5G Small Cell Backhaul Networks using mmWave bands

Andreas Kassler
Karlstad University, Sweden
The 5G Vision – Unified Connectivity

- Enhanced Mobile Networks
- Mission Critical Services
- Massive Internet of Things

- Extreme Datarates
- Software Defined and Cloud
- Massive amount of Small cells

- Multi-Gigabits per second
- Network Flexibility
- 10 Tbps per Km2

- Ultra Low Latency
- High Availability
- Strong Security
- High Reliability

- <1 millisecond
- <1 out of 100 million packets lost
- challenging locations
- 10+ years of battery life

- Ultra High Density
- Deep Coverage
- Low Cost
- Ultra low Energy

- Ultra Low Energy
- High Availability
- Strong Security
- High Reliability
Extreme Mobile Broadband

- Extreme Capacity to each user and extremely dense deployments
  - Multi Gbps air interface (mmWave Spectrum – NR)
  - Challenging interference management and backhaul design
  - Flexible architecture: NFV, SDN and CloudRAN
Extreme Mobile Broadband

- Extreme Low Latency
  - Tactile Internet < 1 ms
  - Challenging air interface and system architecture design
Extreme Mobile Broadband

- Immersive Experience
  - 4K plus life streaming
  - VR (Pokemon Go is just the beginning)
5G as enabler for New Applications

- Extreme Reliability
  - Negligible E2E loss rate
  - Low latency: Avoid Retransmissions
  - Link and Path diversity for fault tolerance and seamless mobility
5G as enabler for New Applications

- Autonomous Manufacturing
- Autonomous Drones
- Smart Grid
- Remote Surgery

Pictures courtesy Qualcomm
1. Open interface to switch hardware
   Southbound Interface, e.g. OpenFlow

2. At least one good operating system
   Extensible, possibly open-source

3. Well-defined open API
   Northbound Interface

This is precisely how you must process packets!

McKeown et.al.: OpenFlow: Enabling Innovation in Campus Networks, CCR 2008
Example: Google applies several SDN principles
- Jupiter: Datacenter interconnect
- B4: WAN interconnect
- Andromeda: NFV stack for containers
- Espresso

Google Brings SDN to the Public Internet
Amin Vahdat, ONS, April 4, 2017
Network Function Virtualization (NFV) - Principle

- Apply Cloud principles to Telco&Networking
  - Flexibility – decoupling software from hardware
  - Agility – Scale-In and-Out
- But:
  - Additional complexity – more components, interfaces, more things that can go wrong
  - Key difference IT Cloud vs. Telco Cloud: advanced networking needs to be automated

SDN helps NFV in network automation and virtualization \(\rightarrow\) less errors

Avaya’s Everywhere Data Center Architecture Includes VNFs

Avaya has introduced a framework to help enterprises manage networks across campuses. The framework includes the Pivot platform for distributing virtual network functions (VNFs), the Arc orchestration system, and a new switch optimized for this architecture.

The company is referring to the architecture as the “everywhere data center.” The phrase appears to come from the application of networking techniques developed specifically for traffic within data centers to now also include traffic generated at the edge.
5G RAN and Core Research challenges

- High Capacity and reliable Baseband Pool Interconnection from the Cloud
- Cooperative Radio and low latency
- **Fronthaul/Backhaul joint optimization**
- Base Station Platform on commodity servers
- NFV realtime performance aspects due to virtualization
- NFV Management, Orchestration and Security
- NFV Performance Benchmarking
- NFV Placement Optimization
- Control&Data plane split
- Programmable Control and Dataplanes
- Signalling traffic explosion (scaling VMs)
New Airinterface and Deployment

- **<1GHz**: Long range, low power IoT
- **1..6 GHz**: Advanced LTE type for mission critical
- **>6 GHz**: MMwave, extreme bandwidth, short range, directional antennas, fronthaul and backhaul

Wide area deployment and local hotspot
Diverse dense deployment (mesh, peer-to-peer)
MMWave Challenges

- Propagation Effects
  - LOS/NLOS/Outage due to high pathloss, intermittent links
  - Atmospheric effects, rain

- Antenna
  - Directional Antennas
  - Beamforming, Highly Directional Beams
  - Challenge for Access and Transport

- Radio
  - Challenges for Power Amplifier due to linearity and high bandwidth
  - Low Tx Power and Rx Sensitivity
MMWave Challenges

- **Propagation Effects**
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Transport Layer issues for 5G NR

- Problems for Transport Layer
  - Intermittent Link at mmWave Frequencies
  - Low Latency queuing schemes (e.g. CoDel) lead to low effectiveness

Marcus Pieska, Andreas Kassler, TCP Performance over 5G mmWave Links - Tradeoff between Capacity and Latency, submitted to IEEE Wimob 2017
Dense Small Cell Networks

- **Dense Deployment of Small Cells**
  - Reuse eNB Umbrella cell → HETNET
  - Wireless mesh backhaul to save cabling costs
  - Small inter-cell distance → low energy for AN
  - Cost Efficient solutions with high capacity
    - Minimize Energy Consumption by switching Off SC
    - Guarantee backhaul is connected

