Software Defined Networking

SDN Mobile Wireless

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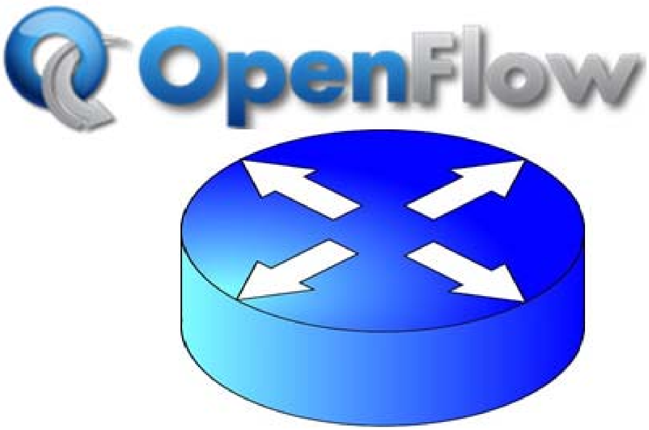

*Based on original slides by Giuseppe Bianchi (University of Roma Tor Vergata)

Wireless MAC layer Reconfigurability *from an SDN perspective*

Giuseppe Bianchi, University of Roma Tor Vergata

Credits to: I. Tinnirello, P. Gallo, D. Garlisi, F. Giuliano, F. Gringoli

Software-Defined Radio (from wikipedia)

- A software-defined radio system, or SDR, is a radio communication system where **components** that have been typically implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead **implemented by means of software** on a personal computer or embedded system.

- **20+ years long research path**
  - AirBlue, CalRadio, GNURadio, RUNIC, SORA, USRP, WARP,...

- **Niche commercial exploitation**
  - Military, etc

Software-Defined Networking (from wikipedia)

- Software defined networking (SDN) is an approach to building computer networks that **separates and abstracts elements of these systems** [...] SDN allows network administrators to have programmable central control of network traffic without requiring physical access to the network's hardware devices.

- **5 years long research path**
  - Pioneered by 2008 OpenFlow paper

- **Almost 2B$ company acquisitions in 2012**
  - Mainly Nicira, but also Contrail, Big Switch, Cariden, Vyatta,...

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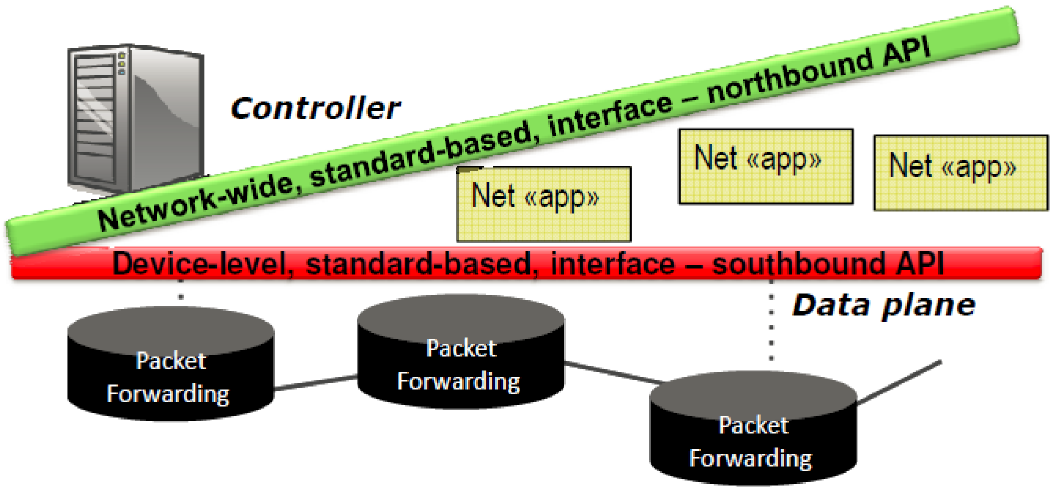
Why SDN == $$$



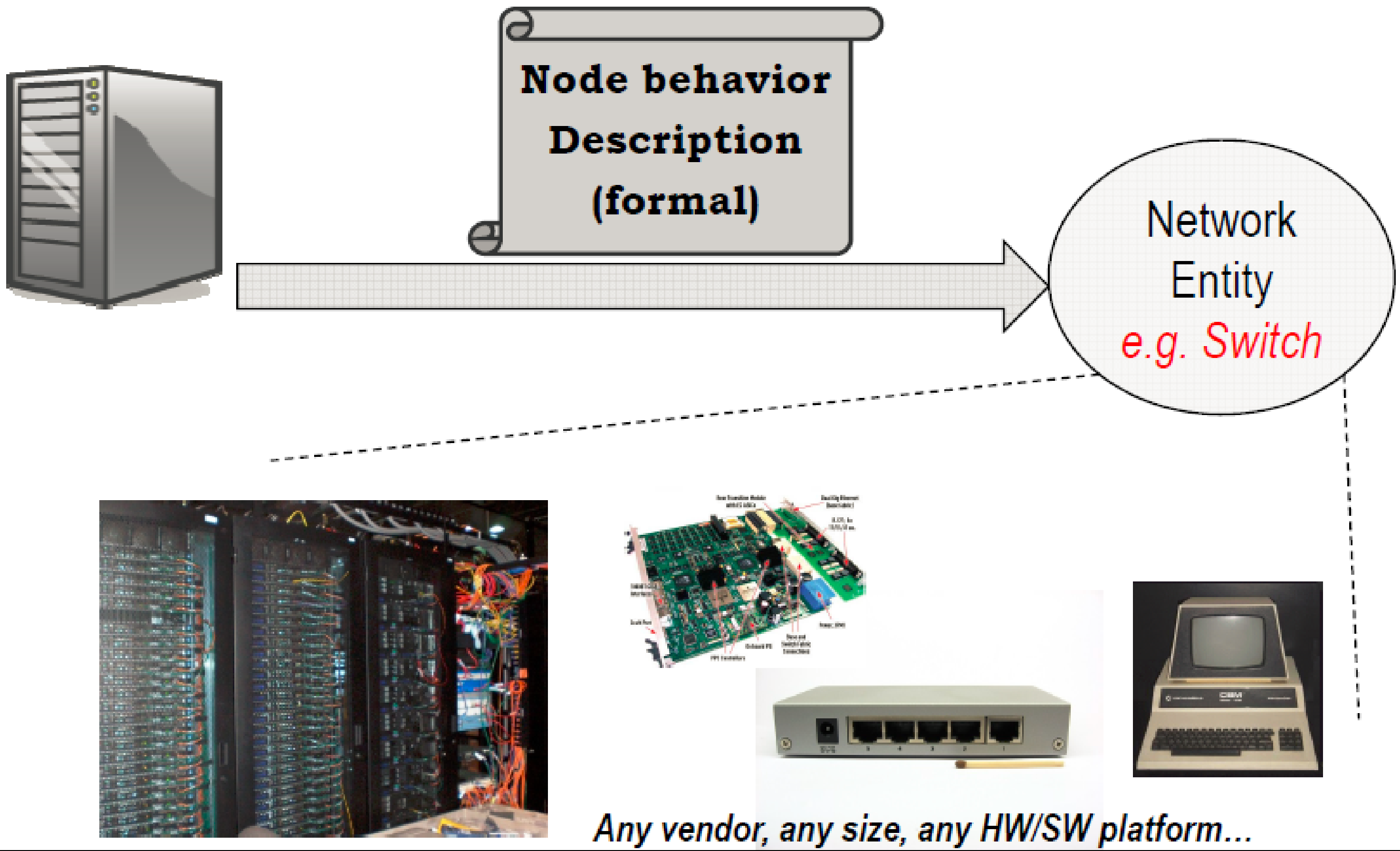
- Business: provisioning and control of network services
  - Fostering easy deployment => fast innovation
- Technical enabler: open configuration APIs
  - Southbound (device level): typically openflow (but not necessarily)
  - Northbound (network control): hot topic
- Today: mostly on southbound (wireless differs!)

Common misconceptions

- SDN = OpenFlow
  - OpenFlow is just ONE possible data-plane API
- SDN = control/dataplane separation
  - SDN relies ALSO on control/data plane separation
  - but does not reduce to just this
- Would not nearly be new, especially in wireless!
  - Well established separation in the wireless domain
  - Enterprise WLAN controllers, CAPWAP, etc: around for more than a decade

SDN: it’s all about abstractions

- So far mostly dealt with in wired networks



OpenFlow: a compromise

- **Best approach**: "persuade commercial name-brand equipment vendors to provide an open, programmable, virtualized platform on their switches and routers"
  - Plainly speaking: *open the box!! No way...*

