Merging mmWave and Mobile Edge Computing in Future 5G Networks

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Acknowledgment

H2020 EU/Japan Project 5G-MiEdge:
Millimeter-wave Edge Cloud as an Enabler for 5G Ecosystem

List of participants

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Summary

- Major thrusts of 5G:

  - Millimeter wave communications
  - Mobile Edge Computing

- The 3 Primary Colors of 5G: Communication-Computation-Caching (C^3)

  - communication vs. caching
  - communication vs. computing

- Computation offloading: Joint optimization of comm/comp resources

- Merging MEC & mmWave

- Conclusion

MEC: a key ingredient of 5G

Major players in 5G roadmap

- Millimeter wave links
- Dense deployment of small cell base stations
- Massive MIMO
- Network functionality virtualization (NFV)
- Application-centric architecture
- Mobile edge computing

How to achieve 1,000 increase of system capacity

$$10^3 = 10 \times 10 \times 10$$

How to achieve 1,000 increase of system capacity

$$\frac{\text{bit/sec}}{\text{Km}^2} = \frac{\text{bit/sec/Hz}}{\text{cell}} \times \frac{\text{cell}}{\text{Km}^2} \times \text{Hz}$$

spectral efficiency x 10

massive MIMO

dense deployment of access points x 10

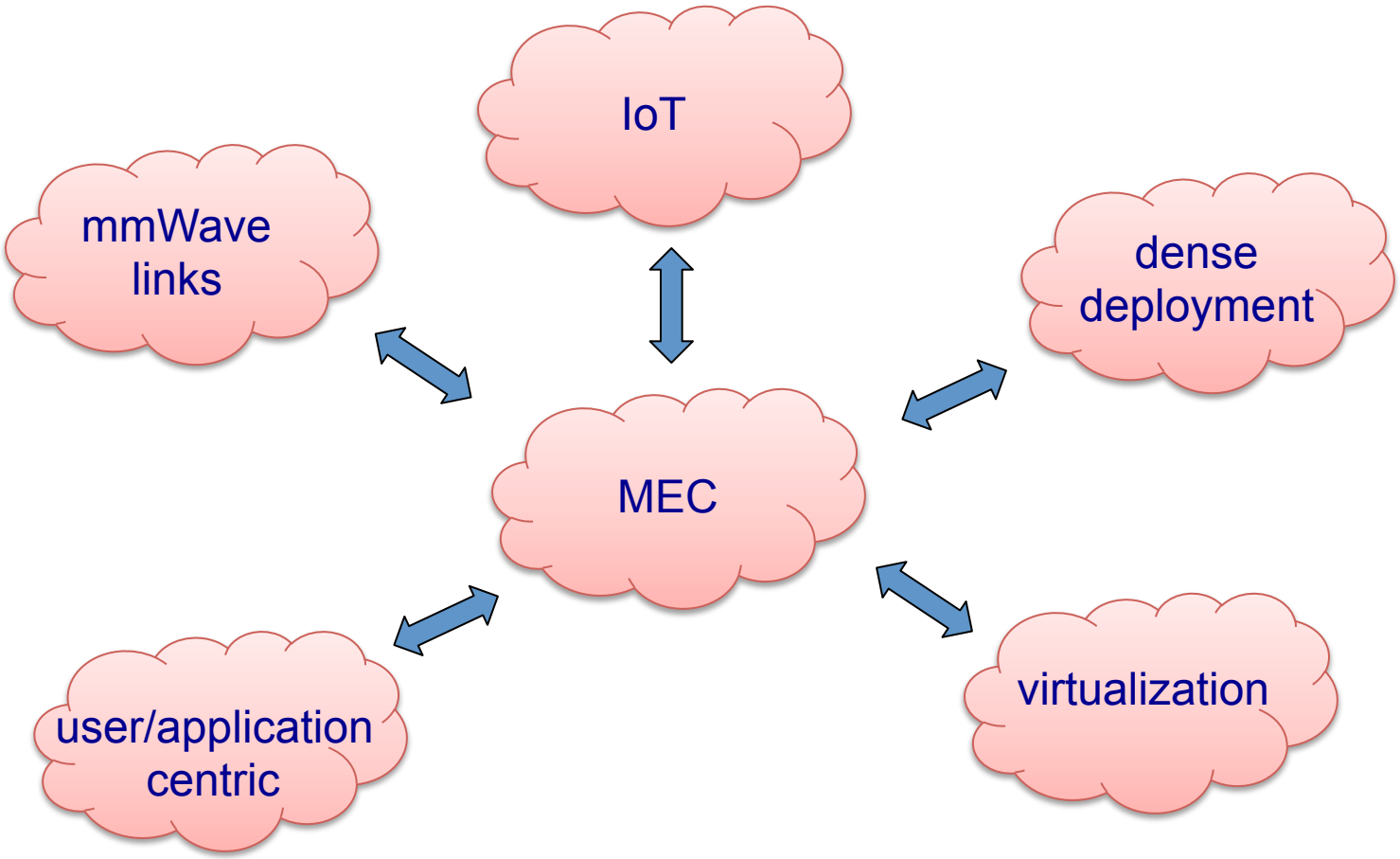
bandwidth x 10

increase carrier frequency

mmWave communications facilitate all three improvements

MEC: a key ingredient of 5G

MEC fits 5G roadmap perfectly well !



MEC vs. mmWaves

MEC ⟸ **mmWaves**

mmWaves provide high capacity radio access and wireless backhauling, facilitating low latency access to MEC services

MEC ⟹ **mmWaves**

MEC provides local computation power useful to optimize performance of mmWave communications

MEC vs. dense deployment

MEC ⟸ **dense deployment**

dense deployment of access points (AP) endowed with MEC functionalities bring IT services close to mobile end-user

MEC ⟹ **dense deployment**

MEC enables implementation of sophisticated interference mitigation techniques in a dense environment

MEC vs. virtualization

MEC ⟸ **virtualization**

virtualization enables deployment of virtual machines (VM) when/where needed

MEC ⟹ **virtualization**

MEC facilitates orchestration of VM's and their management taking into account user mobility

MEC vs. application-centric design

MEC ⟸ **application-centric design**

Application-centric design benefits from multi-tier service delivery where applications run as close as possible to end user

MEC ⟹ **application-centric design**

MEC promotes development of context-aware and RAN-aware applications

MEC vs. Internet of Things (IoT)

MEC ⟸ **IoT**

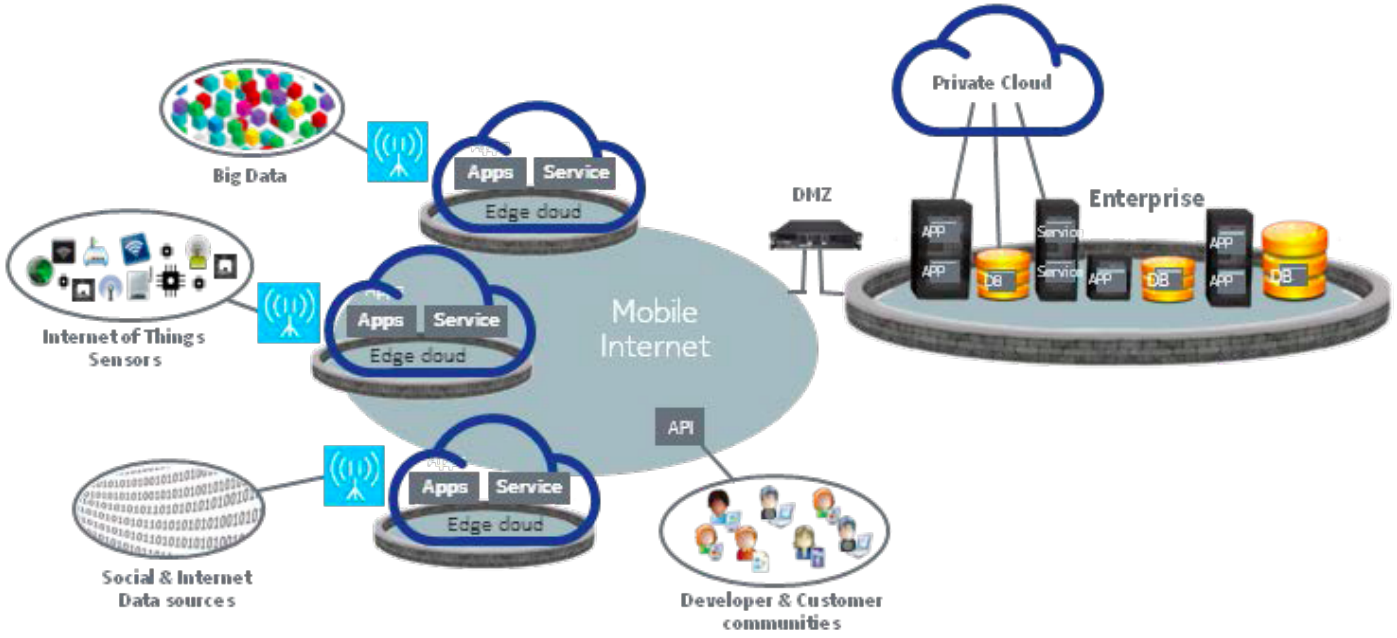
IoT expands MEC services to all “things”: sensors, actuators, …