Mesh backhaul provides resiliency against link failures and loadbalancing → Fast SDN based local reconfiguration
Energy Efficient Small Cell Backhaul Operation

- One sector of a Macro eNB with fixed access to the Internet
- Several Small Cells (SeNBs) are deployed to increase capacity

Energy Efficient Small Cell Backhaul Operation

- mmWave backhaul (BH) links to connect the SeNBs and the MeNB
- Mesh BH
Energy Efficient Small Cell Backhaul Operation

- mmWave BH links
- Some users (UEs) in the area downloading data
- We consider downlink only
  - MeNB is the sender
  - UE is the receiver
Energy Efficient Small Cell Backhaul Operation

- mmWave BH links
- Some users (UEs) in the area downloading data
- **Multiple possibilities to connect**
  - Microwave access (LTE) on access links (AL)
    - Macro AL
    - Small Cell AL

INTERNET

SeNB1

UE1

SeNB 2

UE2

SeNB

3

SeNB

4

SeNB

5

SeNB

6

MeNB

UE3

UE4
Energy Efficient Small Cell Backhaul Operation

- mmWave BH links
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INTERNET

- mmWave BH links
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  - Small Cell AL

Route 1: associate with Macro

Route 2: associate with Small cell 5
power on SeNB3 and SeNB5

Route 3: associate with Small cell 6
power on SeNB3, SeNB4 and SeNB6
Modelled as Mixed Integer Linear Program

1) save power and
2) satisfy users demand
MILP: Goal

1) save power and
2) satisfy users demand

User association to eNB $i$

Routing on meshed BH links $(i,j)$

Configured through SDN based on Model

eNB $i$ activation
MILP: Goal

1) save power and
2) satisfy users demand

User association to eNB i

Routing on meshed BH links (i,j)

Configured through SDN based on Model

eNB must be powered ON

eNB i activation
MILP: Goal

1) save power and
2) satisfy users demand

User association to eNB $i$

Routing on meshed BH links $(i,j)$

Configured through SDN based on Model

1) save power
2) satisfy users demand

eNB must be powered ON

eNB must be powered ON only if used

eNB $i$ activation

User association to eNB $i$
MILP: Goal

1) save power and
2) satisfy users demand

User association to eNB $i$

eNB must be powered ON

Routing on meshed BH links $(i,j)$

Use only links where users data flows

eNB $i$ activation

eNB must be powered ON only if used

Configured through SDN based on Model
MILP: Goal

- Model formulated as a Mixed Integer Linear Problem
  - CPLEX $\rightarrow$ branch-and-cut search strategy

- GOAL: Minimize the total energy consumption (of all the eNBs) while guaranteeing the rate demanded by each user

$$\begin{align*}
\text{minimize} & \quad \sum_{i \in \mathcal{M}} e_i \\
\text{s.t.} & \quad R^u \geq d_u, \quad \forall u \in \mathcal{U}
\end{align*}$$

- Users' demanded rate provided as an input to the problem
- Energy consumption at each eNB and users rate: output
INTERNET

**MILP: Solutions**

- If the total demanded rate can be satisfied by the MeNB
  - Switch off all the SeNBs and all the BH links
  - Solution with the *lowest power consumption*
• As the demand from the UEs increases, we need to switch on the SeNBs
• E.g.: 2 SeNBs are switched on
• Solution with higher power consumption

• Some users may demand more rate than available
  • Pre-process: assign 0 Mbps to such users and count as blocked users
Total Network Power Consumption

The graph shows the total network power consumption in watts for different demanded rates per user in Mbps. The power consumption is categorized into AL (AL power (U)), BH (BH power (U)), AL (AL power (H)), BH (BH power (H)), blocked probability (U), and blocked probability (H). The x-axis represents the demanded rate per user in Mbps, while the y-axis shows the total power consumption in watts. The graph indicates the power consumption and blocking probability for varying demands, with the rate of energy consumption and blocking probability increasing with the demanded rate.
# Results

### #Active SC

<table>
<thead>
<tr>
<th>Demanded rate [Mbps]</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
<th>22</th>
<th>24</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>On/Off - U</td>
<td>0.0</td>
<td>3.5</td>
<td>10.8</td>
<td>14.5</td>
<td>16.3</td>
<td>17.9</td>
<td>19.5</td>
<td>20.5</td>
<td>21.2</td>
<td>21.7</td>
<td>22.7</td>
<td>22.7</td>
<td>23.0</td>
</tr>
<tr>
<td>On/Off - H</td>
<td>0.0</td>
<td>3.9</td>
<td>10.7</td>
<td>13.3</td>
<td>15.5</td>
<td>17.4</td>
<td>18.6</td>
<td>19.7</td>
<td>20.8</td>
<td>21.1</td>
<td>22.1</td>
<td>22.3</td>
<td>23.1</td>
</tr>
<tr>
<td>Always ON - U/H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

![Graph](image-url)