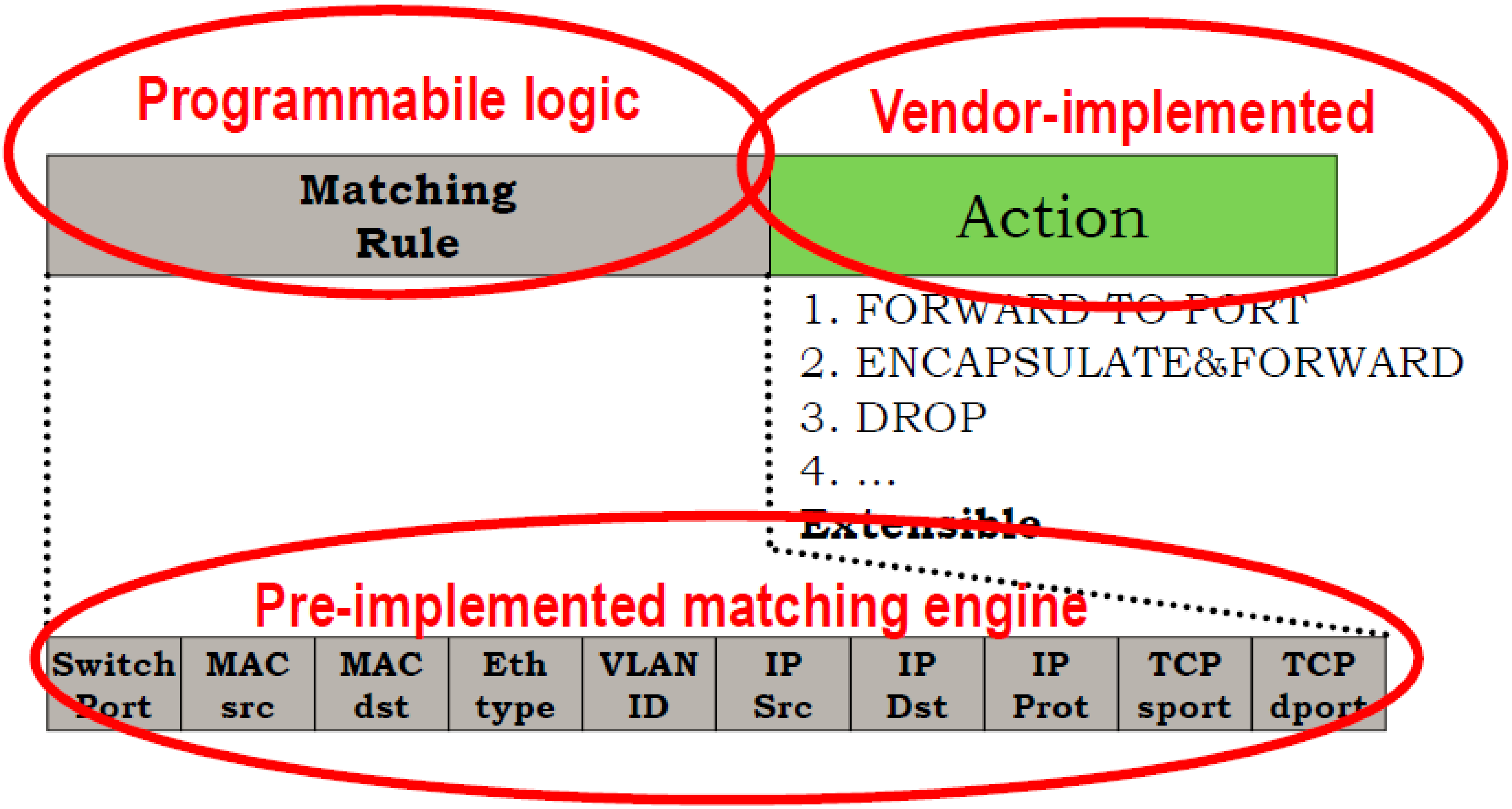
- **Viable approach**: "compromise on generality and seek a degree of switch flexibility that is
  - High performance and low cost
  - Capable of supporting a broad range of research
  - **Consistent with vendors' need for closed platforms.**

- A successful compromise, indeed... ask Nicira ...

[original quotes: from OF 2008 paper]

OpenFlow: just *one* abstraction

- Good for switches, not for «all»



What about SDN in wireless?

- Wireless Openflow...
  - Wireless specific actions: very helpful...
  - ... but match/action API way too skinny
    - We all agree now: SDN >> OpenFlow

- Challenge: which viable programming abstractions for wireless terminals and nodes?
  - Without requiring to «open the box»

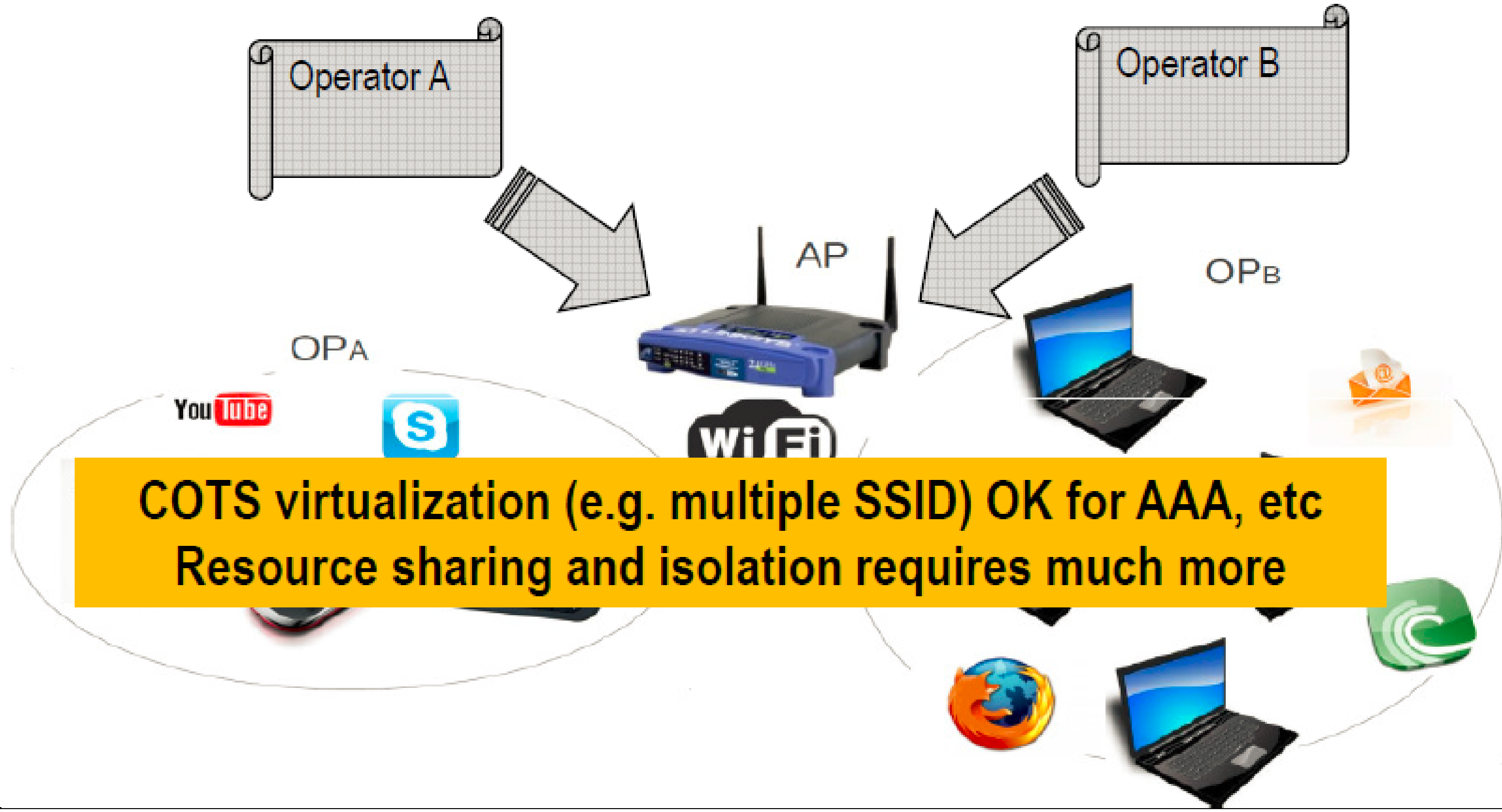
Beneficial to multiple scenarios

- Dynamic spectrum access
- Cognitive
- Performance optimization in niche environments
  - Home, industrial, ...
  - Adaptation to specific context or applications
- Improved support for new PHY
- Virtualization and access network sharing

- And many more...

