SoftAir:
A Software Defined Networking and Network Function Virtualization Architecture for 5G Wireless Systems

I. F. AKYILDIZ

Ken Byers Chair Professor in Telecommunications
Georgia Institute of Technology
School of Electrical and Computer Engineering
BWN (Broadband Wireless Networking) Lab
Atlanta, GA 30332, USA
http://www.ece.gatech.edu/research/labs/bwn
EVOLUTION OF WIRELESS SYSTEMS

Global Mobile Data Traffic, 2015 to 2020

<table>
<thead>
<tr>
<th>Year</th>
<th>Exabytes per Month</th>
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</thead>
<tbody>
<tr>
<td>2015</td>
<td>3.7</td>
</tr>
<tr>
<td>2016</td>
<td>6.2</td>
</tr>
<tr>
<td>2017</td>
<td>9.9</td>
</tr>
<tr>
<td>2018</td>
<td>14.9</td>
</tr>
<tr>
<td>2019</td>
<td>21.7</td>
</tr>
<tr>
<td>2020</td>
<td>30.6</td>
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1 Exabyte = $10^{18}$ Bytes

Pictures taken at St. Peter’s Square for papal inauguration ceremonies of Pope Benedict (2005) and Pope Francis (2013)

OBJECTIVES OF 5G WIRELESS SYSTEMS

- Ultra High Data Rates
  - 100x
  - 10 Gbps peak data rate
  - 100 Mbps cell edge data rate

- Mobile Cybersecurity

- Ultra High Capacity
  - 1000x capacity/km²

- Flexible Network Architectures

- Reduced Latency
  - RAN Latency < 1ms
  - (Almost Zero Latency)

- Connection of Billions of Things & People
  - (7 Billion People, 7 Trillion Things)
  - Scalability

- Always Connected to Best Networks
  - Anytime, Anywhere

- Energy Savings (90%) & Cost Reduction

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10 KEY ENABLING TECHNOLOGIES FOR 5G
I. F. Akyildiz, S. Nie, C. Han, and M. Chandrasekaran, “5G Roadmap: 10 Key Enabling Technologies,”

- Software Defined Networking (SDN)
- Network Function Virtualization (NFV)
- Internet of Things
- Device-to-Device Communications
- Millimeter Wave & Terahertz Band
- Ultra-Densification
- Massive MIMO
- Multiple Access Techniques
- Green Communications
- Big Data & Mobile Cloud Computing
Current 5G Projects @ BWN LAB

SoftAir Project
- Software Defined Networking (SDN)
- Network Function Virtualization (NFV)

TeraNets Project
- Terahertz Band & Ultra Massive MIMO (1024 x 1024)

MetisX
- CHANNEL MODELING & SIMULATION TOOL

IoT
- * Internet of Things
- * Internet of NanoThings
- * Internet of BioNanoThings

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TRAFFIC ENGINEERING FOR SOFTWARE DEFINED NETWORKS


PATENTS WITH HUAWEI-SHENZEN
SOFTWARE-DEFINED NETWORKING AND NETWORK FUNCTION VIRTUALIZATION SOLUTIONS: CORE NETWORK


REVIEW OF EXISTING W-SDN ARCHITECTURES

I. F. AKYILDIZ, S.-C. LIN, P. WANG,
"WIRELESS SDNS & NFV FOR 5G CELLULAR SYSTEMS: AN OVERVIEW AND QUALITATIVE EVALUATION,"
COMPUTER NETWORKS (ELSEVIER) JOURNAL, VOL. 93, PART 1, PP. 66-79, DECEMBER 2015.

- **CellSDN**
  - * SD Cellular Core Network Design

- **C-RAN**
  - * SD Radio Access Network Design
    - China Mobile Research Institute. (Jun. 2014). C-RAN White Paper:

- **DoCoMo W-SDN**
  - * Modified C-RAN

- **SK Telecom W-SDN**
  - * Integrated SD-CN and SD-RAN Architecture

L. E. Li, Z. M. Mao, and J. Rexford, “Toward Software-Defined Cellular Networks,”
European Workshop on Software Defined Networking (EWSN), 2012.