MEC ⟹ **IoT**

MEC empowers tiny devices with significant additional computational capabilities through computation offloading

Mobile Edge Computing

Main idea: Offer application developers and content providers cloud-computing capabilities and IT services at the edge of the mobile network

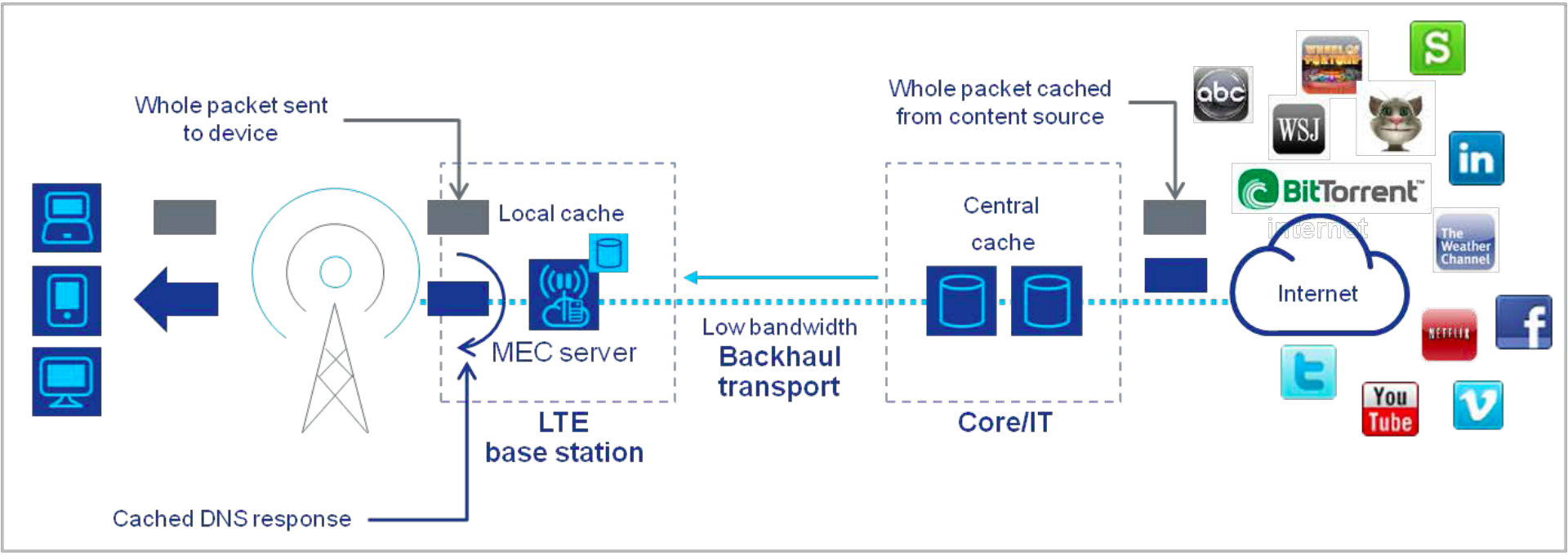


Specific features: - Proximity

- Ultra-low latency
- Real-time access to radio network information
- Location awareness

M. Patel et al.. "Mobile-Edge Computing – Introductory Technical White Paper", ETSI white paper, Sep 2014

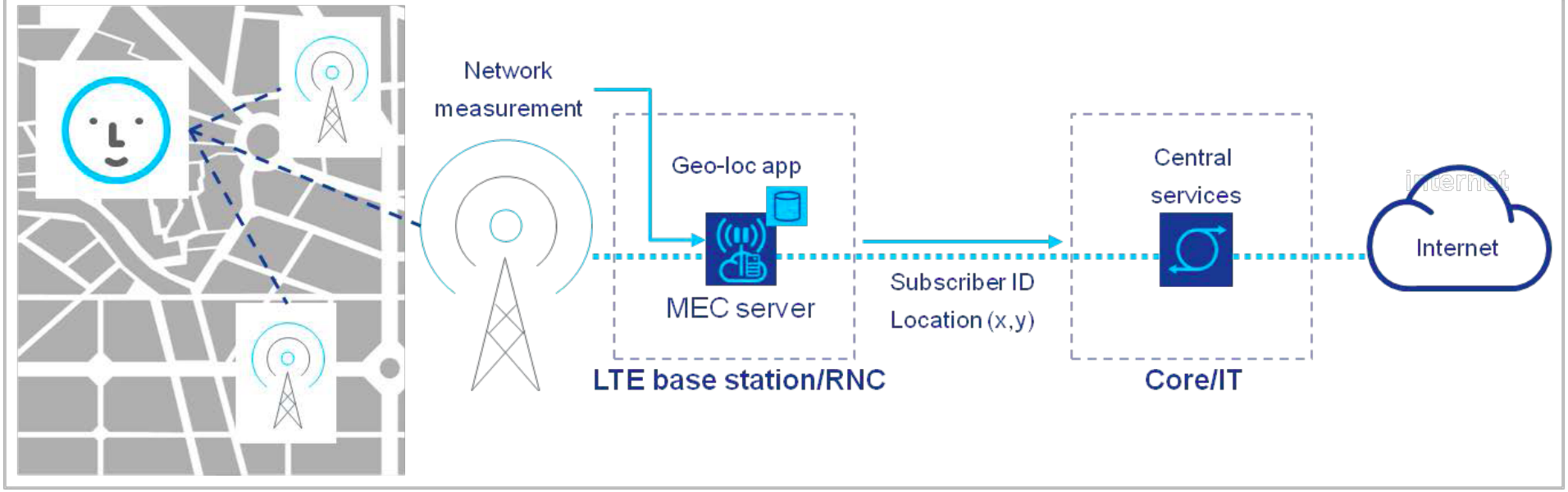
Use cases: Distributed Content and DNS Caching



- Popular content/data stored at the Base Station
- Backhaul and Transport savings (up to 35%)
- Improved QoE (20% improvement for loading a Web page)

M. Patel et al.. "Mobile-Edge Computing – Introductory Technical White Paper", ETSI white paper, Sep 2014

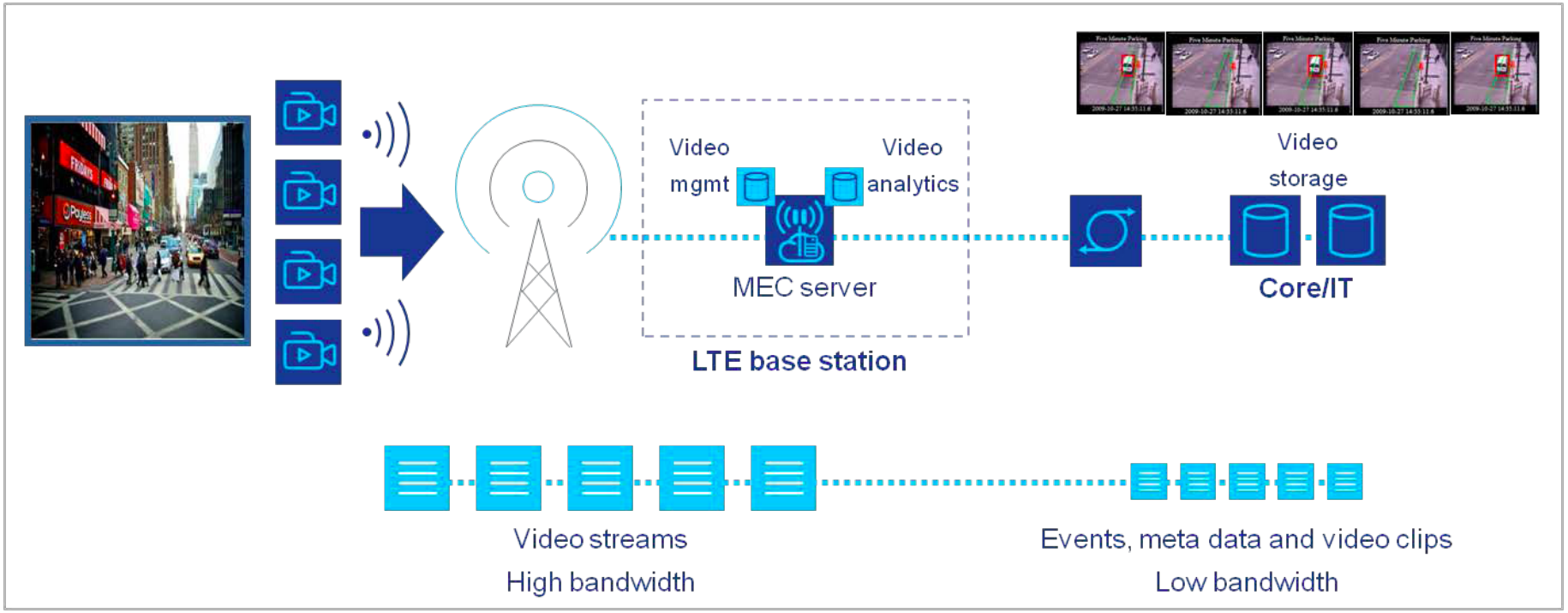
Use cases: Active Device Location Tracking