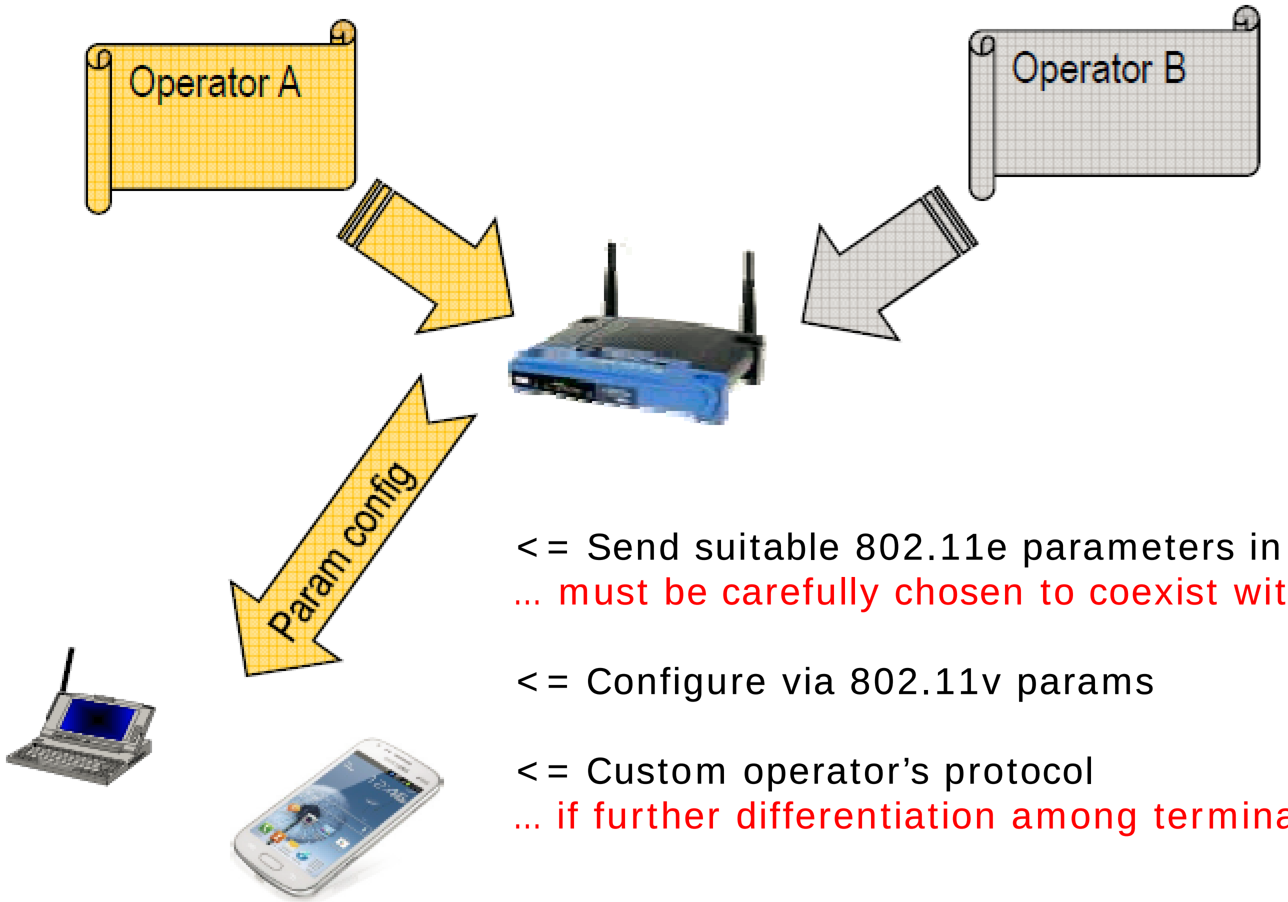
A basic (but compelling) use case: multi-tenant WLAN sharing

- Virtual Operators over shared WLAN infrastructure
  - e.g., airport, hotel, enterprise, etc.



COTS virtualization (e.g. multiple SSID) OK for AAA, etc
Resource sharing and isolation requires much more

Well, we might «hack» this



<= Send suitable 802.11e parameters in OP_A Beacon
... must be carefully chosen to coexist with OP_B

<= Configure via 802.11v params

<= Custom operator’s protocol
... if further differentiation among terminals needed

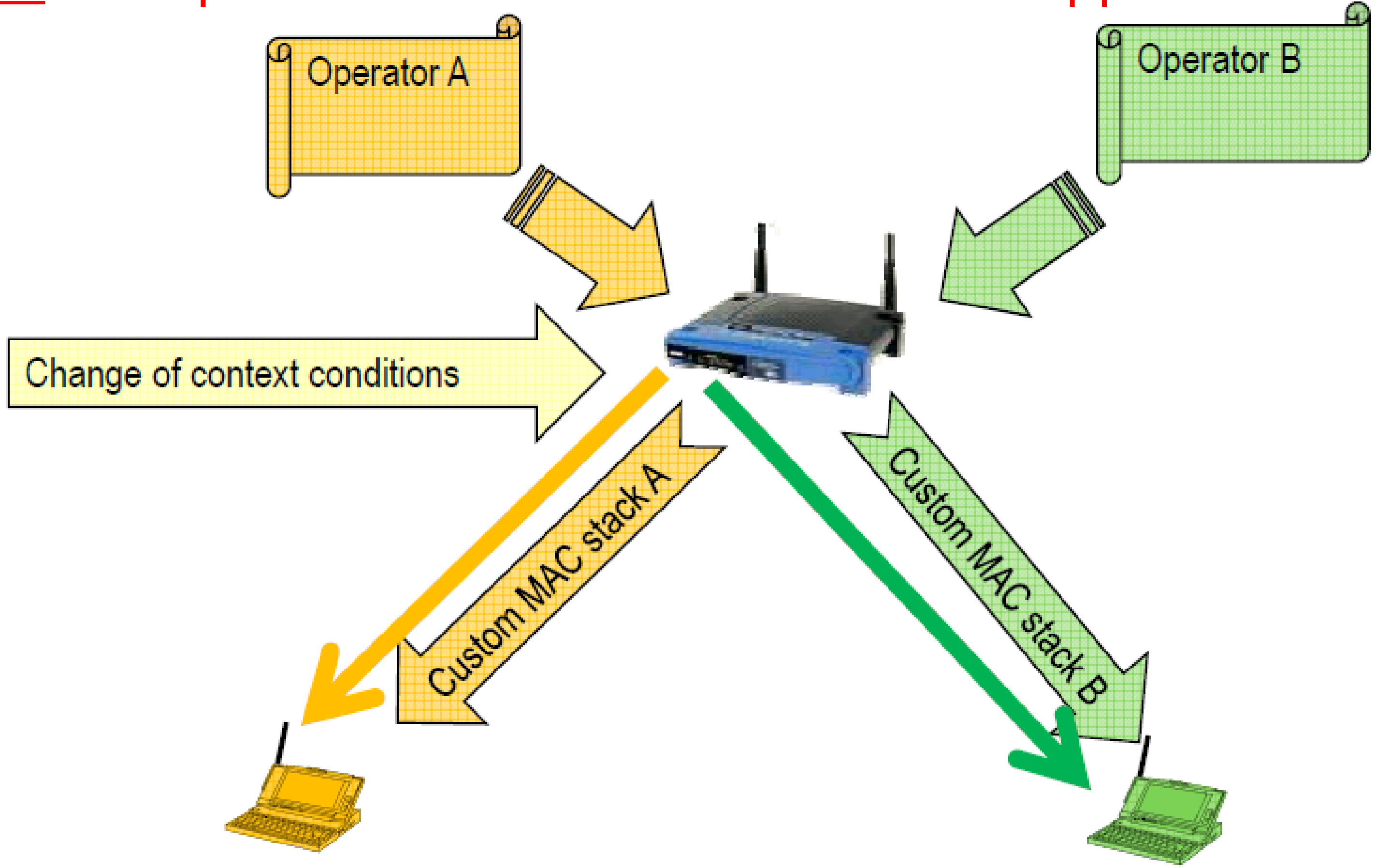
The point is another

- All-in-one MAC protocol, e.g. 802.11
  - We can probably stretch it to fit our context
    - Creative parameter configs, overlay tricks, ...
    - We are good at mastering complexity
      - and brings to accepted papers
  - When impossible? Just promote an amendment!

- But what if... we could change the MAC protocol for each and every context?
  - And we could trivially program our MAC operation?
  - Much simpler!
  - No anymore amendments, unless HW changes

Vision: Software-Defined MAC…

- Whole MAC protocol stack as a sort of JAVA applet



… but…

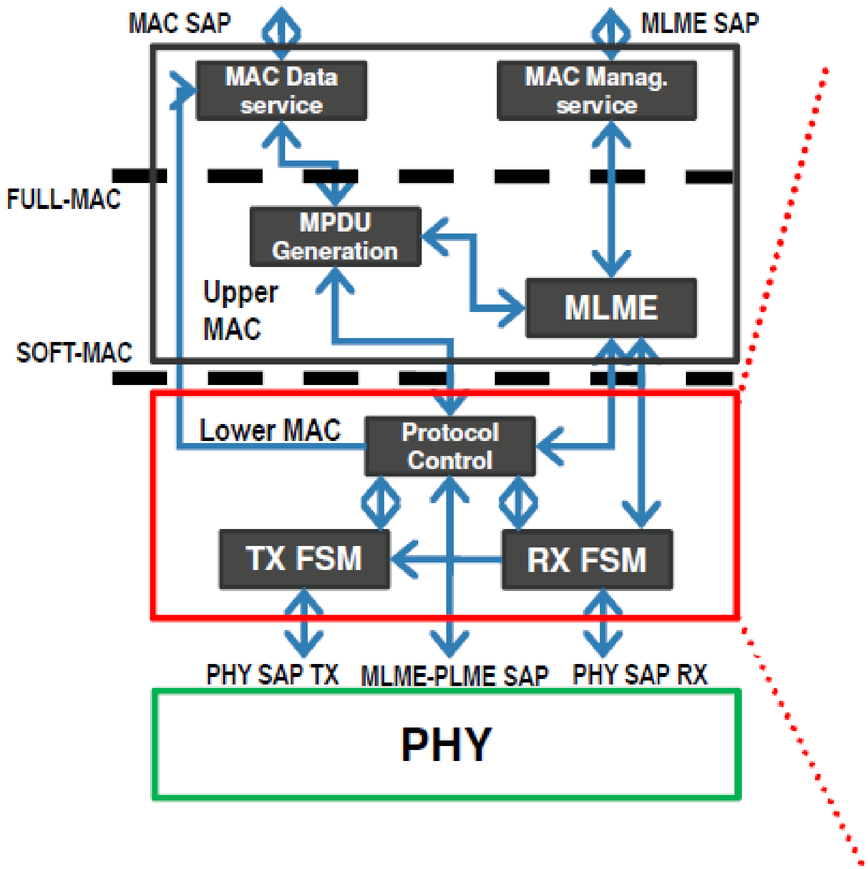
- **Best approach**: "persuade commercial name-brand equipment vendors to provide an open programmable platform on their Wireless NICs"
  - Plainly speaking: *let me hack your NIC!! No way…*

- **Viable approach**: "compromise on generality and seek a degree of Wireless NIC flexibility that is
  - High performance and low cost
  - Capable of supporting a broad range of research
  - Consistent with vendors' need for closed platforms.

