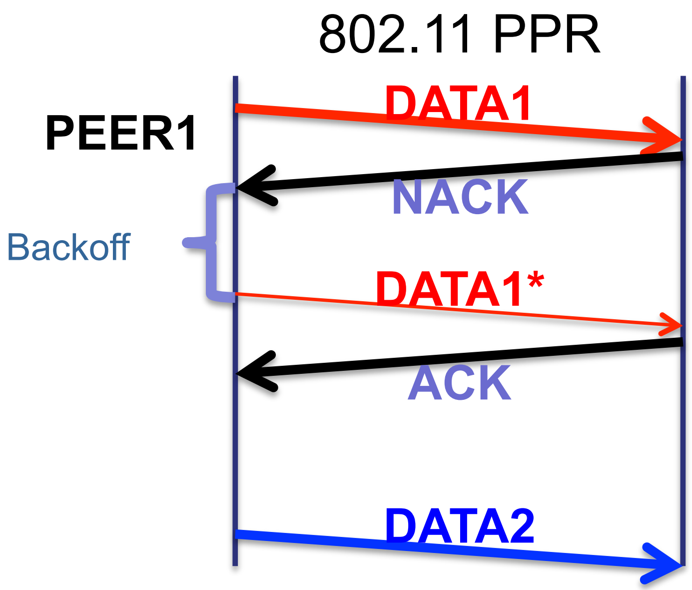


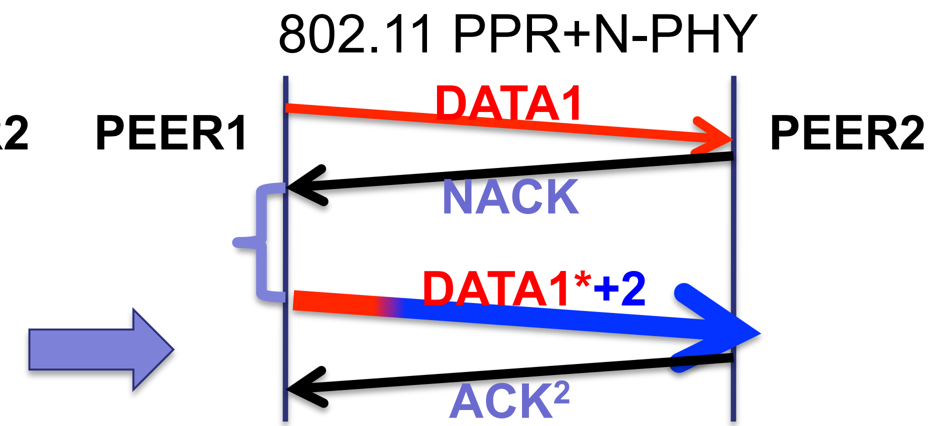
What to Do Next?

- Complete Bologna evaluation
- Evaluating checksum strength
  - E.g., is ok Fletcher16? Or Fletcher32 is better?
- Different block sizes
- Back-to-Back packet aggregation
- Interaction between rate control and error recovery protocols
  - Better bit rate for retransmissions

What to Do Next?/2

- Packet aggregation with Partial Packet Recovery:
  - For failed packets if retransmission is short
  - Instead of retransmitting only the corrupt part
  - Transmit corrupt part + new packet (if any ☺!)

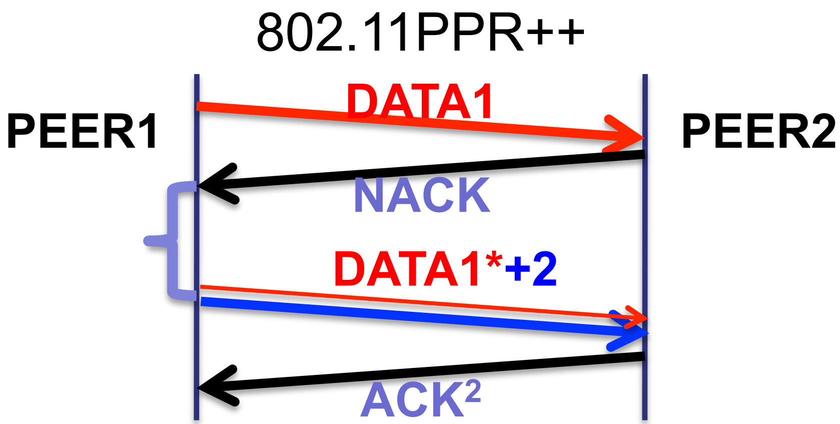




Use the same airtime of DCF and may re-transmit + new-transmission!!