- **Total power "Always ON"**
- **Blocking probability**
## Results

Almost half of the total SCs are ON

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<td>22.1</td>
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<td>23.1</td>
</tr>
<tr>
<td>Always ON - U/H</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Note:** The table shows the percentage of active SCs for different demanded rates. The highlighted values indicate a significant number of SCs are active, almost half of the total. The diagram further illustrates this with a comparison of total power consumption and blocking probability.
Almost all the SCs are ON
UE Blocking Probability

Due to the random nature of users’ drops and not to any limited capacity in the backhaul network and/or in the routing scheme.
Avg rate obtained by each user vs demanded rate

The graph shows the relationship between the mean rate per user and the demanded rate per user. The graph includes two sets of data points:
- Mean rate per user (U)
- Mean rate per user (H)
- Mean extra power (U)
- Mean extra power (H)

The x-axis represents the demanded rate per user in Mbps, while the y-axis represents the mean rate per user in Mbps. The data points are connected by a line, indicating a linear relationship between the mean rate and the demanded rate.
Avg extra power consumption relative to the "Always ON" case
Avg extra power consumption relative to the "Always ON" case

Flattens because almost all mmWave BH transceivers are ON
Avg rate that flows on all the BH links that are active
Balance between Energy and Spectrum Efficiency

Target:
- High spectrum (SE) and energy efficiency (EE)

Problem:
- UE association & BH traffic routing
- No switching off this time
- SE: AN→ Minimum PRBs to satisfy QoS of UE i (deviating up to a threshold from the fewest)
- EE: AN+BH→ Minimum power needed to serve the UE traffic (among all BSs and alternative BH paths)

Example

- Rate demand $\rightarrow$ 100 Mbps

<table>
<thead>
<tr>
<th>BS index</th>
<th>PRBs</th>
<th>BS index</th>
<th>PRBs</th>
<th>BS index</th>
<th>PRBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>eNB</td>
<td>4</td>
<td>SC 3</td>
<td>7</td>
<td>SC 6</td>
<td>5</td>
</tr>
<tr>
<td>SC 1</td>
<td>18</td>
<td>SC 4</td>
<td>5</td>
<td>SC 7</td>
<td>4</td>
</tr>
<tr>
<td>SC 2</td>
<td>12</td>
<td>SC 5</td>
<td>6</td>
<td>SC 8</td>
<td>5</td>
</tr>
</tbody>
</table>

$\delta_{\text{thres}} = 1 \rightarrow$ no deviation from min PRBs $\rightarrow$ maximum SE

$\min (P_{\text{AN}} + P_{\text{BH}}) \rightarrow$ maximum EE

$P_{\text{AN}}$ Type of BS (number of Tx chains, scaling factor, power per PRB)

Number of PRBs

eNB: $P_{\text{AN}} = 59.87$ W

SC 7: $P_{\text{AN}} = 1.28$ W
Example

- $P_{BH} \rightarrow$ BH route

Link bandwidth, channel conditions

BH traffic

eNB$ \rightarrow$ no BH link

SC 7, route 1$ \rightarrow$ L1(750 MHz, -57.25dBm, 100Mbps)
L2 (100 MHz, -62.45dBm, 100 Mbps)

SC 7, route 2$ \rightarrow$ L3(500 MHz, -55.29dBm, 300Mbps)
L4 (200 MHz, -66.34dBm, 100 Mbps)

Algorithms

w/o LB$ \rightarrow$ BH power calculation as if BH links were exclusively used by UE $i$

LB$ \rightarrow$ by jointly considering the traffic of the already associated UEs, starting with the UEs with the fewest candidates

**Solutions**

w/o LB$ \rightarrow$ SC 7, route 2

LB$ \rightarrow$ SC 7, route 1

eNB: $P_{BH}=0$ W

SC 7, route 1:
w/o LB: $P_{BH}=0.752$ nW
LB: $P_{BH}=2.09$ nW

SC 7, route 2:
w/o LB: $P_{BH}=0.671$ nW
LB: $P_{BH}=2.89$ nW
Simulation Scenario

- 100, 150, 300 Mbps GBR demands
- Hotspot traffic
- Orthogonal channels SCs-eNB
- SCs in different clusters interfere
- BH: 73 GHz, variable BW (0.02-1 GHz)
- Algorithms:
  - Proposed ESE w/o LB, ESE with LB
  - Highest SINR with random path in BH
  - RangeExpansion (+13 dB) with random path in BH
  - MPL (minimum path loss) with random path in BH
  - BH-hop with LB [9]
    - BS with max. spectrum efficiency, among them select the one with the minimum number of BH hops, least loaded
Simulation Results

- Relative percentage difference compared to MPL-random
- Positive percentage $\rightarrow$ increase in the studied metric compared to MPL-random, whereas negative $\rightarrow$ decrease
Conclusions

- 5G will be based on
  - Applying Cloud Paradigms to the Telco World
  - Using Software Defined Networking for flexible traffic steering
  - New Radio providing large capacity

- New challenges
  - Dense networks require energy efficient operation
  - User association and offloading need to consider backhaul
  - Transport Layer needs to be more efficient
  - Optimization more complex