Mobile Networks Evolution from LTE to 5G: Algorithms and Architecture

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(joint work with Anand Bedekar and Suresh Kalyanasundaram and several others)
Outline

• Drivers of Mobile Network Evolution and Key Enablers
• Spectrum - current and future
  - Carrier aggregation, multi-connectivity
• Sites – current and future
  - Small cells and eICIC
• Spectral Efficiency
  - Coordinated Scheduling, CoMP
  - Massive MIMO
  - Other Spectral Efficiency techniques
• Cloud RAN
Explosive growth in mobile traffic
Drivers for Network Evolution

- Smart phones/devices
  - Open ecosystem of apps
  - Social media
  - Video
  - Augmented/Virtual Reality
- Internet of Things
  - Connected cars
  - Smart cities/homes
  - Verticals – health, industry

- 3.7 Exabytes per month in 2015
- ~500 MB/month per person
- ~1GB/month per unique sub
Heterogeneous use-cases
Three-pronged requirements for 5G networks

"Unlimited experience" 100 Mbps whenever needed

>10 Gbps peak data rates

10-100 x more devices

Extreme Mobile Broadband

10 000 x more traffic

10 years on battery

Massive machine communication

M2M ultra low cost

Critical machine communication

<1 ms radio latency

Ultra reliability

For everything

Instant action

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Value, Capability & Cost Transformation for End User and Operator

Massively scale: Throughput/Capacity, Latency, Resilience/Coverage, Quality of Experience

New End User Services: Internet of Things, Connected Cars, Verticals (Smart X)

Capability & Cost Transformation
- Distributed Cloud and NFV
- Transport and SDN
- Scalable Core
- Automation Programmability
- Cognition
Keys to Massively Scaling **Throughput/Capacity**

**Spectrum**
- Sub-6GHz to Cm/Mm Wave
- Opportunistically exploit unlicensed spectrum
- Aggregate all available spectrum – Carrier aggregation, multi-connectivity
- High Peak Throughputs

**Cell Density**
- High density of cells
  - Small cells, Hetnet
  - High-capacity zones
  - Cell Splitting at Macro layer

**Spectral Efficiency**
- Multi-cell coordination, interference cancellation
- Massive MIMO
- More efficient access to spectrum – Dynamic TDD etc

**Centralized & Cloud RAN**
- Centralize
- Pooling
- Transport
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- Centralize Pooling Transport
Spectrum

Roughly consistent across many geographies – snapshot of APAC shown (ranges from 700MHz – 3.5GHz)

Up to 750MHz total already allocated

sub-3GHz: (450-700 MHz, 1.3-1.5, 2.7GHz)
3-6GHz: (3.5-5, 5.9-6.4GHz)
cm/mmWave: (28, 39, 65-75 GHz)

More spectrum will be made available

BUT...

Licensing terms for new bands may be more constrained (e.g. shared spectrum, unlicensed)

Expensive, challenging terms, coverage constraints
Opportunistic use of unlicensed, shared-licensed, unreliable spectrum
Complement reliable but limited licensed spectrum
Starting in LTE (LAA, LWA, MulteFire), evolving into 5G

Additional spectrum in Sub-6GHz bands, plus larger swaths in cm/mmWave bands

Simultaneous use of multiple bands
Higher peak UE throughput, optimal load-balancing
Intra- as well as inter-site

Unlicensed and Shared-licensed

Sub-6GHz plus cm/mm-Wave

RAN Multi-connectivity anchor

Carrier aggregation and Multi-connectivity
Carrier Aggregation scenarios

F1 and F2 cells are co-located and overlaid, providing nearly the same coverage.

F1 and F2 cells are co-located and overlaid, but F2 has smaller coverage due to larger path loss.

F1 and F2 cells are co-located but F2 antennas are directed to the cell boundaries of F1 so that cell edge throughput is increased.