- Get Mobile Device location in real time and in a passive way (no GPS)
- Understand how the crowd is distributed or locate specific users
- Relevant in Smart City (Macro cells), retail (micro cells), and advertising

M. Patel et al.. "Mobile-Edge Computing – Introductory Technical White Paper", ETSI white paper, Sep 2014

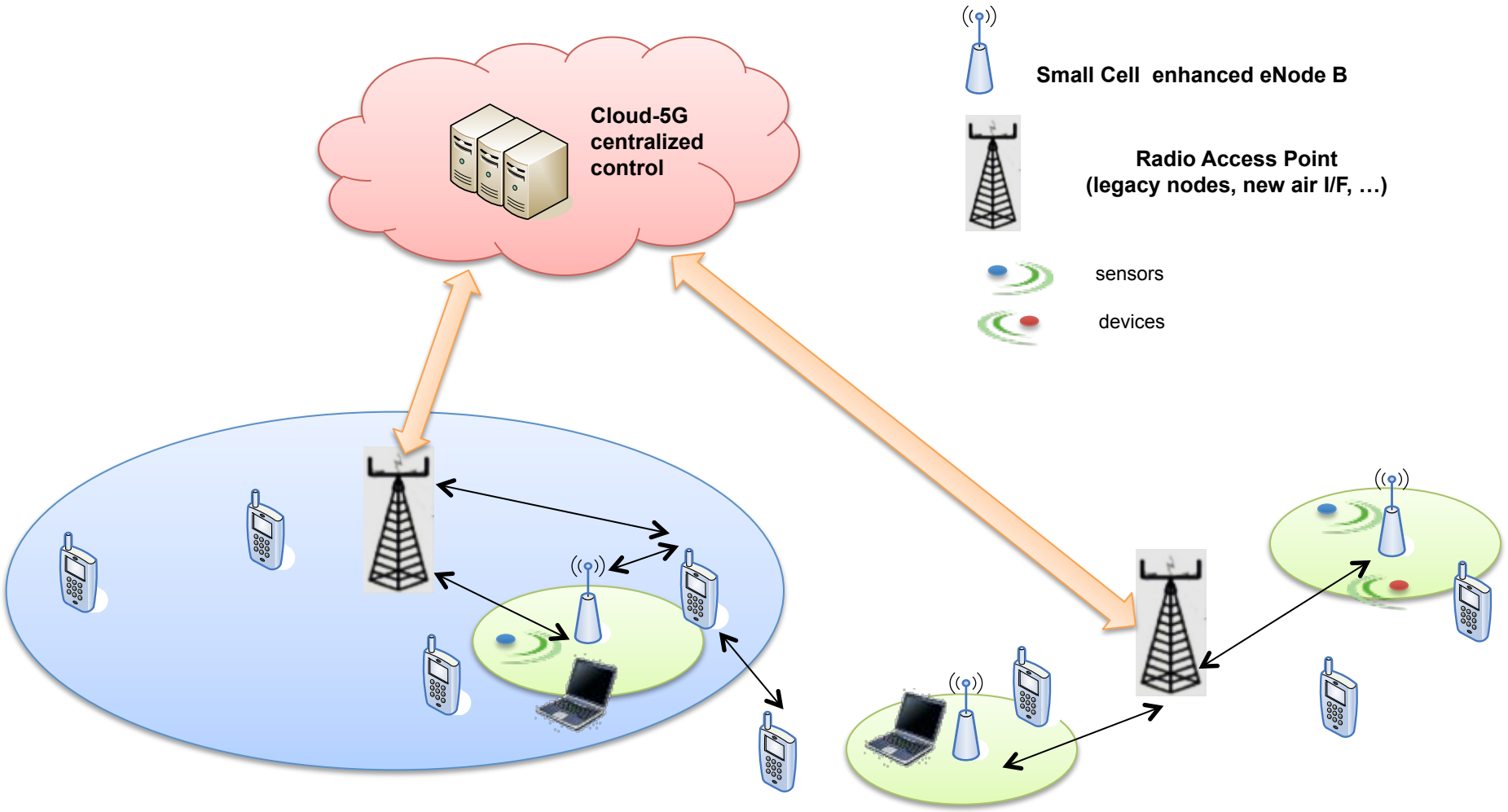
Use cases: Intelligent Video Analytics



- Analyze live video streams at the base station
- Trigger events automatically (e.g. abandoned bags, missing objects, crowd, etc.)
- Public safety, smart cities

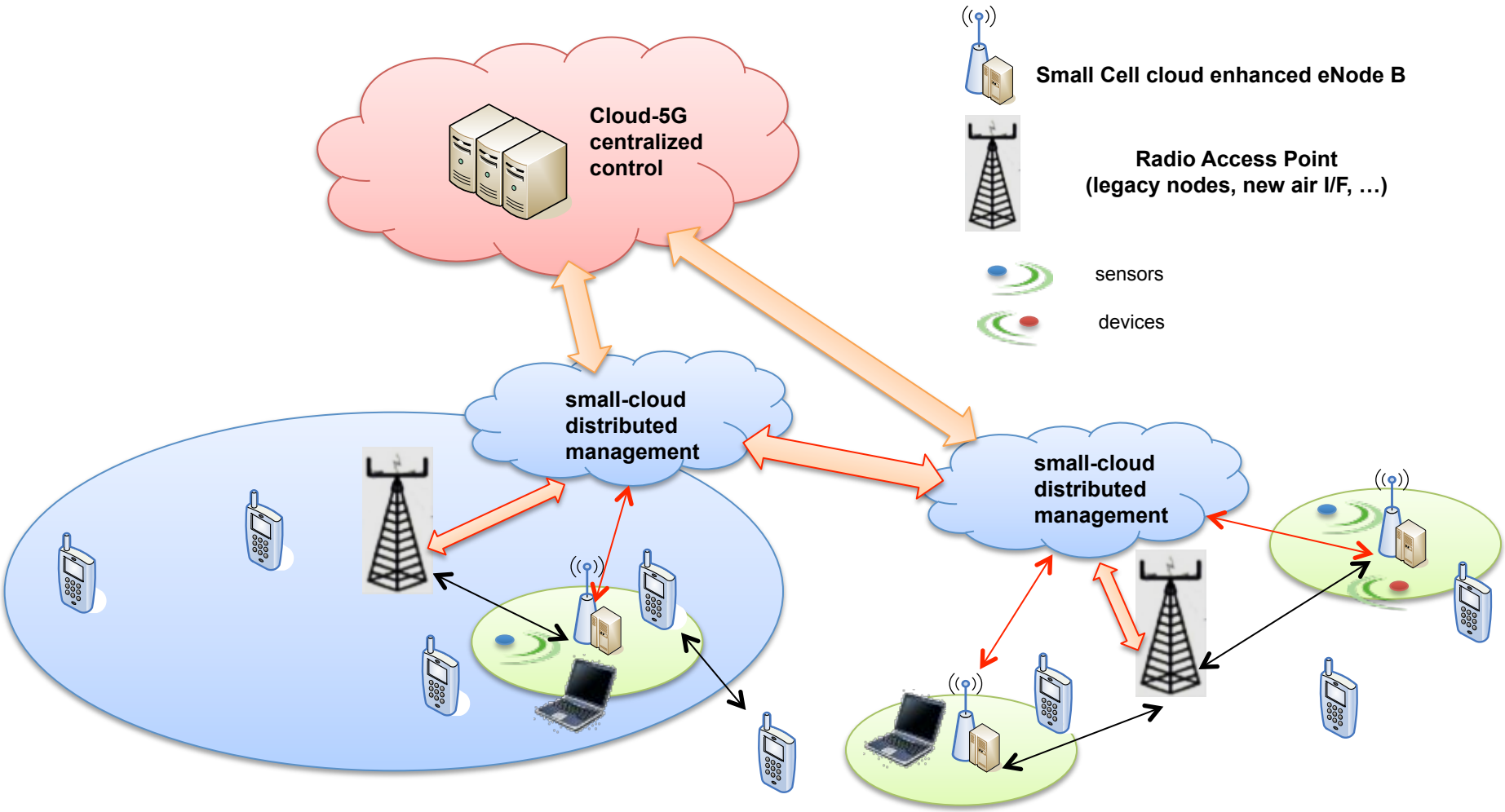
M. Patel et al.. "Mobile-Edge Computing – Introductory Technical White Paper", ETSI white paper, Sep 2014