What to Do Next?/3

- Without N-PHY we can use OpenFWWF Hack



Experiment: block error distribution

- Use "superblockanalyzer" to tx/rx traffic
- Use "codeanalyzer2" to compute distribution
- A virtual iface in monitor mode is needed on TX/RX

```
$: sudo iw dev wlan0 interface add fish0 type monitor
$: sudo ifconfig fish0 up
```

- On receiver

```
$: sudo ./supercodeanalyzer -i fish0 -s -p 10000
```

- On transmitter

```
$: sudo ./supercodeanalyzer -c larrybird.trento -p 10000 \
   -r ./packet.pcap -B Bologna/58//fletcher16/64 \
   -x 00:22:15:87:87:b3 -y 00:13:d4:bb:2c:bf -i fish0
```

Experiment: block error distribution/2

- Check RX screen
  - Never ending? Why?
  - Focus on “wrong blocks”? Always 0?
  - Should we have in kernel space wrong packets?
- I will manage kernel and firmware switch!
- Run again the tools…
- Finally display statistics

```
./codeanalyzer2 -e f16 -r packet_exp0.pcap -p /
  ./packet.pcap -x 00:22:15:87:87:b3 /
  -y 00:13:d4:bb:2c:bf
```

Some recent news

News from .11 hardware world ATHEROS/1

- Atheros AR9170USB
  - USB dongle, supports a/b/g/n-draft
- Atheros released opensource fw and driver
  - Otus driver: features missing, code style--
- C. Lamparter introduced carl9170
  - Pro: Everything implemented, station, ap, monitor
  - Pro: Firmware sources can be compiled from C code
  - Issue: random firmware crashes
    - Kernel handles crashes and restart wireless subsystem

News from .11 hardware world ATHEROS/2

- Got in touch with C. Lamparter
  - FW/Processor is not the MAC processor
    - Resembles SoftMAC
  - FW/Processor polls the hardware (e.g., MAC), no IRQ
    - Filters packets from air by type and forwards to host on DMA
    - No way(unknown?) to build responses and send them back
    - ACKs handled by MAC processor: "Response Controller"
    - ACKs can be only disabled
    - **Not a real time platform!**
  - But…
    - …CCA can be disabled ☺
    - **Is this enough?**

News from .11 hardware world BROADCOM/1

- Pros
  - Broadcom boards ARE realtime
  - Opensource firmware available: **OpenFWWF**
  - L2 protocol exchanges: can be deeply customizated
    - E.g., Partial Packet Recovery (Maranello/Bologna MAC)
- Drawbacks
  - We know how to do this on b/g boards:
    - What about 11n?
  - We don't know how to handle CCA
    - Minimum space between packets is 10us (follows from .11e)
  - We can't change modulation
    - E.g., no way to modify MPDU format (i.e., PLCP is fixed)

News from .11 hardware world BROADCOM/2

- 10/10/2010 Good news!
  - Broadcom released OS drivers
  - Builds on mac80211 linux module
  - For their latest N-PHY boards (43224/225)
    - Same architecture, firmware that drives the MAC processor!
- Drawbacks
  - No open-source firmware yet, will ever?
  - Only managed mode implemented (no AP)
  - 43224/225 boards still hard to find: we have two since last week
  - We will add RE instruments to Broadcom driver