F1 provides macro coverage and on F2 RRHs are used to provide throughput at hot spots.
Joint scheduling for “Many groups of resources” arises in:
- **Carrier aggregation** – multiple (possibly non-contiguous) bandwidth chunks
- **Cell Selection** or **DL CoMP (DPS – Dynamic Point Selection)** – multiple cells on same carrier frequency
- **5G** – large contiguous bandwidth which can be viewed as union of smaller groups of resources
- Generically calling “a group of resources” = “a cell”

- Users may be eligible to be scheduled on all cells (for higher peak rates)
- Want to design “Jointly optimal scheduler” across all cells
- Scalability problem – complexity grows super-linearly with resources, number of users (e.g. max-max algorithm)
Cell selection + user scheduling

Problem formulation

- A user may be associated with more than one cell (within this localized set)
  - $\rho_{c,u}$ – fraction of cell $c$’s resources given to user $u$
  - $\rho_{c,u} = 0$ unless cell $c$ is in coordination set of user $u$.

- **User Throughput** $T_u = \sum_c \rho_{c,u} R_{c,u}$

- Utility maximization:
  - Decide allocations $\rho^*_{c,u}$ to maximize $\sum_u U(\sum_c \rho_{c,u} R_{c,u})$

- Assumptions for simplifying problem – help to understand key principles
  - Assume channel is semi-static: stays constant long enough to reach optimal allocations
Cell selection + user scheduling (cont’d.)

Optimality condition

• Key result [specialized to \( U() = \log() \) – extends to more general utility functions]:

\[ \frac{R_{c,u}}{T_u} = v_c \text{ if } \rho^*_{c,u} > 0 \]
\[ \leq v_c \text{ if } \rho^*_{c,u} = 0 \]

**Optimality condition:** Allocation rule \( \rho^* \) is optimal iff for some cell-specific constants \( v_c \)

• Cell Metrics \( v_c \) (“PF metric”) represent “load” in the cell

• At optimal, user gets non-zero allocation from “highest throughput cells”:
  - Non-zero allocation from cell \( c \) only if \( \frac{R_{c,u}}{v_c} \geq \frac{R_{d,u}}{v_d} \) for any other cell \( d \)
  - Also handles case where user gets non-zero allocation from multiple cells
Relation between PF metrics $v_c$ and optimal allocations $\rho^*_{c,u}$:

- Let $\beta_{c,u}$ = fraction of user $u$’s throughput received from cell $c$
  - $\beta_{c,u} = \frac{\rho^*_{c,u} R_{c,u}}{\sum_d \rho^*_{d,u} R_{d,u}}$

**Result:** $v_c = \sum_u \beta_{c,u}$

**Interpretation:**
- If all $\beta$s are 0 or 1 (each user receives allocations only from one cell), then $v_c = N_c$, number of users associated with cell $c$
- But in general $\beta_{c,u}$ can be a fraction –
- Then, cell $c$ would treat user $u$ as a **fractional user** with mass $\beta_{c,u}$:
  - $v_c = \text{“total mass”}$ associated with cell $c$

**Result:** For any two cells, at most one user “straddles” the two cells
Cell selection/association + user scheduling (cont’d.)

Determining the optimal allocation $\rho^*_c,u$

- In practice, $\rho^*_c,u$ within a cell for a given cell association can be found by a “scheduler”
  - Each cell’s scheduler implements the “gradient method” – in each slot, schedules the user that currently has the highest gradient of the utility
  - E.g. for $U() = \log()$, gradient $= \frac{R_{c,u}}{T_u}$ (Proportionally fair scheduler)

- Gradient-scheduler’s allocations converge to the optimal $\rho^*_c,u$
- User PF metrics in cell $c$ converge to $v_c$ if scheduler allocates non-zero $\rho^*_c,u$

