Evolving Wireless Technology
Towards 6G

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Mobile/cellular networks

**Coverage:** Where mobiles “reach” base stations

**Bit rate:** bits per second

**Capacity:** Total bit rate of all mobiles
How fast bit rates do we need?

Video streaming [1-25 Mbit/s]
Social media
Gaming
Web, shopping, …
Call, SMS

Refine technology: Increase capacity

Increase by 40%/year

Gigabyte per month per person
Capacity improvements between 4G and 5G

A few broad beams

Many narrow beams

"Massive MIMO"
The global challenge: Sustainability

Use too much resources

Economic growth: Improved living standard

More efficient resource utilization

Digital transformation?
Some components of digital transformation

- “Big” data
- Internet of things
- Artificial intelligence
- New technology
- Automation

Requirements on wireless technology will rise!

The digitalized society requires perfect connectivity?
The big challenges

1. Poor availability
2. Trustworthiness
3. Sustainability
Predominant 6G visions

- The high-level message is very much on sustainability, trustworthiness, availability

- Actual technical solutions: more of the same
  - Even higher peak bit rates
  - Higher spectral efficiency for extreme cases
  - Extremely short delays
  - Enormously many user devices


<table>
<thead>
<tr>
<th>KPI</th>
<th>5G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak data rate</td>
<td>20 Gb/s</td>
</tr>
<tr>
<td>Experienced data rate</td>
<td>0.1 Gb/s</td>
</tr>
<tr>
<td>Peak spectral efficiency</td>
<td>30 b/s/Hz</td>
</tr>
<tr>
<td>Experienced spectral efficiency</td>
<td>0.3 b/s/Hz</td>
</tr>
<tr>
<td>Maximum bandwidth</td>
<td>1 GHz</td>
</tr>
<tr>
<td>Area traffic capacity</td>
<td>10 Mb/s/m²</td>
</tr>
<tr>
<td>Connection density</td>
<td>$10^4$ devices/km²</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>not specified</td>
</tr>
<tr>
<td>Latency</td>
<td>1 ms</td>
</tr>
<tr>
<td>Reliability</td>
<td>$1 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

The issues with this vision

Best-case performance metrics only relevant in extreme/expensive situations
Buzzwords: No measurable targets for sustainability, trustworthiness, availability
Swedish Wireless Innovation Network (SweWIN)

Vinnova Competence Center, 2024-2028

“Realizing sustainable, resilient, and fair wireless communication and sensing for in the digitalised era”
SweWIN’s vision

- **Shift actual focus** to new key value indicators (KVIs)
  - New performance metrics require new competences
  - Precise goals require careful research!

5G

- **Performance indicators**
  - Bit rates
  - Spectral efficiency
  - Connection density
  - Bandwidth
  - Latency

6G

- **KVIs**
  - Sustainability
  - Resilience
  - Fairness
How can 6G achieve a uniform coverage?
Principles for wireless communications

Time for a “symbol” = \frac{1}{\text{Bandwidth}}

Received signal with noise:

How many bits per symbol?
Depends on the signal strength!
Claude Shannon’s limit

Long sequence of symbols
Send one out of $x$ messages per symbol **without error**
if the signal is $x - 1$ times stronger than the noise

Signal strength = Noise strength

1 bit  2 bits  3 bits  4 bits  5 bits

1  3  7  15  31

Photo: Konrad Jacobs (CC BY-SA 2.0 DE)
Signal energy vanishes rapidly...

8 meter: 1 million part
250 meter: 1 billion part
Reflections, penetration losses, blockage, …
Mobile Networks for Uniform Data Speeds

Today

Large distance variations
High power and visible
Sensitive to blocking

MIMO = Multiple input multiple output

Designed for voice calls!

Future: “Distributed MIMO”

Small distance variations
Low power and invisible
Diversity: Unlikely to block all

5G: MIMO

MIMO = Multiple input multiple output
Intelligent densification is key

16 times more masts

Bit rate [Mbit/s]

Distance [m]

Avstånd [m]

Our solution

Bit rate [Mbit/s]

Distance [m]
Philosophy of Interference Suppression

Cellular network:

3 desired signals: One per transmitter

Each receiver: 1 observation
1 desired signal
2 interfering ones

Too few observations to remove interference

Cell-free network:

3 desired signals: One per transmitter

Joint signal decoding

Enough observations: 3 observation
3 desired signal
Future “cell-free” networks

Cellular network

“Cell-free” network

Small masts
Fiber cables
Edge cloud

Radio stripes:
Cultural places
Factories
Where do we stand?