RE work will start soon

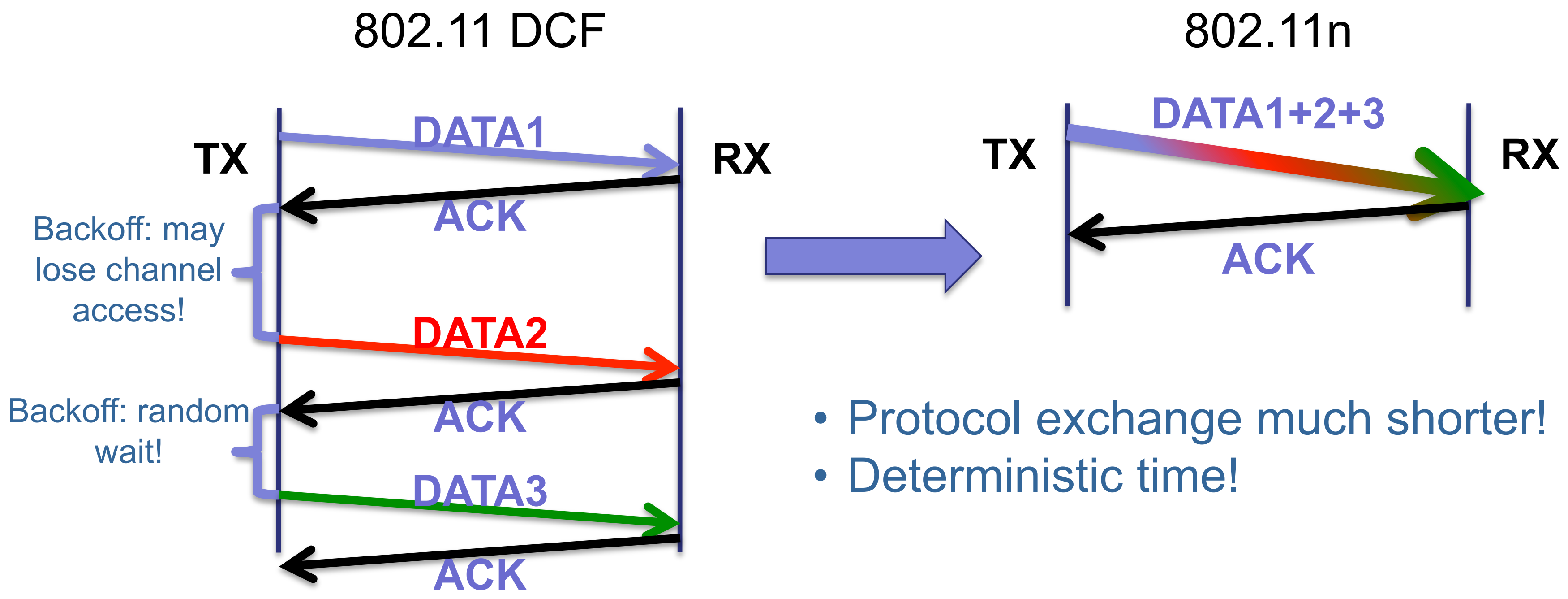
News from .11 hardware world BROADCOM/3

- Original developers of Broadcom drivers for Linux
  - They were(are) working on N-PHY support
  - More devices included, not only latest-state-of-the-art
- After Broadcom announcement
  - Request to open the firmware source
  - Broadcom said **NO!**
- Got in touch with main developer R. Miłecki
  - We now have an opensource driver
- **What about firmware…**
  - **We are working on our own firmware: Ope(N)FWWF**
  - **RE Broadcom Firmware: interestingly they simply added features**
  - **So we will do building up OpenFWWF!**

Projects starting soon

Issues with 802.11 DCF
Packet aggregation (helper)/1

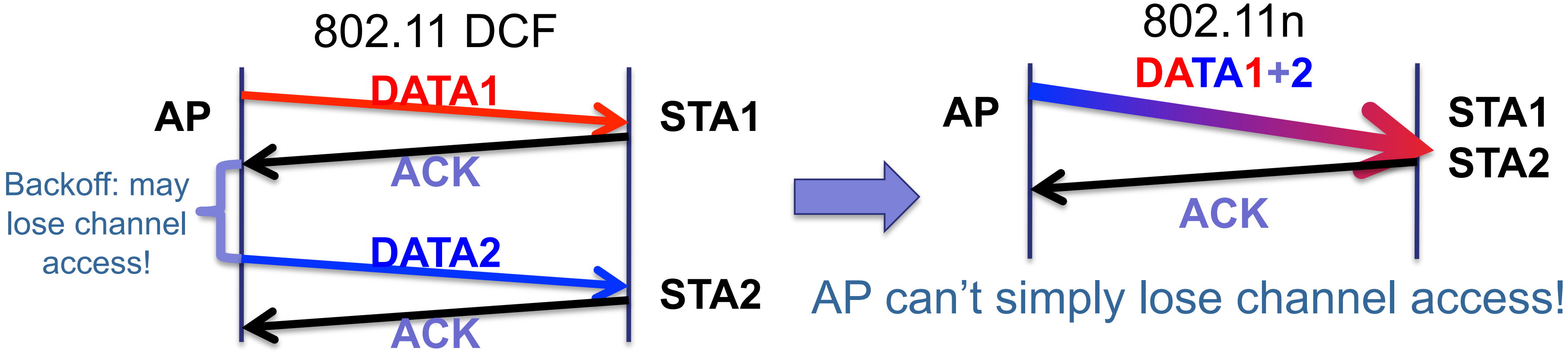
- (Real) Packet aggregation started with .11N
  - Packets TO THE SAME dst packed & sent in single A-MPDU



- Protocol exchange much shorter!
- Deterministic time!