- Compromise in Wireless MAC cannot be just a rule-action table!

Current SW coding is wrong answer

- [even assuming Boxes are opened]



- DSP/FPGA SDR boards
  - Cost, performance: just for research
  - «open» box approach: must convince vendors
- Open firmware
  - Probably only openFWWF, sneaked out…
  - not "much" (?!) vendor support
- BUT in both cases…
  - Huge skills/experience, low level languages, inter-module dependencies
    - Assembly, VHDL, low level C, …
  - Complexity! Slow deployment time

Right answer

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- Find the right abstractions!
  - Must yield simple programming models
  - Must not impair performance
  - Sufficient flexibility to support most customization needs
  - Must be «vendor-friendly» ☺
- Another attempt at this:
  - Wireless MAC processor: Computing environment and abstractions for programming MAC protocols
  - MAClets: from offline programming to online, dynamic, MAC stack injection and ultra fast reconfiguration, << 1 micro second

Learn from computing systems?

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- 1: Instruction sets: perform elem entary tasks on the platform
  - A-priori given by the platform
  - Can be VERY rich in special pu computing platforms
    - Crypto accelerators, GPUs, D
- 2: Programmi uctions + conditions
  - Convey desired platfor rithm
- 3: Central Processing U): ex ogram over the platform
  - Unaware of what t ogram specifically
  - Fetch/invoke inst uctions, update registers, etc

Let's MIMIC all this!

Clear decoupling between:
- platform's vendor => implements (closed source!) instruction set & CPU
- programmer => produces SW code in given language

1: Which elementary MAC tasks?
(“our” instruction set!)

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- ACTIONS
  - frame management, radio control, time scheduling
    - TX frame, set PHY params, RX frame,
      set timer, freeze counter, build header,
      forge frame, switch channel, etc
- EVENTS
  - available HW/SW signals/interrupts
    - Busy channel signal, RX indication,
      inqueued frame, end timer, etc
- CONDITIONS
  - boolean/arithmetic tests on available registers/info
    - Frame address == X, queue length >0,
    - ACK received, power level < P, etc

Actually implemented API

- Platform: Broadcom Airforce54g commodity card

events	*actions*	*conditions*
CH_UP	set/get(reg, value)	dstaddr
CH_DOWN	switch_RX()	myaddr

Just "one" possible API

convenient on our commodity platform

"others" possible as well

improved/extended

tailored to more capable radio HW

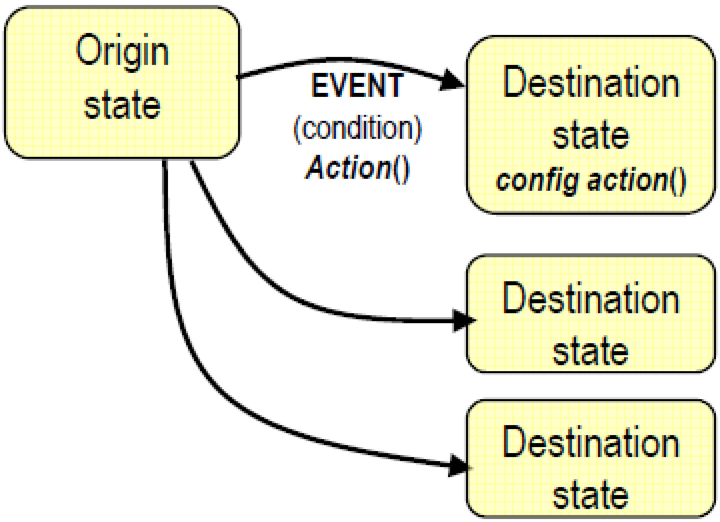
Our point:

<u>have a specified set </u>of actions/events/conditions,

not "<u>which</u>" specific one)

2: How to compose MAC tasks?
("our" programming language!)

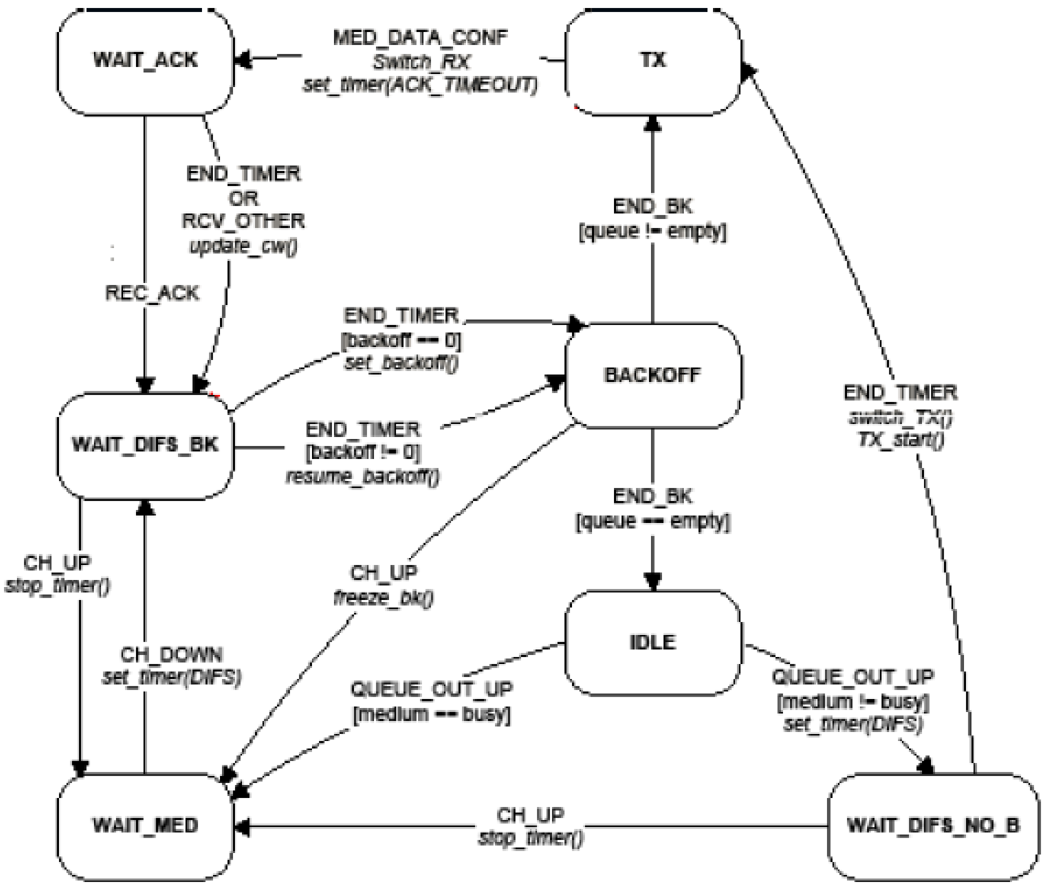
- Convenient "language": XFSM
  eXtended Finite State Machines
  - Compact way for composing available acts/ev/cond to form a custom MAC protocol logic



XFSM formal notation		meaning
S	symbolic states	MAC protocol states
I	input symbols	Events
O	output symbols	MAC actions
D	n-dimensional linear space $D_1 \times \cdots \times D_n$	all possible settings of n configuration registers
F	set of enabling functions $f_i : D \to \{0,1\}$	Conditions to be verified on the configuration registers
U	set of update functions $u_i : D \to D$	Configuration commands, update registers' content
T	transition relation $T : S \times F \times I \to S \times U \times O$	Target state, actions and configuration commands associated to each transition

XFSM example: legacy DCF

- simplified for graphical convenience



Actions:
set_timer, stop_timer, set_backoff, resume_backoff, update_cw, switch_TX, TX_start

Events:
END_TIMER, QUEUE_OUT_UP, CH_DOWN, CH_UP, END_BK, MED_DATA_CONF

Conditions:
medium, backoff, queue

3: How to run a MAC program?
(MAC engine – XFSM onboard executor - our CPU!)

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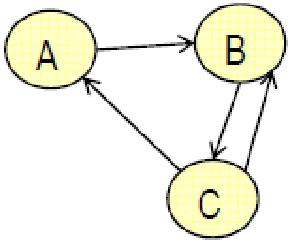
- MAC engine: specialized XFSM executor
  (unaware of MAC logic)
  - Fetch state
  - Receive events
  - Verify conditions
  - Perform actions and state transition

- Once-for-all “vendor”-implemented in NIC
  (no need for open source)
  - “close” to radio resources = straightforward real- time handling

MAC Programs

- MAC description:
  - XFSM

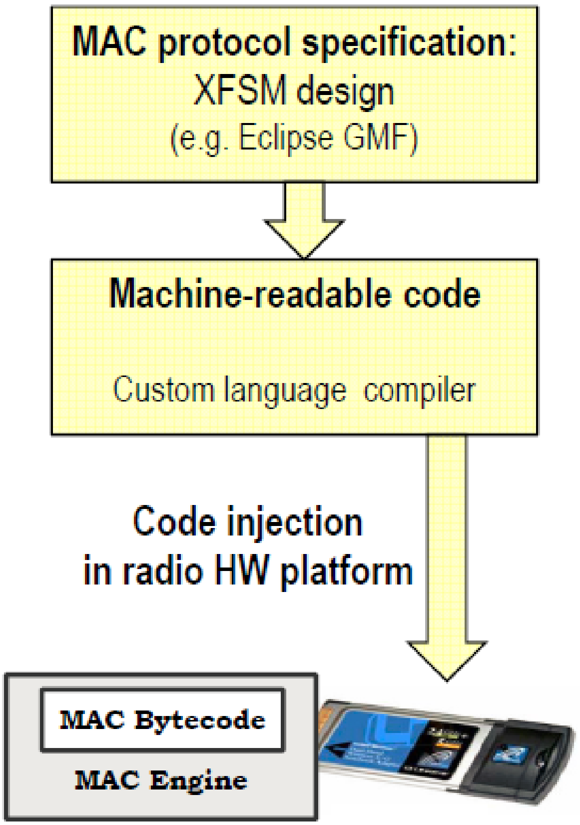


- XFSM => tables

	A	B	C
A		T(A,B)	
B			T(B,C)
C	T(C,A)	T(C,B)	