Mobile Cloud Computing (MCC)



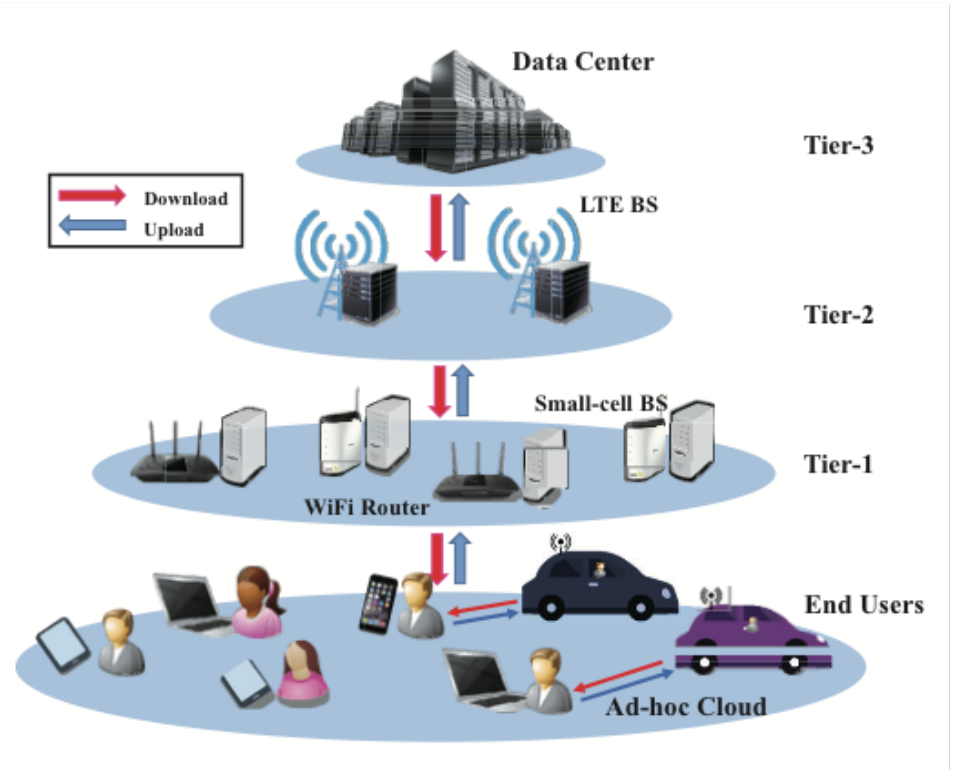
MCC is a centralized architecture: Intelligence is in the cloud

MEC: multi-tier IT service delivery



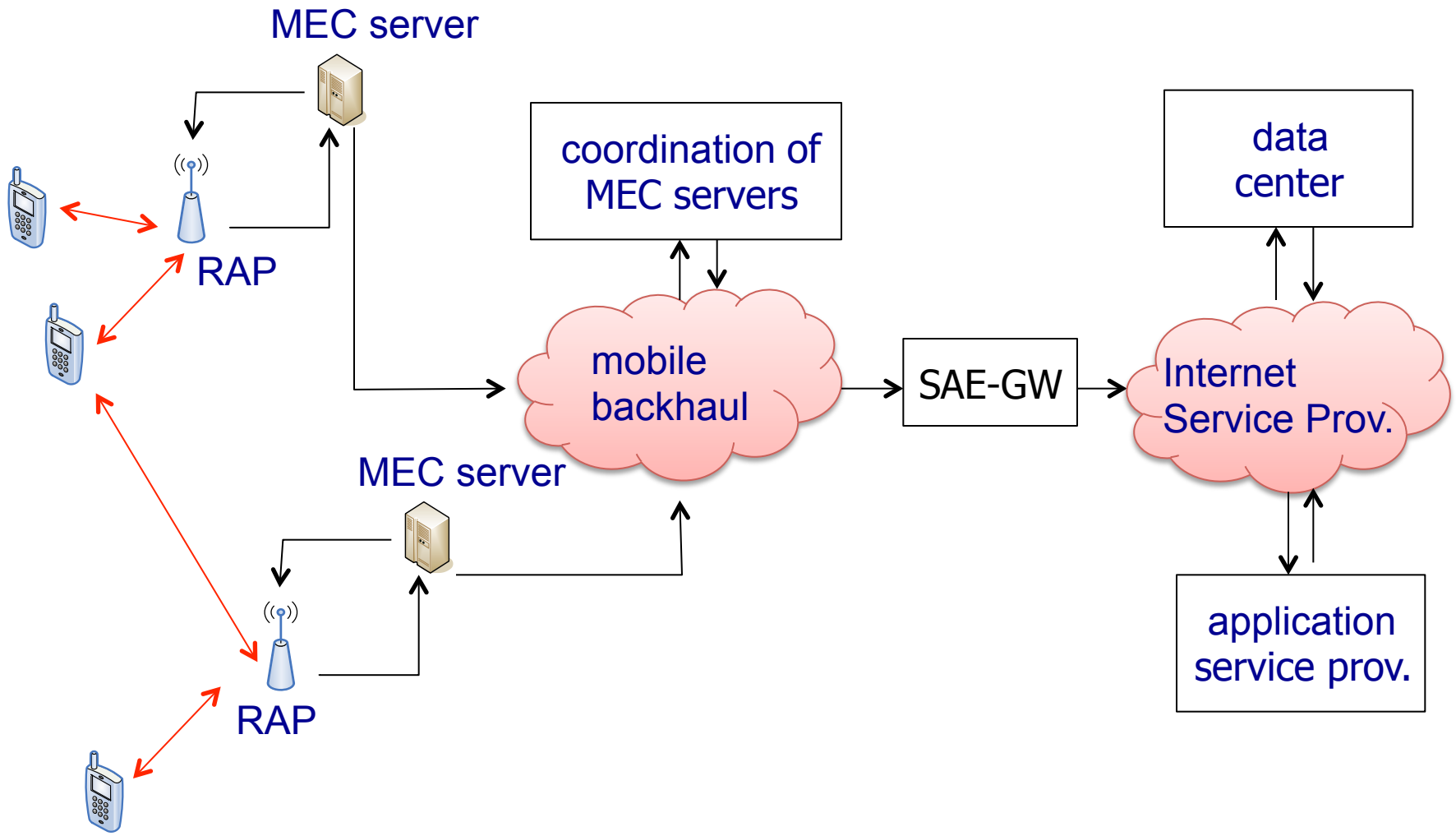
MEC is decentralized: Intelligence spreads towards the periphery