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LIMITATIONS OF C-RAN & NTT DOCOMO & SK TELECOM

* Limited Scalability and Evolvability of RANs: Coarse-Grained BS Decoupling
* No NW virtualization functionalities
* Only RAN considered without the CN functionalities
* Traffic Engineering solutions discussed mainly at PHY layer
**SoftAir PROJECT**

I. F. Akyildiz, P. Wang, and S.-C. Lin,

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**SoftAir Architecture**

1. Scalable Design for SD-RAN & SD-CN (Scalable Cloudification)
2. Network Function Virtualization (NFV)

---

**SoftAir Management Tools**

1. Control Traffic Management
2. Network Virtualization
   * Network Hypervisor
   * Wireless Hypervisor
   * Switch Hypervisor
3. Traffic Classifier

---

**SoftAir Traffic Engineering Solutions**

1. Dynamic RRH Formation
2. Collaborative Scheduling
3. Mobility Management
4. SD-Gateway (to IoT/WSN)
SOFTAIR ARCHITECTURE: (SCALABLE DECOUPLING PLATFORM)

- Customized Applications
- Managing Tools

Open, programmable & virtualizable NW forwarding infrastructure

Control Plane

Data Plane Interface (e.g., OpenFlow and SNMP)

Network Controller

Data Plane

Baseband Servers (BBS)

SD-CN

SD-RAN

Fronthaul Network

Backhaul link

SD-BS1

Baseband Unit 1

SD-BSN

Baseband Unit N

SD-RAN

Fronthaul Network

RRH: Remote Radio Head
**QUANTITATIVE EVALUATION OF SOFTAIR**

**Cloud-RAN based 5G Systems**

- **Centralized Baseband Processing**
  - CPRI: Used to separate HW antenna (RRHs) and SW algorithms (BBS)
  - Bandwidth required I-Q transmissions becomes a bottleneck

**SoftAir: Scalable SD-RANs**

- **Partial Baseband Processing at RRHs**
  - MODEM is put on the RRHs
  - I-Q transmissions are eliminated
**UPLINK PHYSICAL LAYER PROCESSING CHAIN AT SD-BS (RX CHAIN)**

**Uplink Signal Flow**

- **Signal from UE**
  - RF to BB
  - S/P Conversion
  - Remove Cyclic Prefix + FFT
  - Resource Demapping
  - QPSK⁻¹ Equalizer
  - FEC⁻¹
  - MAC

**Split A: C-RAN**
- **Encode to CPRI**
- **Raw I/Q samples are transmitted between RRHs and BBSs (Massive redundancies transmitted over fronthaul links)**

**Split B**
- **Cell Processing**
  - RRHs remove CP, apply DFT to transform samples into frequency domain, and remove guard band subcarriers

**Split C**
- **User Processing**
  - Further include resource element (RE) demapper in RRHs, which categorizes REs with respect to served UEs
  - Per-cell processing in RRHs; per-user processing in BBSs

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UPLINK PHYSICAL LAYER PROCESSING CHAIN
AT SD-BS (RX CHAIN)

Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Bandwidth (MHz)</td>
<td>1.4, 3, 5, 10, 15, 20</td>
</tr>
<tr>
<td># of UE transmit antennas</td>
<td>4</td>
</tr>
<tr>
<td># of RRH receive antennas</td>
<td>4</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
</tr>
<tr>
<td>Cyclic prefix</td>
<td>Normal</td>
</tr>
<tr>
<td>Cyclic shift</td>
<td>0</td>
</tr>
<tr>
<td>Duplex mode</td>
<td>FDD</td>
</tr>
</tbody>
</table>

Data rate requirements on the fronthaul link for QPSK modulation

- Split A
- Split B
- Split C
- Symbol rate

Uplink channel bandwidth (MHz)