- Also works when a user is allowed to associate with multiple cells
  - In each time slot, user throughput $T_u$ updated with allocations received in all cells
1. Each cell scheduler calculates $v_c$ (gradient scheduler - PF), for users currently assigned to it
   - (Not shown) Cells exchange $T_u$ of “straddling” users with other cells
2. Each cell (periodically) exchanges its $v_c$ with other cells
3. Decision at anchor cell – determine which user’s association to update, based on threshold rule
   - Given current set of $v_c$, “improve” a user $u$ by allowing it to also receive resources from cell $c^*_u$ that maximizes its estimated throughput $R_{c,u} / v_c$
   - If a user $u$ gets $\rho^{*}_{c,u} = 0$ from some cell $c$, then remove that cell from its allocated set of cells
     - $\rightarrow$ Provable convergence to optimal under mild conditions
4. Notify chosen cells of user association changes
5. Each cell’s scheduler uses updated user association to schedule users and calculate its $v_c$
Scalable scheduling

Many users, all eligible on all resources

"Jointly optimal scheduling"

Many groups of resources

Joint scheduler decomposed into "cooperating per-cell Schedulers"

Users mapped to groups of resources: Some users mapped to multiple groups

Per-cell Sch

More scalable

Even more scalable
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**Spectrum**

**Cell Density**

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  - Small cells, Hetnet
  - High-capacity zones
  - Cell Splitting at Macro layer

**Multi-cell coordination, interference cancellation**

**Massive MIMO**

**More efficient access to spectrum – Dynamic TDD etc**

**Centralized & Cloud RAN**

**Centralize**

**Pooling**

**Transport**
Cell Sites

Worldwide Macro Base Sites

- ~2000 subs/site
- Global macro base sites growing at ~8-10% per year
- Forecast for Small cells to grow even faster
- New sites likely for capacity in high traffic areas than coverage (already rolled out) – even more density increase there

Cell Density likely to increase significantly

Worldwide Small Cell Sites

- Cell-splitting, introduction of small cells will lead to greater interference
- Need to maximize spectral efficiency while combating interference

Interference is an increasing issue
Site Densification for Capacity – Small Cells

Very high density requires greater automation
Sub-optimal, highly irregular site locations → greater need for automatic optimization (vs. manual planning)

Site splitting at wide-area level, + ultra-dense small cell clusters
High capacity zones

Automation for plug-and-play

HetNet environment creates high interference scenarios
Co-channel deployments lead to strong signal and interference

Inter-cell interference coordination
Dynamic eICIC: Adaptation of Muting

- Co-channel HetNets – Macro causes strong interference to picos on same frequency
- Muting with “ABS” (almost blank subframes) – Macro mutes certain subframes so Pico users get better SINR –
  - Pico users can report separate channel-state feedback for ABS and Non-ABS subframes

\[ a = \text{ABS proportion} \]

- **Optimal muting**: Given user assignments to macros and picos, and spectral efficiencies of users in ABS and Non-ABS subframes, determine ABS Muting Proportion \( a \) that macro should use

- **Utility maximization** formulation:
  - Determine \( a \), and resource allocation \( \rho \) to users in macro and pico, to
  
  \[
  \text{Maximize } U(\rho; a) = \sum_i U_i(T_i(\rho; a))
  \]

- Utility function \( U_i(T_i) = \log(T_i) \) leads to Proportional Fairness (PF)
Dynamic EICIC – Optimal Muting

- Can view a pico cell as “two logical cells”, an ABS-cell and a non-ABS cell
  - “ABS-cell” transmits when macro is muted (fraction \( a \) of the resources)
  - “non-ABS cell” transmits when macro is not muted (fraction 1-\( a \) of the resources)

- **Optimal resource allocation**: Users partition into “ABS users” and “non-ABS users”
  - Each user in a pico is in principle eligible for scheduling by both ABS-cell and non-ABS cell
  - But (similar to “user mapping” earlier) – turns out that in the optimal resource allocation, users get mapped into either the ABS cell or the non-ABS cell – only a few users can get resources in both