MEC: multi-tier IT service delivery ⇨ scalability



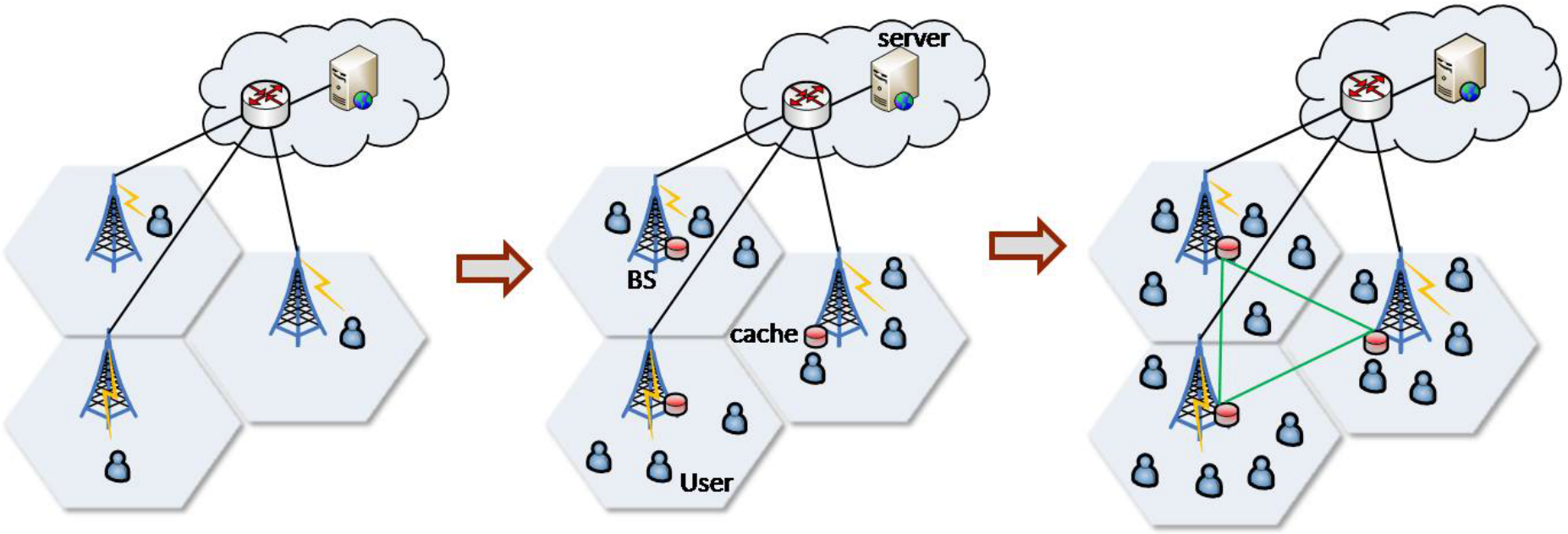
Applications run when/where more appropriate, given latency/reliability constraints and resource availability

MEC basic architecture



The 3 Primary Colors of 5G

Communication-Computation-Caching are three faces of a common framework



Communication

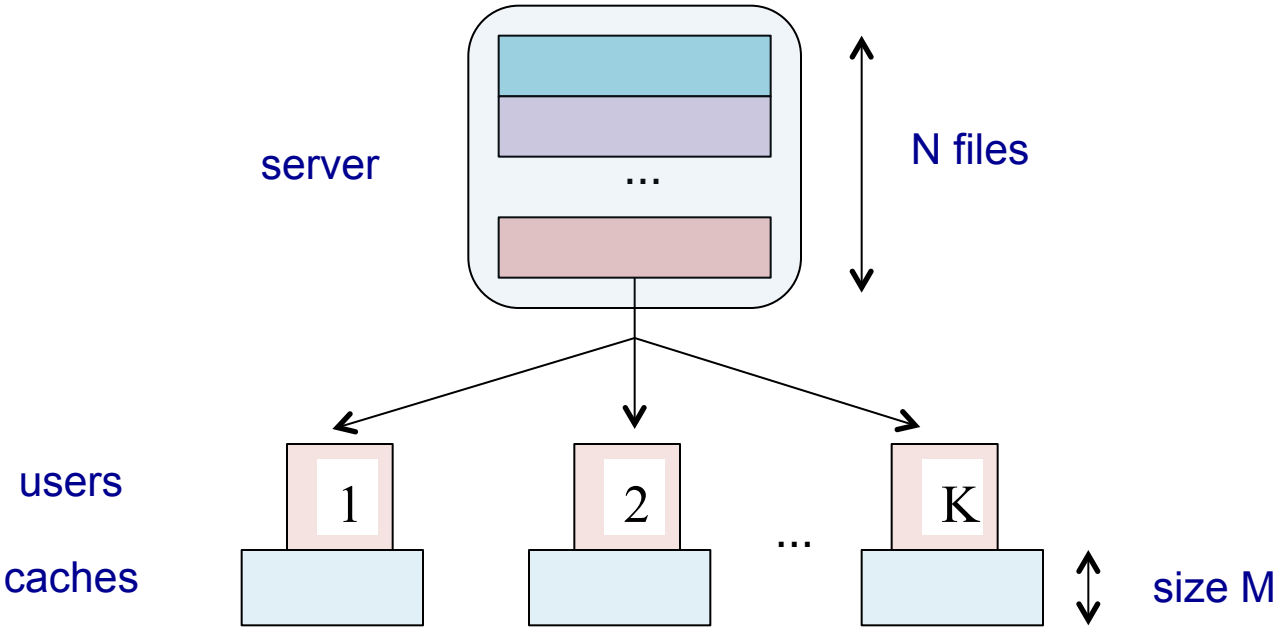
Communication + Caching

Communication + Caching + Computation

This holistic view suggests joint optimization of C^3 resource allocation

The 3 Primary C's of 5G

Fundamental trade-off between communication & caching

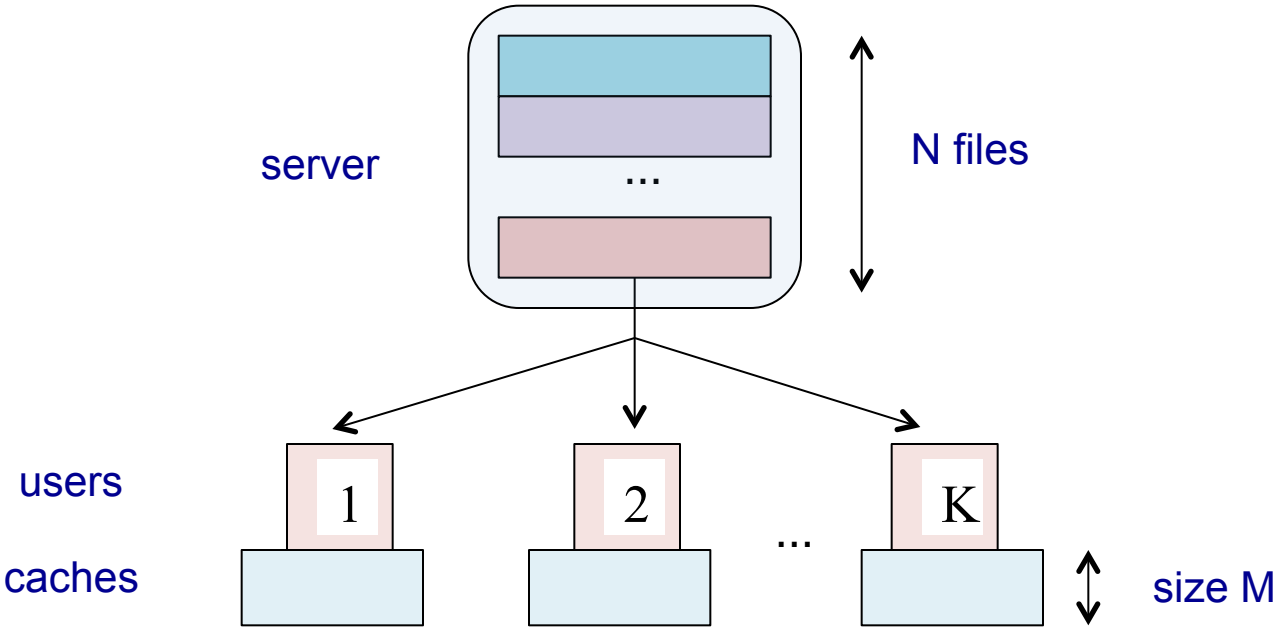


- Placement phase: caches are filled as a function of the database
- Delivery phase: each user may ask for any one of the N possible files

- Objective: design placement and delivery phases so that the traffic load of the shared link in the delivery phase is minimized