Fronthaul data rate requirements (Mbps)
SOFTAIR PROJECT

1. F. Akyildiz, P. Wang, and S.-C. Lin,

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   * Wireless Hypervisor
   * Switch Hypervisor
3. Traffic Classifier
1. Dynamic RRH Formation
2. Collaborative Scheduling
3. Mobility Management
4. SD-Gateway (to IoT/WSN)
CONTROL TRAFFIC MANAGEMENT

Management Tools
- Inter-Controller Synchron.
- In-band Signaling Mechanism
- Optimal Controller Placement

Diagram:
- Control Flow
- Data Flow
- Link Connection
- OF Switch
- Controller
- P-GW MME/S-GW
- eNB
- Server
- Cellular Networks
- IP Networks

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Network Virtualization in SoftAir

Virtual Network 1

Applications
Network Controller 1
OpenFlow Interface
V-BS 1
Forwarding Table
OFDMA
PHY
Wireless Hypervisor
V-BS 2
Forwarding Table
CSMA
PHY

Virtual Network 2

Applications
Network Controller 2
V-Switch 1
Forwarding Table
Switch Hypervisor
Switching Fabric
V-Switch 2
Forwarding Table

Managing Tools

Network Hypervisor
Network Controller 3

Data Messages (Virtual Network 1)
Data Messages (Virtual Network 2)
Control Messages (Virtual Network 1)
Control Messages (Virtual Network 2)
NETWORK VIRTUALIZATION: NETWORK HYPERVERSOR

VO 1
Cellular Operator
- QoS
- Mobility Management
- Subscriber Management

Applications
Controller 1

VO 2
Smart Grid Operator
- Routing
- Fast Failure Recovery
- QoS

Applications
Controller 2

VO N
Global Network Management
- Control Traffic Balancing
- Network Resource Auctioner
- Global Traffic Classifier

Applications
Controller N

Network Hypervisor

Backhaul link
SD-Switch

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• Execute the resource sharing polices determined by the NETWORK HYPERVERSOR

• Wireless Hypervisor:
  Uses a scheduling algorithm in the BBSs to realize the resource sharing determined by the NW Hypervisor.

• Switch Hypervisor:
  Uses a scheduling algorithm in the core SD-switches, e.g., FlowVisor
DESIGN PRINCIPLE: NETWORKVIRTUALIZATION

- “Horizontal”: Optimal resource allocation along the way
  - UL SD-RAN → SD-CN → DL SD-RAN
    1. UL SD-RAN: Multi-user detection
    2. DL SD-RAN: Massive MIMO & Power slicing

- “Vertical”: Joint optimization for congestion control, flow routing, and power slicing
DESIGN PRINCIPLE: NETWORK VIRTUALIZATION

Joint Optimization for Network & Wireless & Switch Hypervisors

- NW-Hypervisor level: Routing Policies (Resource Sharing Policies)
- WIRELESS/SWITCH HV-level: Scheduling Policies
  \[ \Rightarrow \text{Optimally determine at the same time} \]
**DESIGN PRINCIPLE: WIRELESS HYPERVISOR**

*Wireless Link Scheduling:* Find non-conflict set of RRHs by avoiding interference between them
JOINT OPTIMIZATION PROBLEM FOR NETWORK VIRTUALIZATION

**Network Utility Maximization (NUM) Problem**

* **Flow Routing:** NW layer - Network Hypervisor
* **Link Scheduling:** MAC/PHY layer - Wireless/Switch Hypervisors

**Objective:** Maximize total supportable traffic arrival rate from all VOs

**Subject to**
- Flow conservation constraint for routing  ➜ NW HV
- Bandwidth constraint in the core NW  ➜ SWITCH HV
- RAN capacity constraint characterizing the interference for wireless channels  ➜ WIRELESS HV
OPTIMAL SYSTEM DECOUPLING FOR NP-HARD JOINT OPTIMIZATION