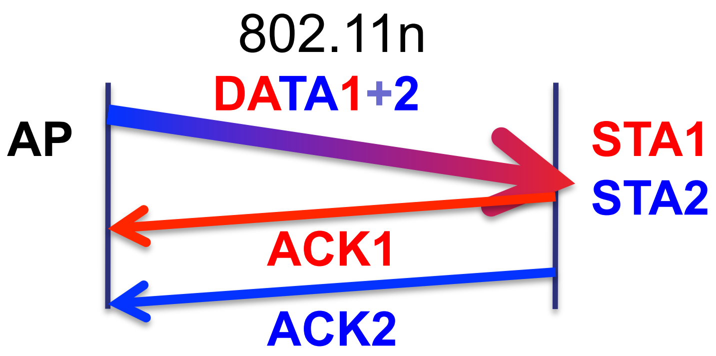
Issues with 802.11 DCF Packet aggregation (helper)/2

- (1) Unfairness in DCF channel access
  - Pack packets to all destinations in a single A-MPDU
  - AP will not lose channel access
  - AP can “steals” more than 1/N access
  - Downlink packets paced as uplinks



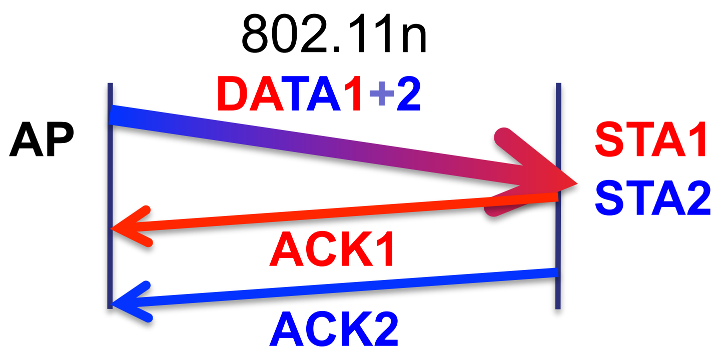
Issues with 802.11 DCF Packet aggregation (helper)/3

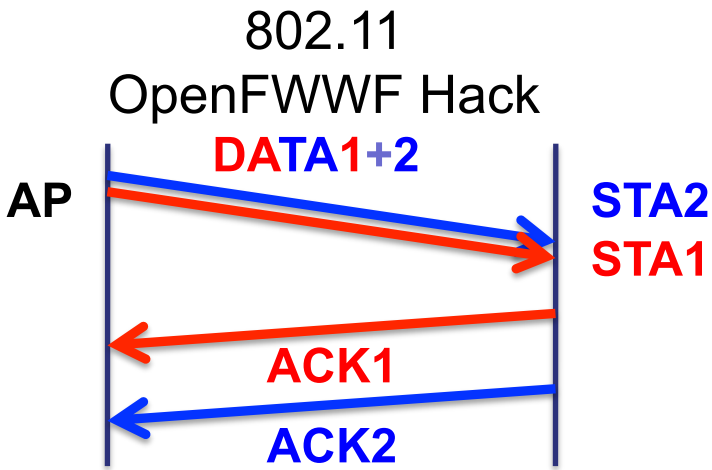
- (1) Unfairness in DCF channel access
- Problems:
  - one A-MPDU means one PLCP: rate?
  - How can we send acknowledgements?