The 3 Primary C's of 5G

Fundamental trade-off between communication & caching



Load of shared link using **uncoded** caching: $K(1-M/N)$

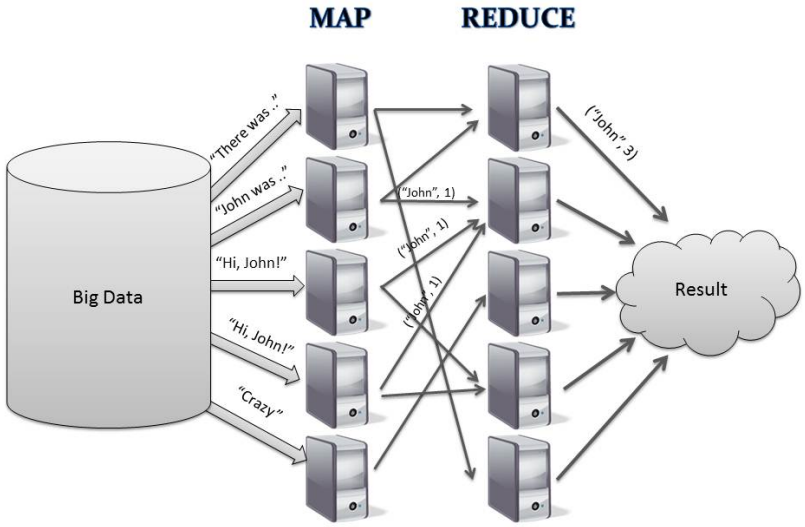
Load of shared link using **coded** caching: $K(1-M/N)\dfrac{1}{1+KM/N}$

MA Maddah-Ali, U Niesen, "Coding for caching: fundamental limits and practical challenges", IEEE Comm. Mag, 2016

The 3 Primary C's of 5G

Fundamental trade-off between communication & computation

Common architecture: MapReduce

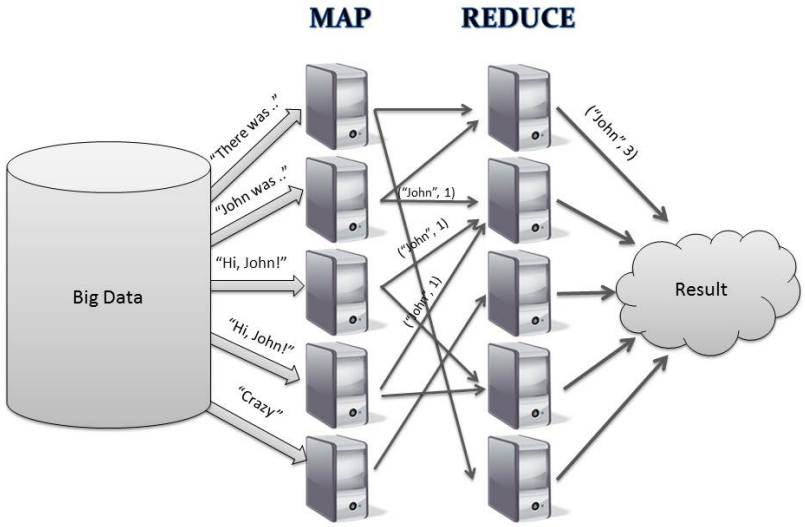


Question: Can coding help distributed computing in reducing the load of communication and speeding up the overall computation?

The 3 Primary C's of 5G

Fundamental trade-off between communication & computation

Common architecture: MapReduce



Answer: Coded Distributed Computing ⇨ $L(r) = \frac{1}{r}\left(1 - \frac{r}{K}\right)$

where K is the # of computing nodes and r is the computation load

S. Li, M. A. Maddah-Ali, Q. Yu, and A. S. Avestimehr, " A Fundamental Tradeoff between Computation and Communication in Distributed Computing", ISIT 2016

Computation offloading

Advantages offered by computation offloading using MEC

- Empower simple devices (e.g., tiny sensors in IoT) with augmented computational capabilities
- Prolong battery lifetime of mobile devices
- Reduce end-to-end latency associated to sophisticated applications
- Facilitate latency control with respect to MCC over wide area networks
- Enable RAN-aware content delivery

Computation offloading: Single-user case

Application parameters:

1. n_k = number of input bits transmitted by user k to offload program execution to the cloud
2. w_k = number of CPU cycles necessary to run user k application
3. f_k = number of CPU cycles/sec assigned to virtual machine associated to user k

Application classification features:

- Computational load vs. nr. of bits to be transferred

Computation offloading: Single-user case

Energy minimization under latency constraint

Overall latency: $\Delta = \Delta_T + \Delta_{exe} + \Delta_R$

where

1. Δ_T = time necessary to transfer the input bits b from MU to the serving SCeNB
2. Δ_{exe} = time for the server to run the application
3. Δ_R = time necessary to receive the result back

Note: Overall latency couples radio access and computational aspects

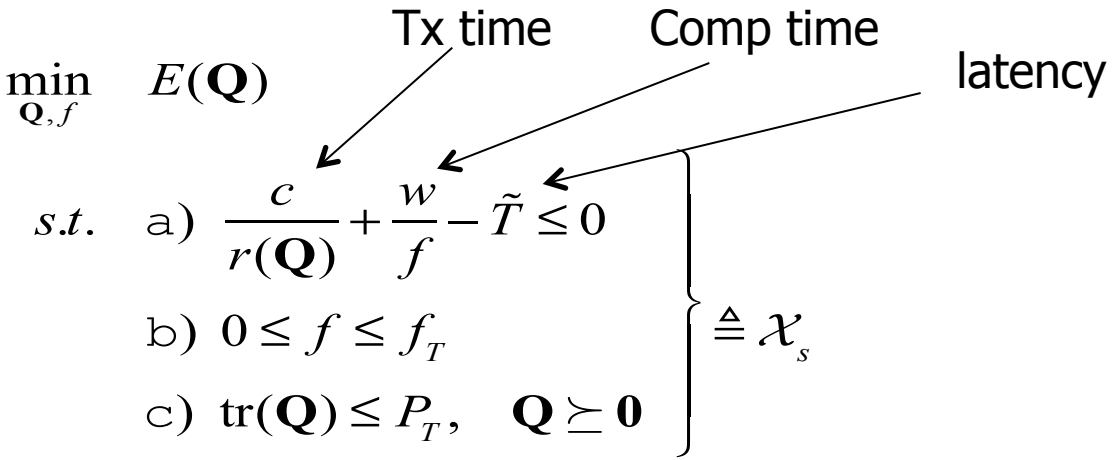
→ Joint optimization of radio / computational resources

S. Barbarossa, S. Sardellitti, P. Di Lorenzo, "Communicating while Computing: Distributed Cloud Computing over 5G Heterogeneous Networks", IEEE Signal Processing Magazine, Nov. 2014

Energy minimization under latency constraint

Problem formulation:

Find precoding matrices for MIMO transceivers and computing rate minimizing energy consumption @ mobile site, under latency constraint



Note: Exploit Adaptive Coding and Modulation (ACM) to adapt transmit rate

Remark: This problem is non-convex

S. Barbarossa, S. Sardellitti, P. Di Lorenzo, "Communicating while Computing: Distributed Cloud Computing over 5G Heterogeneous Networks", IEEE Signal Processing Magazine, Nov. 2014

Computation offloading: Single-user case

Energy minimization under latency constraint

Results:

1) Problem can be converted into a convex problem

2) Solution is found in closed form:

$$f^* = f_S \qquad \mathbf{Q}^* = \mathbf{U}(\alpha\mathbf{I} - \mathbf{D}^{-1})^+\mathbf{U}^H$$

where $\mathbf{H}^H\mathbf{R}_w^{-1}\mathbf{H} = \mathbf{U}\mathbf{D}\mathbf{U}^H$ and $\alpha > 0$ is chosen so that latency constraint is satisfied with equality