- WIRELESS/SWITCH HV-level
  - Scheduling Policies
    
    OPTIMAL non-conflict set of RRHs
    OPTIMAL bandwidth scheduling in core SD-switches

- NW-Hypervisor level
  - Routing Policies (Resource Sharing Policies)

Iteratively (Adaptively) Decide Optimal Policies for 3 Hypervisors
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4. SD-Gateway (to IoT/WSN)
DYNAMIC RRH FORMATION

**WHY?**
* To maximize the **Cooperation Gain**

**PROPOSED SOLUTION:** Optimal Clustering of RRHs

→ Maximize the spectral efficiency while considering specific cooperation costs

→ Can enable **COMP & NW MU-MIMO & Phantom Cell**, **Massive MIMO & mmWaves**
BBS facilitates RRH clustering

- Overlapped coverage areas
- Non-overlapping

BBS facilitates RRH clustering
A CLUSTER CAN ACT AS A MASSIVE MIMO

BBS forms a cluster of SD-BSs with multiple RRHs

Cluster of SD-BSs (Massive MIMO)
CLUSTERING NLOS SOLUTION FOR MM-WAVE SYSTEMS
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CAN SDN/NFV BE USED AS THE FUNDAMENT FOR 5G WIRELESS SYSTEMS ??

- Millimeter Wave & Terahertz Band
- Massive MIMO
- Low Latency Communication
- New Waveforms
- Green Communications
- D2D
- IoT

SDN/NFV
Challenges for mm-WAVE COMMUNICATION

- mm-Waves suffer from high spreading loss
  - Path-loss increases with the square of the frequency

- Transmission Distance

- Sparse-scattering radio patterns

- Blockage effect

- NLOS $\rightarrow$ path loss is too high for a reliable communication
  - Cannot continuously support good qualities at UEs via mm-Wave
Challenges for mm-WAVE COMMUNICATION

- **Dynamic Power Control Algorithm**
  - Channel condition varies largely
  - Signal strengths drop 15~40 dB from LOS to NLOS

- **Cell Search**
  - mm-Wave BS utilizes *directional propagation* for higher channel gain

- **User Scheduling and Congestion Control**
  - Multiple users in same cell
  - Collision avoidance
**mm-Wave: Softwarization**

S.C. Lin and I. F. Akyildiz

Dynamic Base Station Formation for Solving NLOS Problem in 5G mm-Wave Communication

mm-Wave: NLOS Solution

S.C. Lin and I. F. Akyildiz

“Dynamic Base Station Formation for Solving NLOS Problem in 5G mm-Wave Communication”

- Softwarization can solve NLOS problem through efficient coordination of RRHs/antennas
- Form dynamic mm-wave BS
- Dynamic power control, scheduling and congestion control can be easily performed by the central controller
CHALLENGES: DL mm-wave RRHs Transmissions

- **LOS**: No blockage between RRH and UE
  - Assume no beamforming alignment errors

- **NLOS**: RRH-to-UE link is blocked
  - Covariance matrix for small-scale fading: Similar to microwave case

- **Outage**: No link can be established as path loss between RRH and UE is so high
  - In practice, the outage implies the case when the path-loss in either a LOS or a NLOS state is sufficiently large (A more accurate model at mm-wave frequency)
**DYNAMIC BS FORMATION**

S.-C. Lin and I. F. Akyildiz,
“Dynamic Base Station Formation for Solving NLOS Problem in 5G mm-wave Communication,”

---

**Ubiquitous mm-wave Coverage for UE mobility:**

Support good channel quality in an entire geographic area
SD-BSs (BBS pool) dynamically adapt hosting schemes of RRHs to always satisfy UEs’ QoS requirements

**Objective:** Maximize the achievable user sum-rate

**Subject to**
- Users’ QoS requirements
- RRH-user association constraints
- Fronthaul capacity constraints
- RRHs’ beamforming weight constraints

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NP-hard: Mixed-integer non-linear programming (MINLP)
  – Very difficult to compute global optimal solutions; even if possible, (little practical use)

Conduct problem transformation => Successive Convex Approximation (SCA)
  – Propose SCA-based dynamic BS formation

Evaluate in MetisX

Results: Always support each UE with at least 500 [Mbps]
THZ BAND COMMUNICATION

- mm-Wave bandwidth is still limited to 7 GHz

- Why not move to higher frequencies?