- **Optimal ABS proportion** for log() utility: \( a^* = \frac{\sum_{c \in \text{ABS}} N_c}{\sum_{c} N_c} \)

  - \( N_c \) = number of user in cell \( c \) – so optimal ABS proportion = fraction of users who get resources in ABS

- **Cell PF metric** again plays an important role:
  - \( v_c \) = “Cell PF metric” of a cell = (for log() utility) “Number of users per unit resource” \( \rightarrow \) measure of load on a cell
    - \( N_c / a \) for ABS cells or \( N_c / (1-a) \) for non-ABS cells
    - For more general utilities, optimal ABS ratio in terms of “Generalized Cell PF metric”
  - forms the basis of the criterion for mapping pico user to ABS or non-ABS
  - Also forms the basis for determining optimal muting proportion
  - Leads to iterative algorithm to achieve jointly optimal ABS proportion and optimal user assignment
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**Centralize Pooling Transport**
- Centralized & Cloud RAN
Improving Spectral Efficiency

Cell-edge performance in interference-limited scenarios

Key hooks being developed already in LTE, continue evolving into 5G

Higher efficiency with massive antenna arrays

Exploit active antennas, chip-scale massive antenna arrays

Enable more efficient multiple-access and duplexing

Between UL and DL – Dynamic TDD, Full Duplex
Across multiple users – NOMA
Separate cell associations for UL, DL

Better efficiency due to design of frame and control channels

Flexible control channel design
Flexible TTI lengths
Lower control overhead
Better packing of traffic with diverse types

Multi-cell coordination

Massive MIMO

3D MIMO

More efficient channel access and use

Improved Numerology and Frame Structure

More efficient channel access and use

Flexible control channel design
Flexible TTI lengths
Lower control overhead
Better packing of traffic with diverse types

Better efficiency due to design of frame and control channels

Flexible control channel design
Flexible TTI lengths
Lower control overhead
Better packing of traffic with diverse types
Multi-Cell Coordinated Scheduling

- Consider muting (or lowering the power) of a cell
  - Cell in question pays a penalty
  - Neighbor cells benefit
  - Consider Net Benefit and
    - Mute if Net Benefit > 0

Key Issues:
- Which cells should coordinate?
- Centralized or decentralized?
- What information should be shared?
- How often should it be shared?
  - Do we need multiple iterations within a time-slot or is a single exchange adequate?
  - Is there some kind of continuity across time-slots
- How do we combat latencies?
• Each cell **influenced only by some set of neighboring cells**
  - Even if the totality of cells is large, only local influences
  - Spectral efficiency of a user in a cell depends only on interference from a localized neighbor set
• Correspondingly, a cell’s “action” should be influenced only by the **effect on a localized neighbor set**
• Can we capitalize on this localized-influence structure in solving global optimization?
  - Can global optimal be reached by making decisions with only local awareness confined to **cell-specific cluster**?
  - Can it be reached by **distributed decision making** – each cell makes decisions based on some (parsimonious) awareness of state of localized neighbors?
→ Method of update may be **sequential (one cell at a time)** or **parallel (all cells together)** or in-between (some subset of cells update in parallel – e.g. “**independent sets**”)
Localized structure (cont’d.)

• The **cell-specific clusters** are overlapping – in general effects of one cell’s action may have ripple effects propagating outside that cell-specific cluster

• In general, some centralized/global-view optimization may be needed
  - However, such solutions do not scale well, and have single-point-of-failure issues

• So would like to have decentralized algorithms, where actions are taken in a distributed way at each cell

• A cell may coordinate with other cells (message passing) – but ideally confine coordination to the per-cell local cluster

• May require possibly multiple iterations of message passing – either multiple per slot (TTI), or spread out over multiple TTIs

• **Want to identify insights from theory that allow design of decentralized mechanisms**
Sequential or Partially parallel using independent sets

Key results

- Assuming $R = \log (1 + \text{SINR})$, any limit point of the power sequence for Sequential or Partially parallel using independent sets satisfies:

- For linearized (interference price) or full functional form of interference penalty:
  - Value function improves at each step
  - Limit point satisfies KKT conditions
    - Follows from Shi, Honig, Berry for linearized form
  - But not necessarily convergence to global optimum – can’t prove uniqueness of optimal

- In addition for the full functional form:
  - Limit point is also optimal in any one dimension
## Simulation results – Gain percentage

<table>
<thead>
<tr>
<th>Approach</th>
<th>5&lt;sup&gt;th&lt;/sup&gt; percentile gain (%)</th>
<th>Geo mean gain (%)</th>
<th>Average gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary PC</td>
<td>19.0%</td>
<td>3.3%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Binary PC followed by 1-step fully parallel approach</td>
<td>25.1%</td>
<td>6.4%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Binary PC followed by C-step sequential approach</td>
<td>25.2%</td>
<td>6.6%</td>
<td>2.5%</td>
</tr>
<tr>
<td>10xC-step per TTI sequential approach</td>
<td>34.3%</td>
<td>12.1%</td>
<td>7.7%</td>
</tr>
</tbody>
</table>
**Multi-cell coordination benefits from fast inter-connect**

... but can still provide gains over non-ideal inter-connects

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>DL/UL</th>
<th>Interconnect requirements between Cell BBs</th>
<th>&lt;&lt; 1 msec</th>
<th>5 ms</th>
<th>&gt; 10 ms</th>
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</thead>
<tbody>
<tr>
<td>Dynamic eICIC</td>
<td>DL</td>
<td>Signaling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inter-site CA</td>
<td>DL</td>
<td>User data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coordinated Scheduler</td>
<td>DL</td>
<td>Signaling</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DPS CoMP</td>
<td>DL</td>
<td>User data</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>JR CoMP</td>
<td>UL</td>
<td>I/Q data</td>
<td></td>
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</tr>
</tbody>
</table>

Framework described also applicable to Coordinated Beamforming
Massive MIMO
For wide area (<6 GHz) as well as high (cm/mm-wave) bands

At high bands: Massive antenna arrays to overcome propagation challenges
- Beamforming at RF
- Polarization → 2 stream MIMO
- Chip-scale array elements
- ≥ 16 element arrays at base station

Spectrum availability

<table>
<thead>
<tr>
<th>GHz</th>
<th>2.9 GHz</th>
<th>10 GHz</th>
<th>4 GHz</th>
<th>2 GHz</th>
<th>&lt; 6 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-95</td>
<td>2 + 0.9 GHz BW</td>
<td>5 GHz BW</td>
<td>50 MHz BW</td>
<td>150/852 MHz BW</td>
<td>150/852 MHz BW</td>
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<tr>
<td>70-85</td>
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<td>38</td>
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<td>28</td>
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<tr>
<td>&lt; 6</td>
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</tbody>
</table>

Active antennas
- Vertical sectorization
- UE-specific beamforming
Massive MIMO
3D (2D planar array), RF domain BF (in addition to BB domain), Antennas >> BB streams

PHY/RF problems:
- **Beam space design:** What is the set of beams in consideration? Is there any structure to the beam space?
  - Common/cell-specific + selection + UE specific
  - In BB or RF (phase shifts) or hybrid
  - Discrete (e.g. hierarchical/multi-level or other grid-of-beams) or continuous (based on UL pilots/data) set

- **Pilot design & Channel estimation:** How are the common/cell-specific beams chosen? How is the UE-specific beam chosen?
  - Do we have channel reciprocity (TDD)?
  - UL pilots/data
  - DL pilots and UE feedback
  - Some combination of the two

Scheduling, Resource Allocation, RRM problems:
- **Pilot management:** How often to use which pilot?
  - Trade-off between learning and optimization