Back-to-Back packet transmission Why?/1

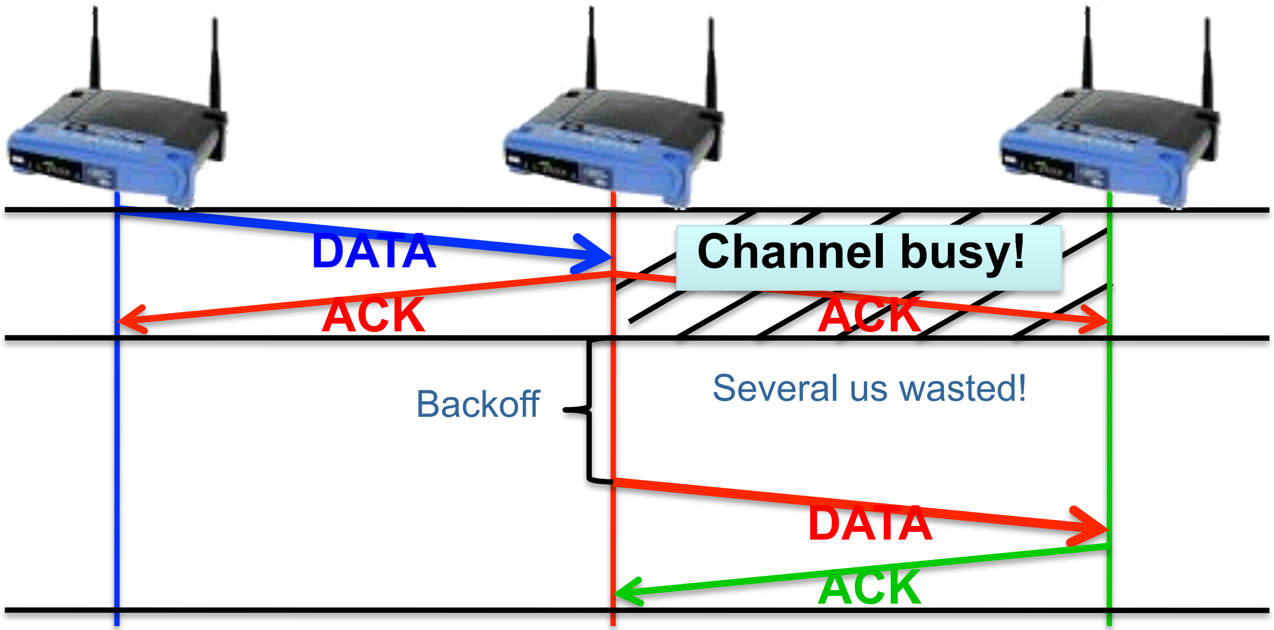
- No .11n && b/g cards + OpenFWWF limited
  - Can build internally packet < 1000bytes
- Fallback to clause 9.10.3 of 802.11e (2005)
  - Packets spaced by minimum possible
  - 802.11e says 10us: can we shorten this?
  - Yes! A minimum of 2us was demonstrated recently





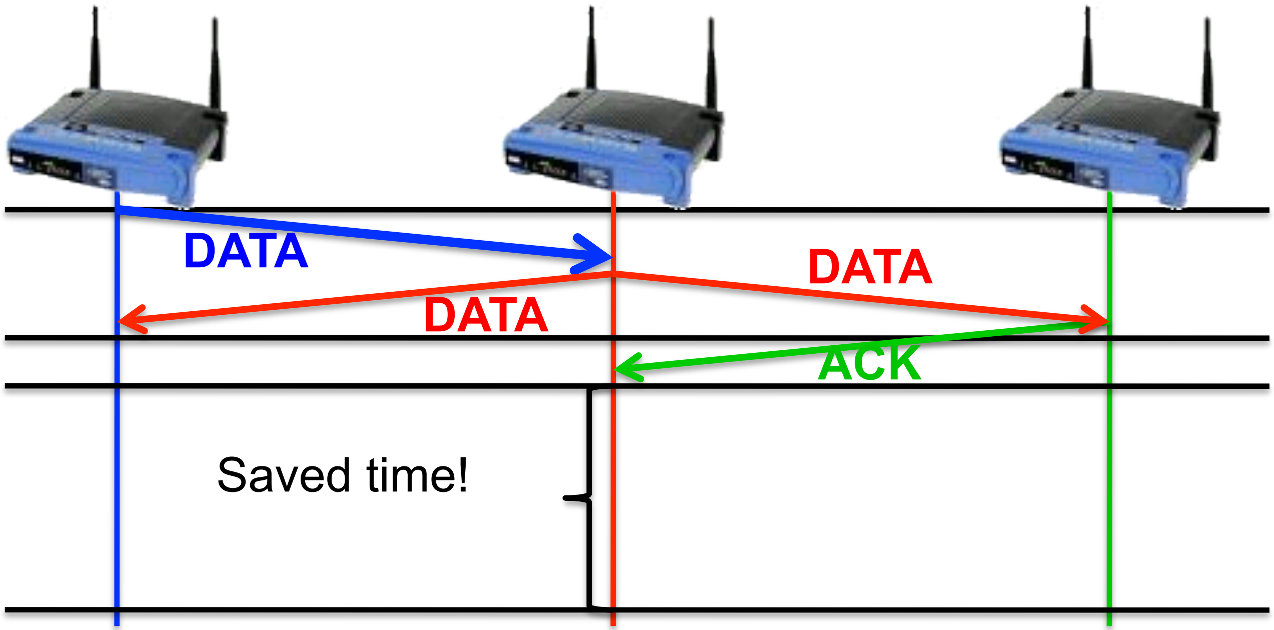
Mesh networks
Simple Forwarder/1

- Packet in transit & single radio interface
  - Best case, no collisions & no noise: two accesses



Mesh networks
Simple Forwarder/2

- Packet in transit & single radio interface
  - Best case, no collisions & no noise: one access + ½~
  - On rx: forwarder broadcasts the rx pkt
  - Left AP receives the broadcast and sets ACK!



END!