- **THz band**: 100 GHz – 10 THz

- Provides incredibly huge bandwidths for short range
  - Can support 1 Tbps link over a distance of 1 m

- Channel has strong dependence on **molecular composition**
  - Presence of water vapor molecules
THZ BAND: SOFTWAREIZATION

SD Controller for mmWave and THz

- Dynamic spectrum switching between mmWave and THz for different throughput needs
- Accommodate multiple users with different motions
- Enhancement on overall throughput and channel gain
MULTIMODE ADAPTIVE MIMO: RESEARCH CHALLENGES

- SU-MIMO for high peak rates
- MU-MIMO for average rate enhancement
- Collaborative MIMO for cell-edge user data rate boost
ULTRA-MASSIVE MIMO
I. F. Akyildiz and J. M. Jornet
Realizing Ultra-Massive MIMO Communication in the (0.06–10) Terahertz Band

- 1024X1024 Antenna Element Array
- Based on Graphene Nanomaterial
MASSIVE MIMO: SOFTWAREIZATION

S.C. Lin and I. F. Akyildiz
Dynamic Base Station Formation for Solving NLOS Problem in 5G Millimeter-wave Communication

Dynamic Base Station Formation for Solving NLOS Problem in 5G Millimeter-wave Communication
A CLUSTER CAN ACT AS A MASSIVE MIMO

BBS forms a cluster of SD-BSs with multiple RRHs

Cluster of SD-BSs (Massive MIMO)
NEW WAVEFORMS

Requirements:

- Low latency
- High data rate
- Compatibility with MIMO
- Less Interference
  - Low out-of-band emissions
  - Less interference to other sub-bands
- Loose or no synchronization
- Power constraints
- Support varying requirements of all devices
  - Ranging from IoT devices to UHD video streaming and tactile internet
NEW WAVEFORMS PROPOSED

- Filtered OFDM
  - Incremental improvement over OFDM

- Filter Bank Multi-Carrier

- Non Orthogonal Multiple Access
  - Can be used in conjugation with any waveform

- Generalized Frequency Division Multiplexing
  - Widely studied

- Universal Filtered Multi-Carrier
PROPOSED WAVEFORMS: DRAWBACKS

- None of them meet all requirements of 5G
- Each has drawbacks in terms of interference, decoding complexity, robustness, etc.
- Further, they cannot support devices with varying requirements simultaneously
Requirements for 5G will be met by using a combination of multiple waveforms
- Adaptively switching waveforms depending on requirements

Easier to implement in SDN
- Since demodulation is carried out in BBS, RRHs can easily adopt to new waveforms easily
D2D COMMUNICATIONS

(a)

(b)

(c)

(d)

Data transfer

Control link
D2D: USE CASES

- Public Safety and Security
- Cellular Offloading
- Disaster Rescue and Relief Operations
- Vehicular Communications (V2V, V2X)
- Social Networking Applications
- Content Distribution
- Smart City
D2D: OPEN PROBLEMS

- **Resource management solutions (admission control, power allocation)** for autonomous operation mode with no network/eNB intervention

- **Spectrum sharing between D2D and cellular communications**
  - Improve operation on licensed and unlicensed spectrum bands

- **Challenge on interference management**
  - Dynamic power control scheme is needed

- **Distributed Device Discovery and Link Setups**

- **Security and privacy**
  - Create “trusted” set of devices for relaying

- **Pricing/Charging (Who will get charged?)**

- **Need global standardization on 5G D2D**
D2D: SOFTWAREIZATION

- SDN/NFV enabled V2X applications
  - Remote sensing and control
  - Cooperative collision management
  - Efficient vehicular traffic management

- Network slicing to support application-specific QoS requirements.