- Transitions
  - «byte»-code event, condition, action
    - Portable over different vendors' devices, as long as API is the same!!
  - Pack & optimize in WMP «machine-language» bytecode

A	T(A,B)	
B	T(B,C)	
C	T(C,A)	T(C,B)



Machine Language Example
(DCF, 544 bytes)

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Memory address | **Memory** | **Description**

Initial State Descriptor

Memory address								
0x0BC0:	0100	FFFF	0B00	0014	A5FF	6ADA	0014	A5FF
0x0BD0:	6ADA	6C00	80A4	FF00	FF00	3600	80EE	FF00
0x0BE0:	0000	0000	0000	0000	0000	0000	0000	0000

Coded state machine

Memory address	00	01	02	03				
0x0C00:	0100	0100	0100	0401	0108	0508	1C01	010B
0x0C10:	010B	3001	010D	0200	FFFF	5101	010E	030D
0x0C20:	0000	0100	010F	C100	0102	0602	E100	0106
0x0C30:	0106	0401	0108	0508	1C01	010B	030B	FFFF
0x0C40:	CD00	0104	0E0C	0000	0100	0D00	FFFF	0E01
0x0C50:	0109	0909	1C01	010B	0D0B	FFFF	C700	0103
0x0C60:	0C03	E100	0106	0106	FFFF	6601	0110	1600
0x0C70:	0000	0100	0100	FFFF	0E01	0109	0109	1C01
0x0C80:	010B	010B	FFFF	5F01	010F	0A00	0000	0100
0x0C90:	0D00	FFFF	C100	0102	0A02	C700	0103	0B03
0x0CA0:	E100	0106	0D06	FFFF	D300	0105	0D05	E100
0x0CB0:	0106	0D06	FFFF	D300	0105	0705	E100	0106
0x0CC0:	0106	FFFF	6D01	0111	1800	0000	0100	0100
0x0CD0:	0000	0100	0D10	7401	0112	1512	0000	0100
0x0CE0:	1111	9601	0113	0513	0000	0100	0500	0000
0x0CF0:	0100	0304	E100	0106	1206	0401	0108	0508
0x0D00:	1C01	010B	120B	FFFF	A901	0115	0100	B401
0x0D10:	0117	1200	0000	0100	0100	0000	0100	1214
0x0D20:	B901	0118	0310	0000	0100	0300	0401	0108
0x0D30:	1708	1501	010A	010A	1C01	010B	010B	C501
0x0D40:	0119	0800	0000	0100	0500	3001	010D	0200
0x0D50:	0401	0108	0508	1C01	010B	180B	CB01	011A
0x0D60:	0200	0000	0100	0100	0000	0000	0000	0000
0x0D70:	0000	0000	0000	0000	0000	0000	0000	0000
0x0D80:	0000	0000	0000	0000	0000	0000	0000	0000

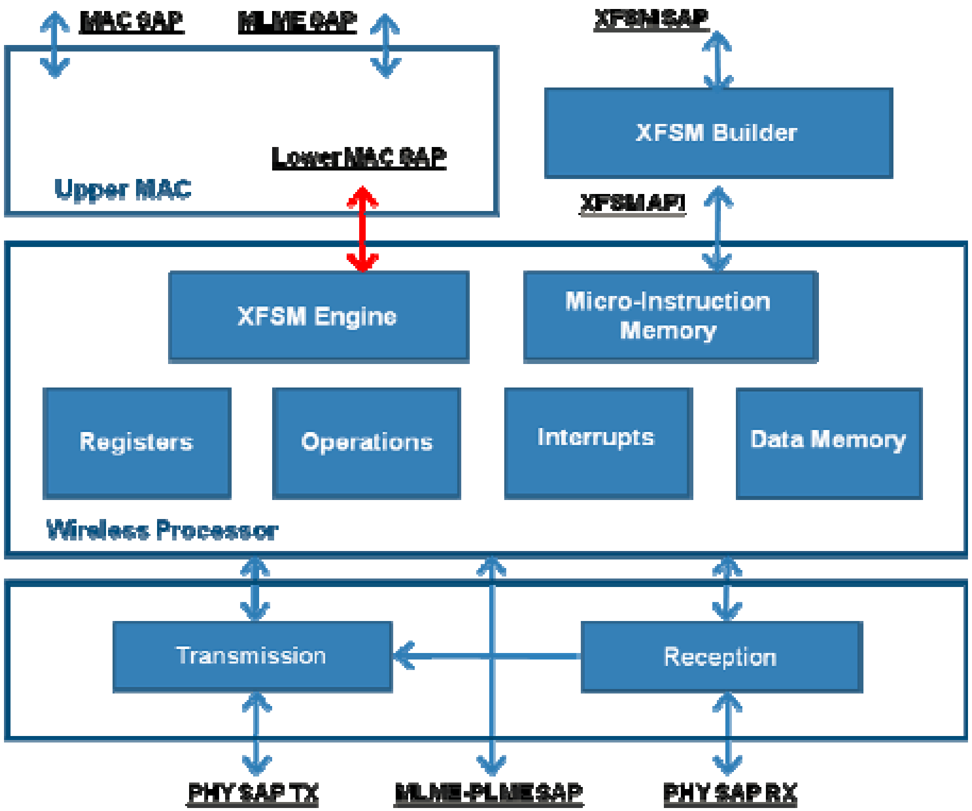
Memory address	00	01						
0x0D90:	00F0	03FE	0DF2	13FE	20FE	27FE	2EFE	35FE
0x0DA0:	0000	0000	0000	0000	0000	0000	0000	0000

```
Outgoing transitions
for state 01
0401 0108 0508 = trans. 1
1C01 010B 010B = trans. 2
3001 010D 0200 = trans. 3
FFFF           = delimiter
```

```
Transition 1
0401 = event pointer
01   = event parameter
08   = event index
05   = target state
08   = action
```

State 01
03 = transitions offset (9 bits)
E = FFFF delimiter

Wireless MAC Processor: Overall architecture



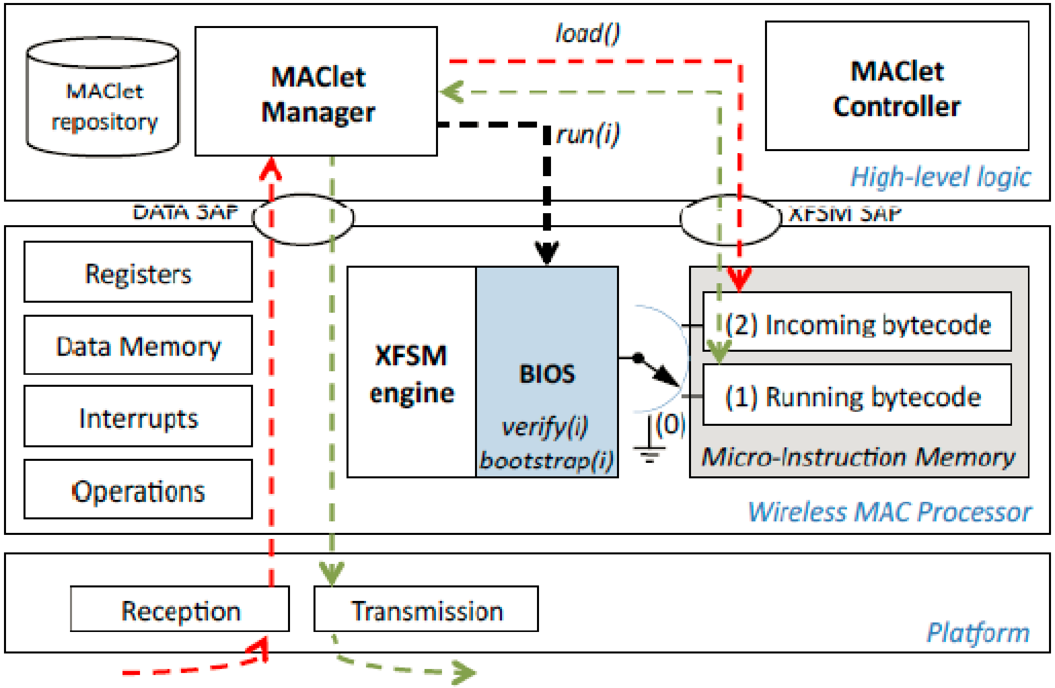
- MAC Engine: XFSM executor
- Memory blocks: data, prog
- Registers: save system state (conditions);
- Interrupts block passing HW signals to Engine (events);
- Operations invoked by the engine for driving the hardware (actions)

From MAC Programs to MAClets

- Upload MAC program on NIC from remote
  - While another MAC is running
  - Embed code in ordinary packets

- WMP Control Primitives
  - load(XFSM)
  - run(XFSM)
  - verify(XFSM)
  - switch(XFSM1, XFSM2, ev, cond)

- Further primitives
  - Synchro support for distributed start of same MAC operation
  - Distribution protocol



"Bios" state machine: DEFAULT protocol (e.g. wifi) which all terminals understand

From theory to practice

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- Obviously, instruction set and MAC Engine can be “easily” implemented in a software-defined radio…
  - e.g., FPGA, WARP, …
- But… can this be done on commodity HW?
  - e.g., ultra-cheap ordinary WLAN NIC
- Yes!!!
  - Reference platform: broadcom Airforce54g 4311/4318
    - Hands-on experience on card’s assembly language FW
    - general purpose processor (88 MHz), 64 registers, 4KB data memory, 32 KB code memory
  - Partly leveraging existing card HW facilities
    - HW configuration registers for radio resource and event handling
    - Frequency, power, channel sensing, frame forging facilities, etc
    - Available HW events (packet queued, plcp end, rx end, rx correct frame, crc failure, timer expiration, carrier sense, etc)

Implementation at a glance

- Delete 802.11 firmware
  - Both Broadcom and openFWWF
    we do NOT want yet another firmware MAC to hack!
- Replace it with *[once for all developed]*:
  - Implementation of actions, events, conditions
    - in part reusing existing HW facilities
  - MAC engine: XFSM executor
- Develop “machine language” for MAC engine
  - Custom made “bytecode” specified and implemented
    - 6 bytes instructions, state transition table (sparseness exploited)
- Address several annoying technical hurdles
  - NO direct HW interrupts control available in Broadcom
  - State and state transition optimizations, ...