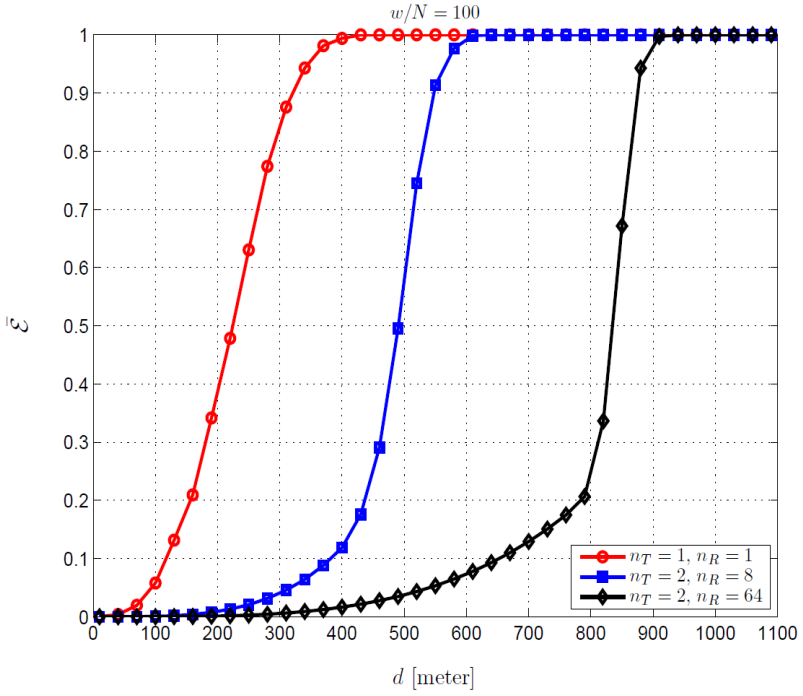
Note: Solution takes the well known water-filling form, where water-level depends on computational parameters and latency constraint

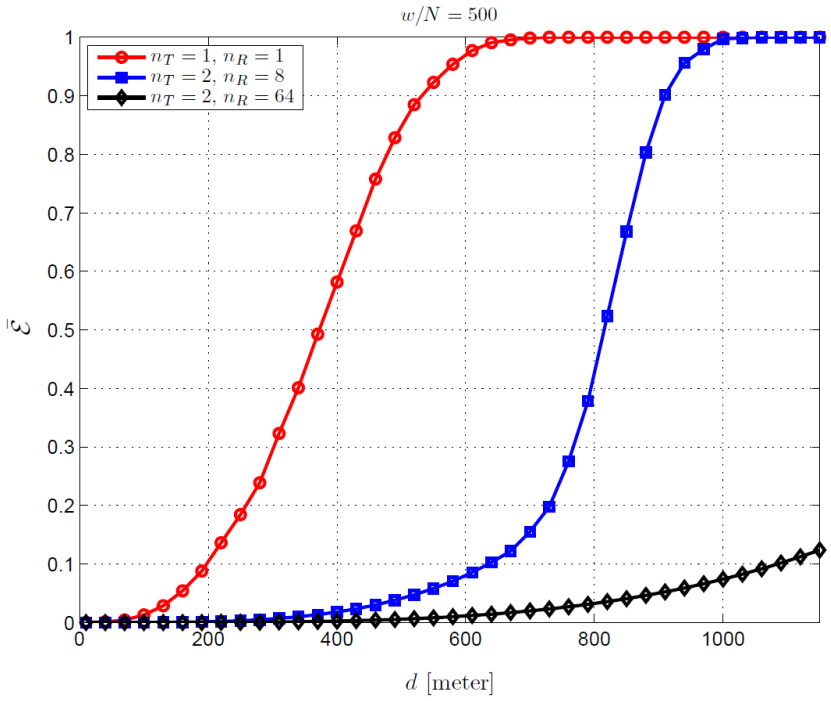
S. Barbarossa, S. Sardellitti, P. Di Lorenzo, "Communicating while Computing: Distributed Cloud Computing over 5G Heterogeneous Networks", IEEE Signal Processing Magazine, Nov. 2014

Energy minimization under latency constraint

Numerical results: normalized average energy vs. MU – SCeNB distance

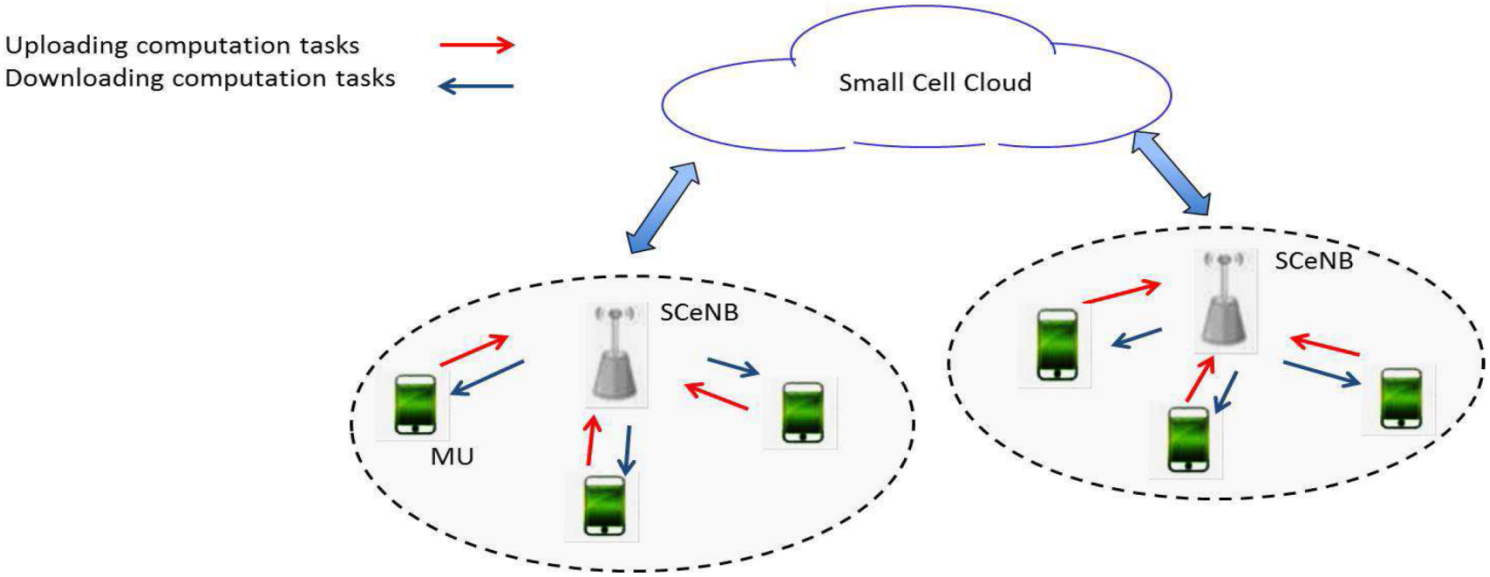
Computationally demanding applications





Single cloud serving multiple cells

MIMO multicell network



Goal: Joint allocation of computational and communication resources to minimize the transmit energy consumption under latency constraint in a dense deployment scenario

S. Sardellitti, G. Scutari, S. Barbarossa, "Joint Optimization of Radio and Computational Resources for Multicell Mobile-Edge Computing", IEEE Trans. on Signal and Information Processing over Networks, June 2015

Single cloud serving multiple cells

Degrees of freedom:

- Radio resources: precoding matrices or, equivalently, covariance matrices $\mathbf{Q} \triangleq (\mathbf{Q}_{i_n})_{i_n \in \mathcal{I}}$
- Computing resources: percentage of CPU cycles assigned to each user (VM) f_{i_n}

Constraints:

- Transmit power budget
- Computational capacity:

$$\sum_{i_n \in \mathcal{I}} f_{i_n} \leq f_S$$

Critical issues: Inter-cell interference, admission control incorporating QoE

Single cloud serving multiple cells

Problem formulation:

Find optimal $\mathbf{Q} \triangleq (\mathbf{Q}_{i_n})_{i_n \in \mathcal{I}}$ and $\boldsymbol{f} \triangleq (f_{i_n})_{i_n \in \mathcal{I}}$ minimizing overall energy spent by MUs

Tx time

Comp time

$$\min_{\mathbf{Q},\mathbf{f}} \; E(\mathbf{Q}) \triangleq \sum_{n,i} E_{i_n}(\mathbf{Q}_{i_n}, \mathbf{Q}_{-n})$$

$$\text{s.t.} \quad \text{a)} \; g_{i_n}(\mathbf{Q}, f_{i_n}) \triangleq \frac{c_{i_n}}{r_{i_n}(\mathbf{Q}_{i_n}, \mathbf{Q}_{-n})} + \frac{\omega_{i_n}}{f_{i_n}} - \tilde{T}_{i_n} \leq 0, \; \forall i_n \in \mathcal{I},$$

users' latency constraints

$$\text{b)} \sum_{i_n \in \mathcal{I}} f_{i_n} \leq f_T \quad \text{and} \quad f_{i_n} \geq 0, \quad \forall i_n \in \mathcal{I},$$

computing rate constraint

$$\text{c)} \; \mathbf{Q}_{i_n} \in \mathcal{Q}_{i_n}, \quad \forall i_n \in \mathcal{I},$$