- **Beam scheduling:**
  - How often to schedule which beam?
  - How often to schedule a set of beams (with potential overlaps)
  - CQI/PMI/RI estimation for UE (based on beam choice and other beams active)
  - Resource allocation problem – similar to resource allocation in eICIC/ABS

- **Mapping users to beams**
  - Similar to cell selection problem

- **Power control –** Power on different beams
  - Similar to coordinated cell muting/power control problem
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**Spectral Efficiency**

**Centralized & Cloud RAN**

**Multi-cell coordination**
- Pooling
- Transport
Centralized/Cloud RAN configurations

Conventional Macro

- Back-haul to EPC
- Fiber or CPRI/OBSAI

Macro including RRHs

- Back-haul to EPC
- Fiber or CPRI/OBSAI
- Local RH
- Remote RH

Centralized RAN

- Back-haul to EPC
- Central Site Aka BBU Hotel (e.g. CO)
- Fronthaul (typically dark fiber)
- Fiber or CPRI/OBSAI

Cloud RAN

- (partly) virtualized, pooled BBUs
- Central Site (e.g. CO)
- Fiber or Ethernet

- Some BB fns

- X-haul
- Fiber or Ethernet

- Some BB fns

- Baseband functions may be split between central site and cell site
- Aim to support packetized X-haul
- Some of the centralized BB functions may be virtualized on GPP servers
- Pooling of processing across cells
- Cloud techniques for automation and orchestration
Cloud RAN – Challenges and Solutions

**Enable Ethernet Fronthaul**

**Maximize use of server platforms**

**RAN software optimized for Cloud operation**

**Cloud Management**

**Multi-cell coordination**

**Optimization of latencies**

- Different functional splits and algorithm enhancements matched to transport needs
- Improve transport networks

- Enable time-sensitive functions on GPP (x86, ARM)
- Some functions may still be on non-GPP hw

- Disaggregate SW architecture for maximizing pooling benefits
- Load-based elastic scaling

- Enhanced Orchestration and Virtualized Infrastructure Management for RAN

- Common algorithm architecture for distributed and centralized
- Exploit per-cell Clusters

- Co-locating RAN across cells and with EPC enables latency optimizations

RAN software optimized for Cloud operation

Cloud Management

Multi-cell coordination

Optimization of latencies
To Centralize or Not to Centralize
Coordination, Pooling, Costs

Distributed Coordination:
- Instantaneous intra-site nbr info, delayed inter-site nbr info

Intra-cloud Coordination:
- Instantaneous nbr info, but delayed fronthaul

Pooled Functions
- PDCP
- RLC
- MAC
- RRC

Distributed vs Centralized Coordination

Site costs in distributed network vs fronthaul costs in centralized

Centralization for cost reduction

Efficient deployment of massive processing resources – pooling across cells (esp for per-user functions)

Maximize pooling gains
Summary

• Traffic growth and new end user services such as IoT are driving mobile network evolution
• Spectrum additions across different bands including licensed, unlicensed and lightly licensed
• Site densification primarily using small cells/hetnets
• Algorithms to combat new challenges due to spectrum addition, site densification and interference management are needed –
  - these all require multi-cell optimization - decentralized algorithms offer scalable solutions
• Massive MIMO offers an important dimension to improve spectral efficiency
• Several other spectral efficiency improvement techniques are also being considered
• Cloud RAN offers a potential disruptive solution to scale baseband compute requirements cost effectively and also offer operators the ability to experiment with new algorithms and features
  - Functionality may get moved around with latency and throughput constraints on the interconnect network

• ➔ Algorithm and architecture design are central to mobile network evolution
RAN and Network Architecture & Algorithms
What we do

Schedulers, RRM Receiver, Channel Est.

Cloud RAN
Multi-Cell Coordination
massive MIMO

Algorithms

Architecture

LTE-Advanced-Pro
5G

RAN & Network

eNB(PHY, MAC), Network

Proof-of-Concept

Technologies

Nokia
Happy 65th Birthday Demos!