Public-domain

- Supported by the FLAVIA EU FP7 project
  - http://www.ict-flavia.eu/
- Ongoing integration in the CREW EU FP7 federated testbed
  - http://www.ict-flavia.eu/
- Public domain release
  - Project page: http://wmp.tti.unipa.it
  - Download: https://github.com/ict-flavia/Wireless-MAC-Processor
- Released distribution:
  - Binary image for WMP
  - You DO NOT need it open source!

    Remember the "hard-coded" device philosophy…
    - Conveniently mounted and run on Linksis or Alix
  - Source code for everything else
  - Manual & documentation, sample programs

WMP Functional validation «static» MAC programs

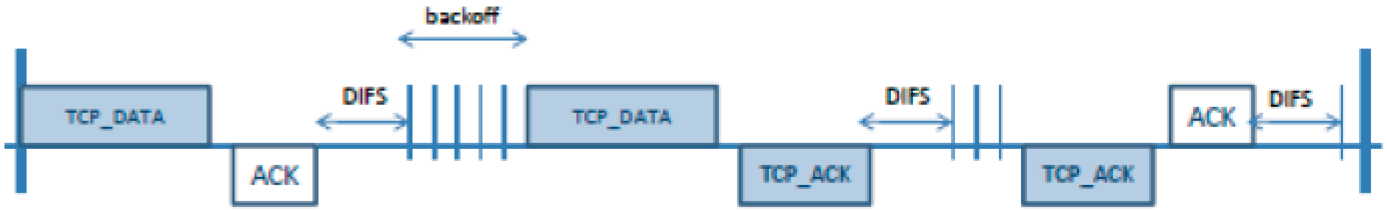
- Success IF WMP permits very easy/fast Lower MAC modifications or re-design (vs months or hands-on experience with openFWWF/assembly

- “scientifically trivial” use cases, tackling distinct MAC aspects recurring in literature proposals
  - Piggybacked ACK
    - Programmable management of frame replies
  - Pseudo-TDMA
    - Precise scheduling of the medium access times
  - Randomized multi-channel access
    - Fine-grained radio channels control
  - Multi-tenant access network sharing, with different protocols
    - Virtualization

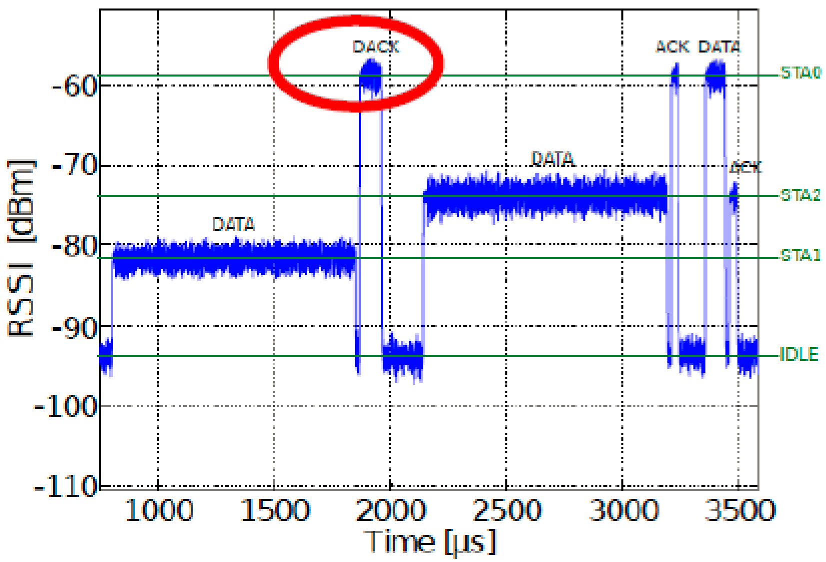
- Development time: O(days)
  - Including bug fixing in engine/API, otherwise hours

Piggybacked ACK

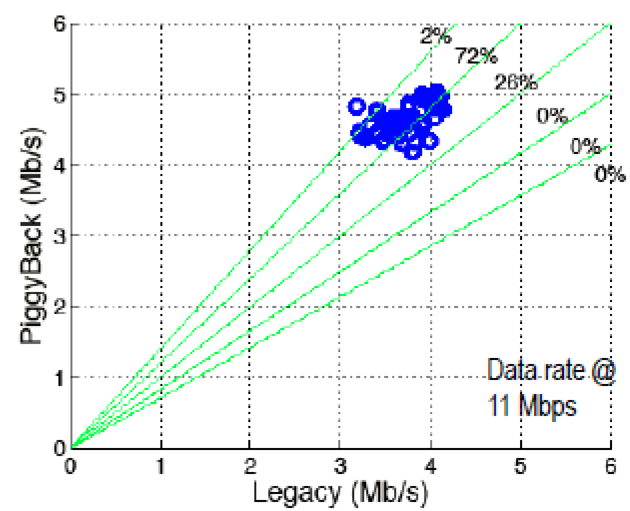
- If available, send TCP ACK instead of MAC ACK, otherwise send normal ACK



Channel activity trace

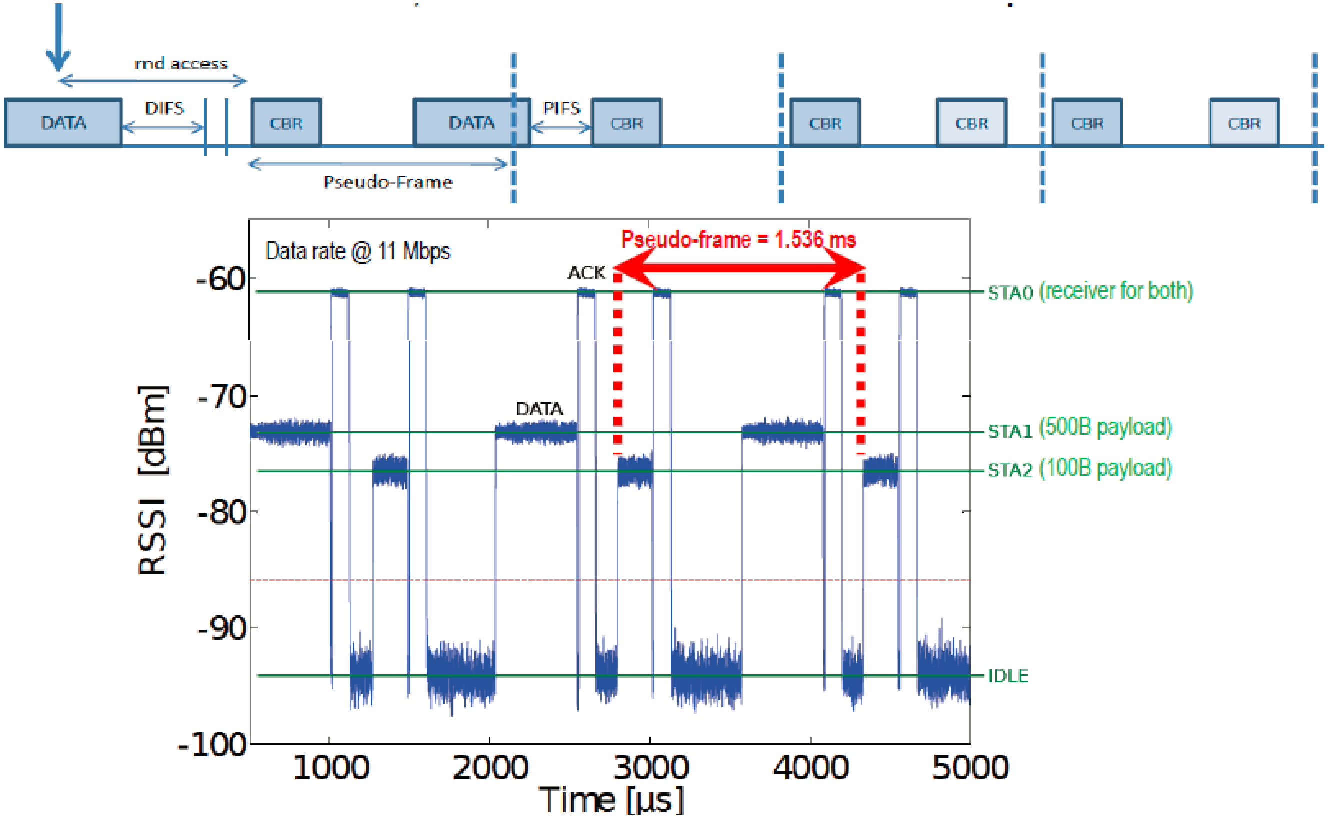


Performance gain



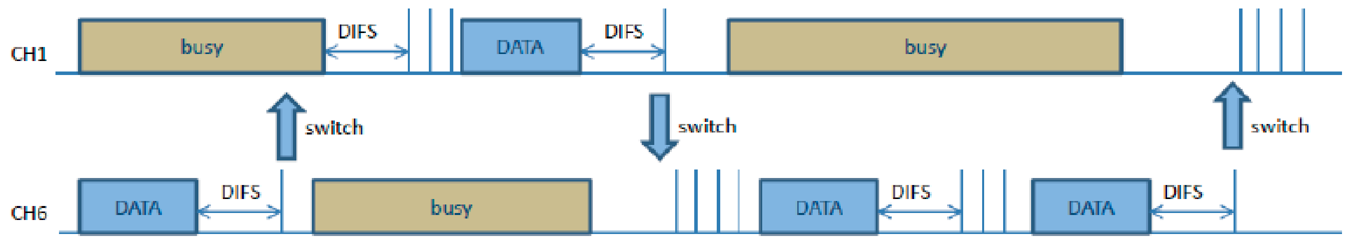
Pseudo-TDMA
[literature proposal]