Communication theory is becoming mature

Challenges
- Synchronization
- Prototyping
- Standardization of interfaces
- Radio resource management

Core network
Samples of recent work

Soft Handover Procedures in mmWave Cell-Free Massive MIMO Networks

Mahmoud Zaher, Emil Björnson, Fellow, IEEE, and Marina Petrova, Member, IEEE.

Abstract—This paper considers a mmWave cell-free massive MIMO (multiple-input multiple-output) network comprised of a large number of geographically distributed access points (APs) simultaneously serving multiple user equipments (UEs) via coherent joint transmission. We address UE mobility in the downlink (DL) with imperfect channel state information (CSI) and pilot training. Aiming at extending traditional handover concepts to the challenging AP-UE association strategies of cell-free networks, distributed algorithms for joint pilot assignment and cluster formation are proposed in a dynamic environment considering UE mobility. The algorithms provide a systematic procedure for initial access and update of the serving APs and assigned pilot sequence to each UE. The principal goal is to limit the necessary number of AP and pilot changes, while limiting computational complexity. We evaluate the performance, in terms of spectral efficiency (SE), with maximum ratio combining (MRC) and uniform power allocation (UPA) in a rayleigh fading channel. Results show that our proposed distributed algorithms effectively identify the optimal AP-UE association and resolves the uPA-UE association with orders-of-magnitude lower computational time compared to the state-of-the-art. It also provides a significantly lower average number of changes compared to an ultra-dense network (UDN). Moreover, we develop an improved pilot assignment procedure that facilitates massive access to the network in highly loaded scenarios.

Index Terms—Cell-free massive MIMO, handover, cluster formation, pilot assignment, mobility management, spectral efficiency.


Özlem Tüfçe Demir, Member, IEEE, Meyram Masoudi, Member, IEEE, Emil Björnson, Fellow, IEEE, and Cicek Cavdar, Member, IEEE.

Abstract—For the energy-efficient deployment of cell-free massive MIMO functionality in a practical wireless network, the end-to-end (from radio site to the cloud) energy-aware operation is essential. In line with the cloudification and virtualization in the real-time network (O-RAN), it is indispensable to envision prospective cell-free infrastructure on top of the O-RAN architecture. In this paper, we explore the performance and power consumption of cell-free massive MIMO technology in comparison with traditional small-cell systems, in the virtualized O-RAN architecture. We compare two different functional split options and different resource orchestration mechanisms. In the end-to-end orchestration scheme, we aim to minimize the end-to-end power consumption by jointly allocating the radio, optical fronthaul, and virtualized cloud processing resources. We compare end-to-end orchestration with two other schemes: 1) “radio-only” where radio resources are optimized independently from the cloud; and 2) “local cloud coordination” where orchestration is only allowed among a local cluster of radio units. We develop several algorithms to solve the end-to-end power minimization and sum spectral efficiency maximization problems. The numerical results demonstrate that end-to-end resource allocation with fully virtualized fronthaul and cloud resources provides a substantial additional power saving than the other resource orchestration schemes.

Index Terms—Cell-free massive MIMO, virtualized O-RAN, joint transmission, end-to-end resource allocation, joint network orchestration.

New networking and new air interface solutions are the two key enablers to support next-generation wireless systems [1]. The networking technologies include the softwareization, virtualization, and open radio access networks (O-RAN), whereas massive MIMO (multiple-input multiple-output) and cell-free massive MIMO are among the main air interface technologies. This paper studies cell-free massive MIMO in the O-RAN architecture, which brings together two inherently compatible networking and air interface entities of beyond 5G networks.

Cell-free massive MIMO has been proposed as a physical-layer technology that combines ultra-dense networks with joint transmission/reception (JT), and the low-complexity linear processing schemes from massive MIMO [3], [4], [5]. By taking advantage of both joint processing and macro diversity, cell-free massive MIMO reduces the large data rate variations across the coverage area, which solves one of the main drawbacks of the current cellular networks. For joint processing of UEs’ signals, it is required to centralize parts of the baseband processing, which constructs the inherent connection between cell-free massive MIMO and the centralized RAN (C-RAN) architecture [6]. The separation of software from hardware not only allows for joint processing in cell-free operation but also creates new energy-saving opportunities with green and self-utilization [7]. To meet the coordination and signal...
Summary

New technology needed
Higher capacity needs
Availability, trustworthiness, sustainability

Part of the solution
Many small base stations
Algorithms for cooperation
Low cost and energy
Reinventing the Wireless Network Architecture Towards 6G: Cell-free Massive MIMO and Radio Stripes

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