- Flow classification prioritizing emergency services

- Flow optimization and usage coordination of multi-link and multi-RAT

- V2X network planning augmented with big data analytics
D2D: SOFTWARIZATION

- **Softwarization also enables the horizontal slicing paradigm**
  - Low power devices (e.g. wearables) establish direct link with full-scale wireless devices (e.g. cell phones, tablets, laptops, etc.)
  - Full-scale device slices out a portion of its computational resources, and reserves it for low power devices
  - Computational offloading occurs as low power device can now use resources of full-scale devices over the established link
  - End result: enhanced user experience with efficient resource utilization
IoT: 4 LAYERS MODEL

- Integrated Application
  - Smart Logistic
  - Smart Grid
  - Green Building
  - Smart Transport
  - Env. Monitor

- Information Processing
  - Data Center
  - Search Engine
  - Smart Decision
  - Info. Security
  - Data Mining

- Network Construction
  - WWAN
  - WMAN
  - WPAN
  - Internet

- Sensing and Identification
  - GPS
  - Smart Device
  - RFID
  - Sensor

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IoT PLATFORMS ON THE MARKET

- GE Predix
- Cisco IoT Cloud
- IBM Watson IoT
- PTC ThingWorx
GE PREDIX

- Uses a platform as a service (PaaS) model and is a cloud-based OS

- Built on Cloud Foundry, an open-source platform, and is optimized for secure connectivity and analytics at scale, both in the cloud and on the edge
IBM WATSON IoT

Cloud Foundry, Docker®, OpenStack®, Watson IoT Platform development

Platform connects sensors to cloud applications using IBM Bluemix®
Three pillars of technology:

- Core application enablement
- Connection services with device and cloud adopters, and
- Edge connectivity using the Edge MicroServer and Edge “Always On” devices

(27% market share)
IoT: CURRENT SOLUTIONS

- ZigBee, BLE, FeD2D
- Ingenu, 802.11 ah
- Cat 1, Cat 1 1RX
- (F)eMTC, (e)NB-IOT
- Lora, Sigfox

**LPWA Segment**

**PAN** (Personal Area Network)

**LAN** (Local Area Network)

**MAN/CAN** (Metropolitan/Campus Area Network)

**WAN Normal coverage** (Wide Area Network)

**WAN Extended coverage** (Wide Area Network)

- 0 - 30 m
- ~ 100 m
- ~ 1 - 2 km
- ~ 3 - 10 km
- > 10 km

Disclaimer: the ranges are provided as a matter of example and depend on frequency, channel mode, line of sight etc.
IoT CHALLENGES

- Scalability
- **PROCESSING AND STORAGE** (Big Data, Fog Computing, Aggregation)
- **SIGNALING AND CONTROL OVERHEAD**
- **STANDARDIZATION**
- Security, Privacy and Authentication
- Interoperability
- Power Consumption Problem
SDN/NFV Based IoT
SoftIoT: Framework

**SoftIoT Architecture**
1. Scalability
2. Channel Characterization
3. NFV
4. Energy Efficiency
5. Low Latency
6. Security

**Distributed SoftIoT Controllers**
1. Optimal Mobile Controller Placement
2. Task-Resource Matching
3. Service Specification
4. Inter-controller Comm. & Sync
5. Flow Scheduling

**SD Mgmt. & Orchestration**
1. QoS Management
2. Traffic Engineering
3. Resource Management
4. Service Centric Analytics
5. Handover Mgmt. between controllers
SOFTIoT: ARCHITECTURE
L. TELLO, S.C.LIN, I.F. AKYILDIZ AND V. PLA,
“SUM RATE ANALYSIS FOR IOT WITH 5G SOFTAIR ARCHITECTURE”,
SUBMITTED FOR PUBLICATION, MAY 2017.
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