- After first random access, schedule next transmissions at fixed temporal intervals

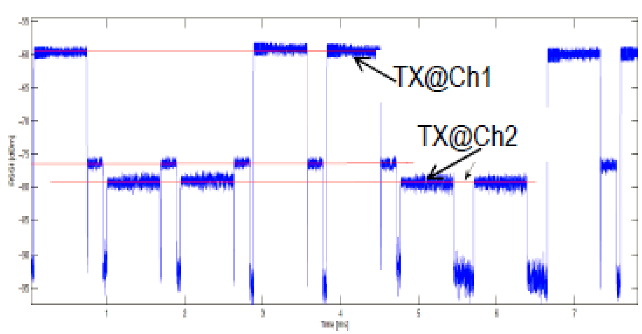


Randomized multichannel access

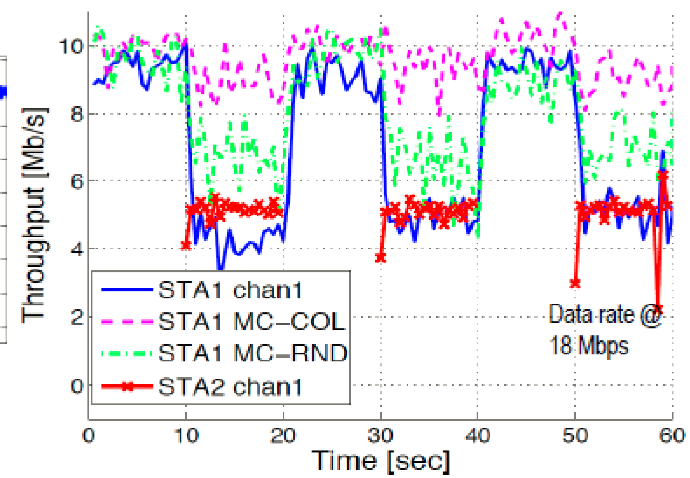
- Per EACH frame, randomly select backoff AND channel (switch on as little as per frame basis)



Channel activity trace

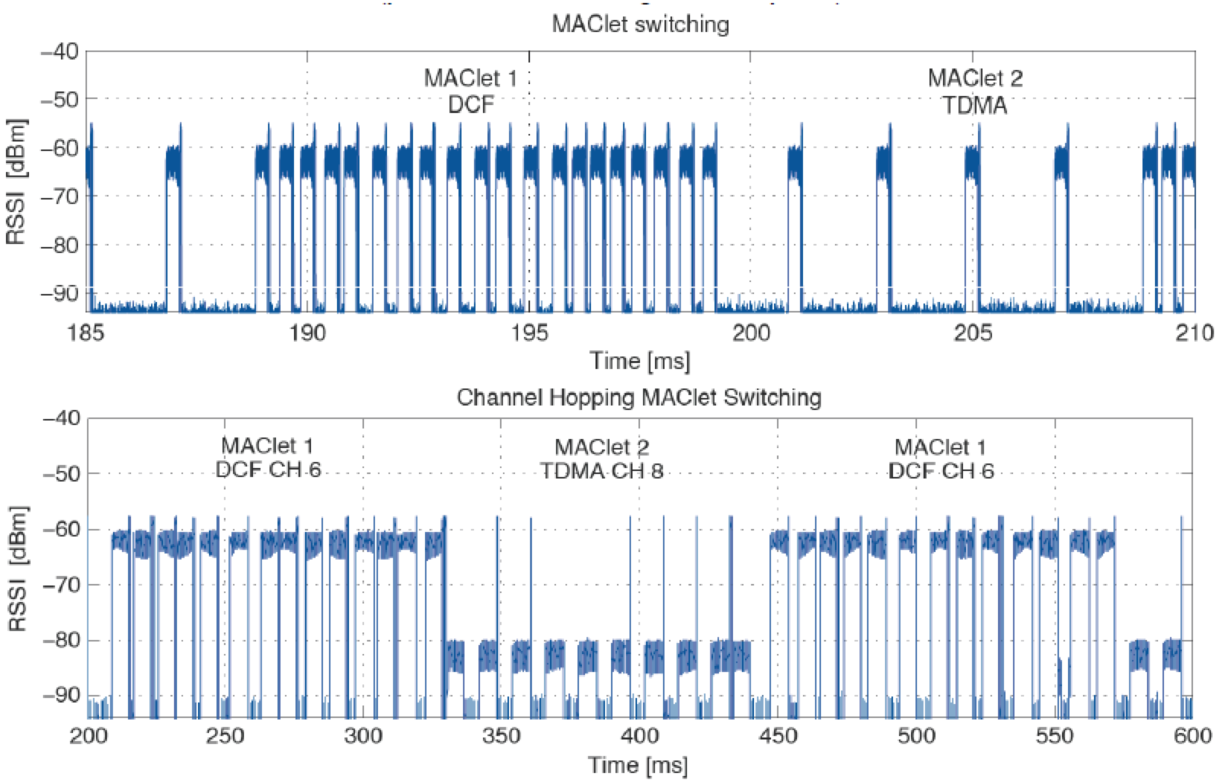


Performance gain



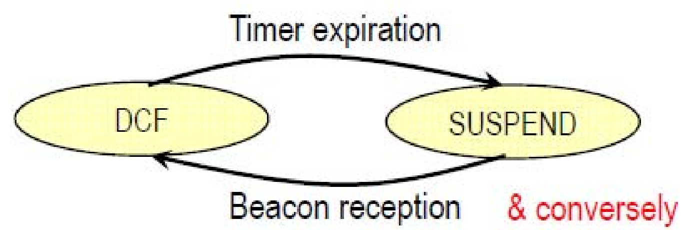
Multi-threaded MAC

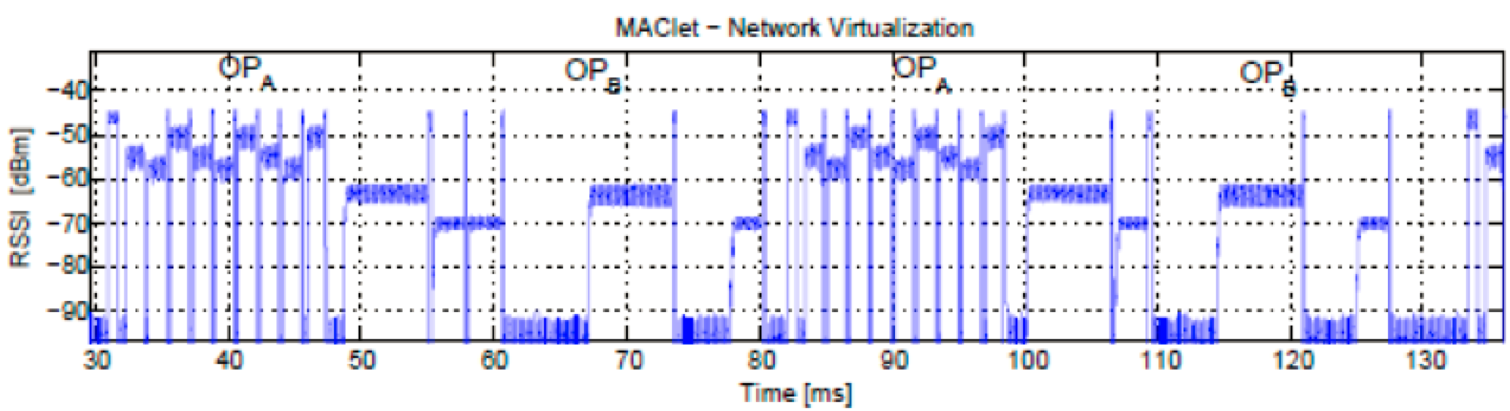
- Success IF seamless switch from one MAC program to another in negligible time
  - Result: less than 0.2 us over such cheap hardware!
    - (plus channel switching time if required)



AP Virtualization with MAClets

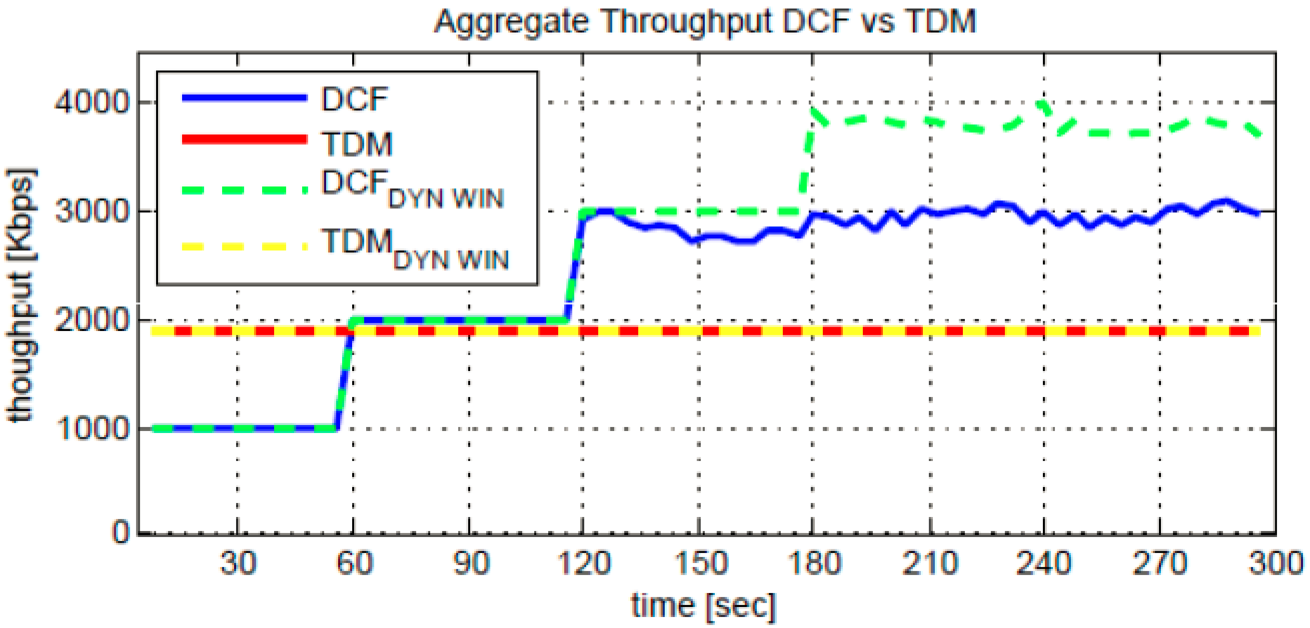
- Two operators on same AP/infrastructure
  - A: wants TDM, fixed rate
  - B: wants best effort DCF
- Trivial with MAClets!
  - Customers of A/B download respective TDM/DCF MAClets!
- Isolation via MAClet design
  - Time slicing DESIGNED INTO the MAClets! (static or dynamic)





An Example of Throughput Performance

- 3 FIXED stations @ 0.63 Mbps vs. 5 BEST stations @ 1Mbps

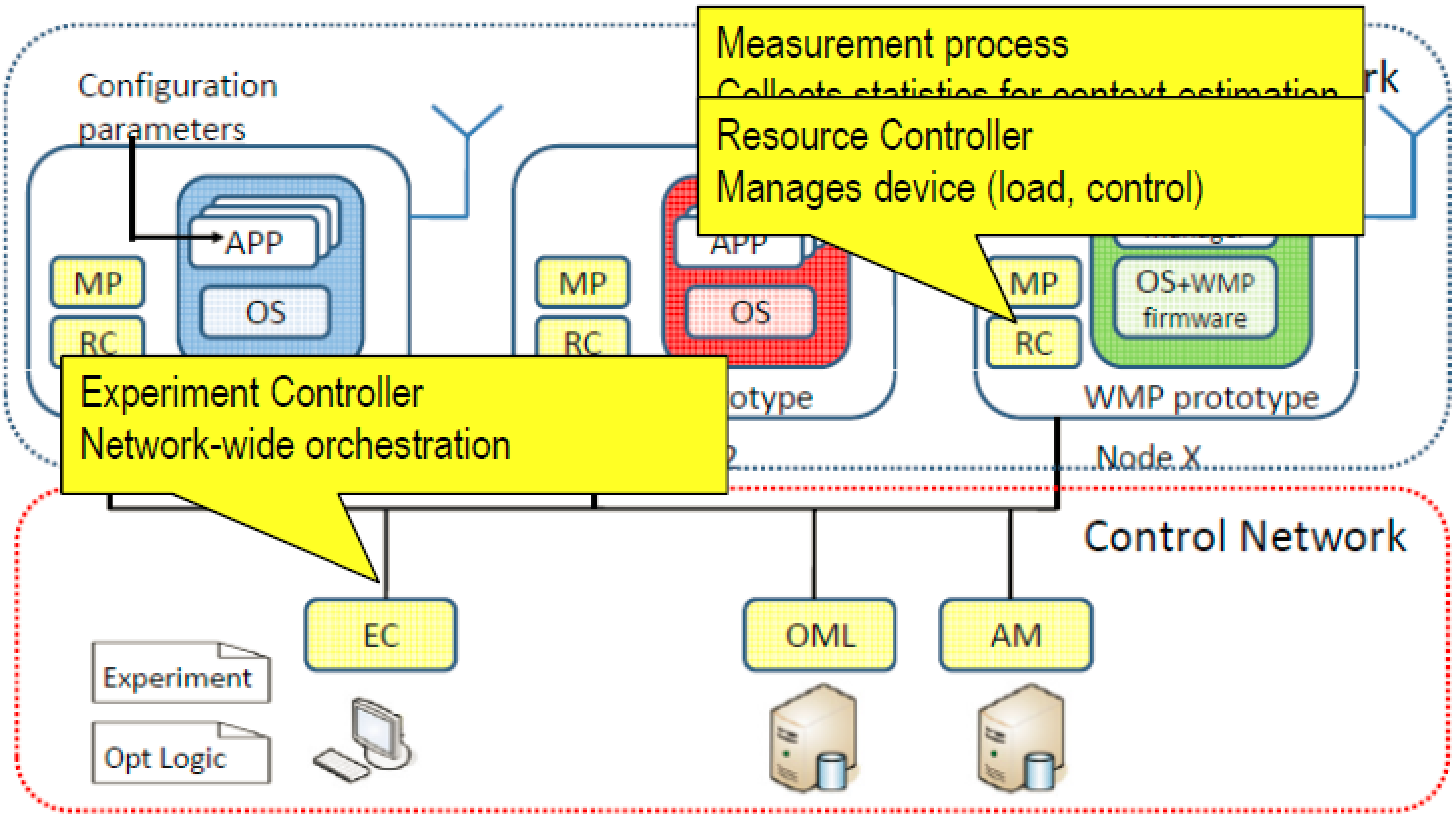


What about control?

- Context-dependent wireless operation
  - Gather context information (measurements)
  - Adapt protocol logic accordingly

- Preliminary insights
  - No need to reinvent the wheel!
  - WMP ported on OMF testbed control framework
    - Different perspective, but same elementary building blocks

Deployed architecture



Control primitives
available on CREW remote testbed

- Loading messages
  - Upload bytecode programs
- Call messages
  - Trigger actions on devices
- Event messages
  - Notifications from devices to Controller
- Management messages
  - Reports on note status and configuration

«network» programs

- Scripting language OEDL (ruby-like)
- Very simple & intuitive

Sensing Configuration

```
defGroup('N1', property.res1 ) do |g|
  g.addApplication('WMPdump') do |app|
    app.property('cw')
  end
end
```

Context Definition

```
defEvent(:HIGH_CW)  do |event|
  app_status =
group('N1').state("apps/app[@name='WMPdump']/io/out/line")
  if !app_status.nil?
    app_status.each do |element|
      event.fire if element>31
    end
  end
end
```

Reaction Mechanism

```
onEvent(:HIGH_CW) do |event|
   group('N1').stopApplication('WMPdump')
   group('N1').addApplication('bytecode-manager') do |app|
    app.setProperty('run', 2)
   end
   group('N1').startApplication('bytecode-manager')
end
```

Scenario

```
onEvent(:ALL_UP_AND_INSTALLED) do |event|
  group('N3').exec('iperf -s')
  wait 1
  group('N2').exec('iperf -c 192.168.0.3 -t 100 -i 1')
  group('N1').exec('iperf -c 192.168.0.3 -t 100 -i 1')
  wait 1
  group('N1').startApplications
  wait 30
  Experiment.done
end
```

Conclusions

- Device-level programming abstraction
  - Consistent with vendors' need for closed platforms
- Context-specific protocol adaptation!
  - Wireless access: no more one-size-fits-all
  - Beyond the need for standards?
- From node to network
  - Preliminary control framework deployment
  - Towards cognitive reconfiguration of whole access logic!

OpenFlow versus SDN in Wireless

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OpenFlow	SDN in Wireless
Switches (e.g. NEC PFLOW PF5240F)	Wireless NICs (e.g. Broadcom Airforce54g)
High performance and low cost Capable of supporting a broad range of research Consistent with vendors' need for closed platforms => Vendor-implemented actions (closed source)	
SDN Controller	XFSM Builder
Flow Entries	State Transitions
Packets	Events (e.g. busy channel, end timer)
Matching Rule (e.g. port == 80)	Conditions (e.g. frame address == X)
Action (e.g. drop packet)	Action (e.g. switch channel, set timer)
FlowVisor	MAClets

References

- Open Networking Foundation: OpenFlow-Enabled Mobile and Wireless Networks, ONF Solution Brief, September 30, 2013. https://www.opennetworking.org/images/stories/downloads/sdn-resources/solution-briefs/sb-wireless-mobile.pdf