Tx power constraint

where $r_{i_n}(\mathbf{Q}) = \log_2 \det \left(\mathbf{I} + \mathbf{H}_{i_n n}^H \mathbf{R}_{i_n}(\mathbf{Q}_{-n})^{-1} \mathbf{H}_{i_n n} \mathbf{Q}_{i_n} \right)$

$$\mathbf{R}_{i_n}(\mathbf{Q}_{-n}) \triangleq \mathbf{R}_n + \sum_{n \neq m = 1}^{N_c} \sum_{j=1}^{K_m} \mathbf{H}_{j_m n} \mathbf{Q}_{j_m} \mathbf{H}_{j_m n}^H$$

S. Sardellitti, G. Scutari, S. Barbarossa, "Joint Optimization of Radio and Computational Resources for Multicell Mobile-Edge Computing", IEEE Trans. on Signal and Information Processing over Networks, June 2015

Single cloud serving multiple cells

Challenges: Non-convex problem / admission control

- Numerical methods may be slow to converge and unreliable

- Depending on channel conditions, not all applications can be offloaded while respecting all constraints (power and latency)

Approach:

Step # 1: Admission control is achieved as solution of feasibility conditions:

$$\tilde{T}_{i_n} > \frac{c_{i_n}}{r_{i_n}(\overline{\mathbf{Q}})}, \forall i_n \in \mathcal{I}, \quad \text{and} \quad \sum_{i_n \in \mathcal{I}} \frac{\omega_{i_n}}{\tilde{T}_{i_n} - \frac{c_{i_n}}{r_{i_n}(\overline{\mathbf{Q}})}} \leq f_T$$

S. Sardellitti, G. Scutari, S. Barbarossa, "Joint Optimization of Radio and Computational Resources for Multicell Mobile-Edge Computing", IEEE Trans. on Signal and Information Processing over Networks, June 2015

Single cloud serving multiple cells

Challenges: Non-convex problem / admission control

Step # 2: Use Successive Convex Approximation (SCA) as a reliable and fast solution method

Original non-convex problem is replaced by a sequence of strongly convex problems exploiting the structure of the problem

Main idea: At each iterate, approximate the original nonconvex nonseparable objective function $E(\mathbf{Q})$ and constraint $g_{i_n}(\mathbf{Q}, f_{i_n})$ around the current iterate with a strongly convex function

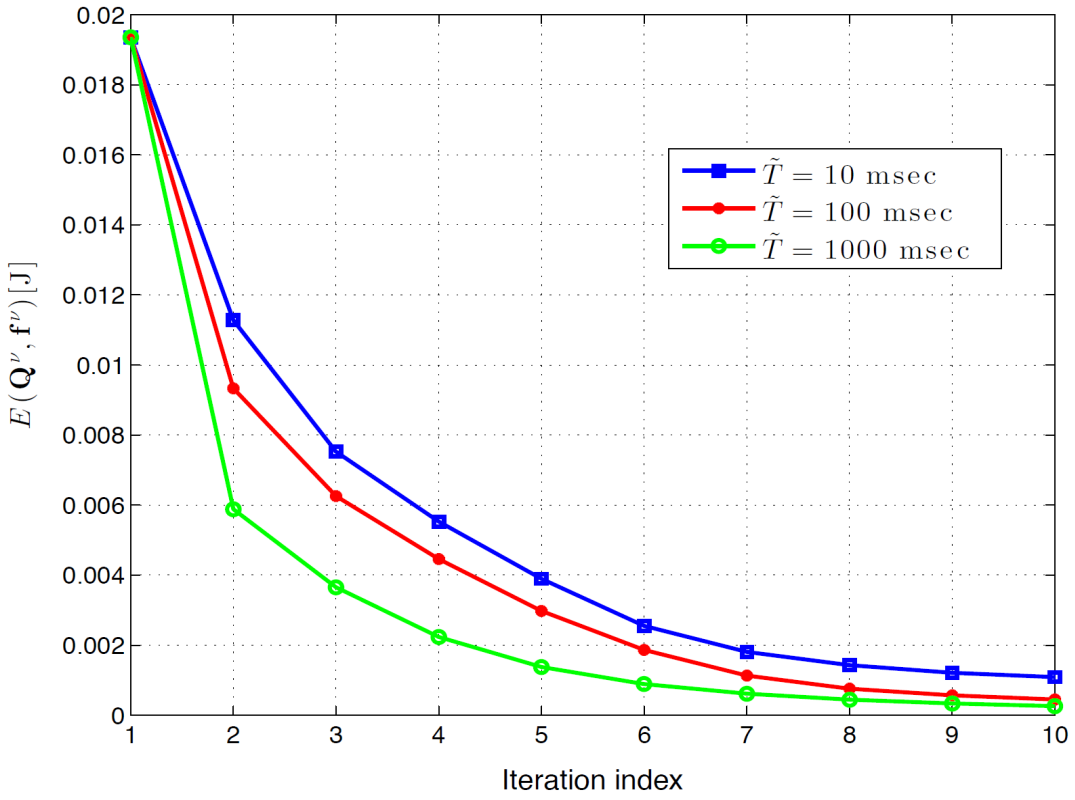
Remark: Different approximation choices (albeit appropriate) are available and lead to:

- Centralized algorithms
- Distributed algorithms with limited signaling overhead

S. Sardellitti, G. Scutari, S. Barbarossa, "Joint Optimization of Radio and Computational Resources for Multicell Mobile-Edge Computing", IEEE Trans. on Signal and Information Processing over Networks, June 2015

Single cloud serving multiple cells

Numerical results: Sum energy vs. iteration number

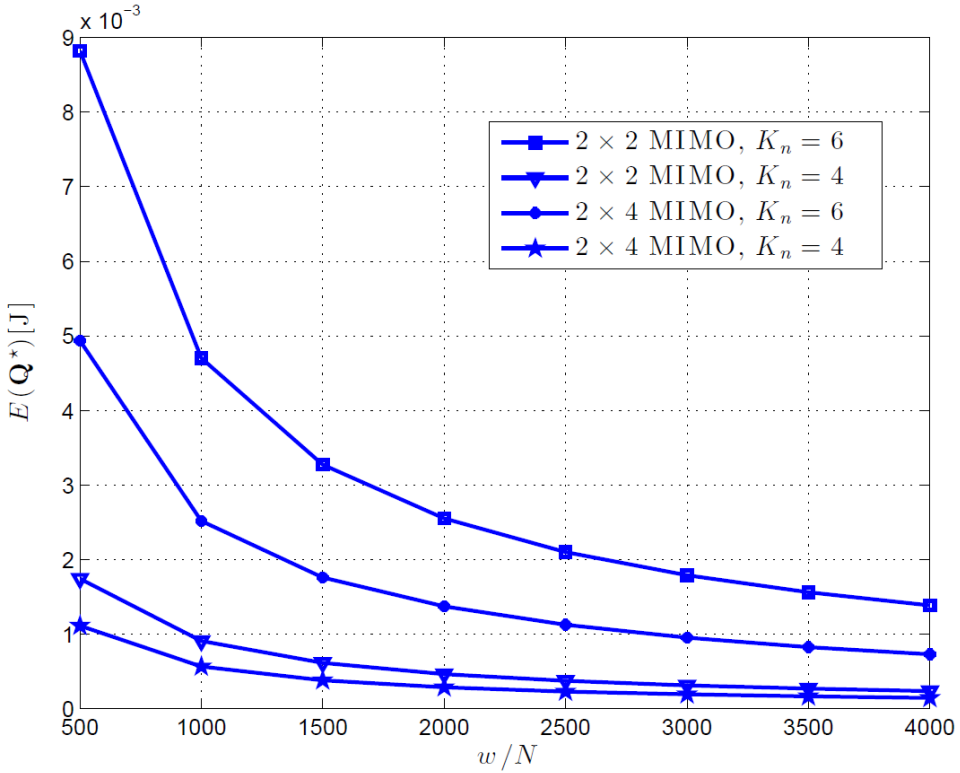


Proposed SCA algorithm converges in a very few iterations

S. Sardellitti, G. Scutari, S. Barbarossa, "Joint Optimization of Radio and Computational Resources for Multicell Mobile-Edge Computing", IEEE Trans. on Signal and Information Processing over Networks, June 2015

Single cloud serving multiple cells

Numerical results: Sum energy vs. computational load

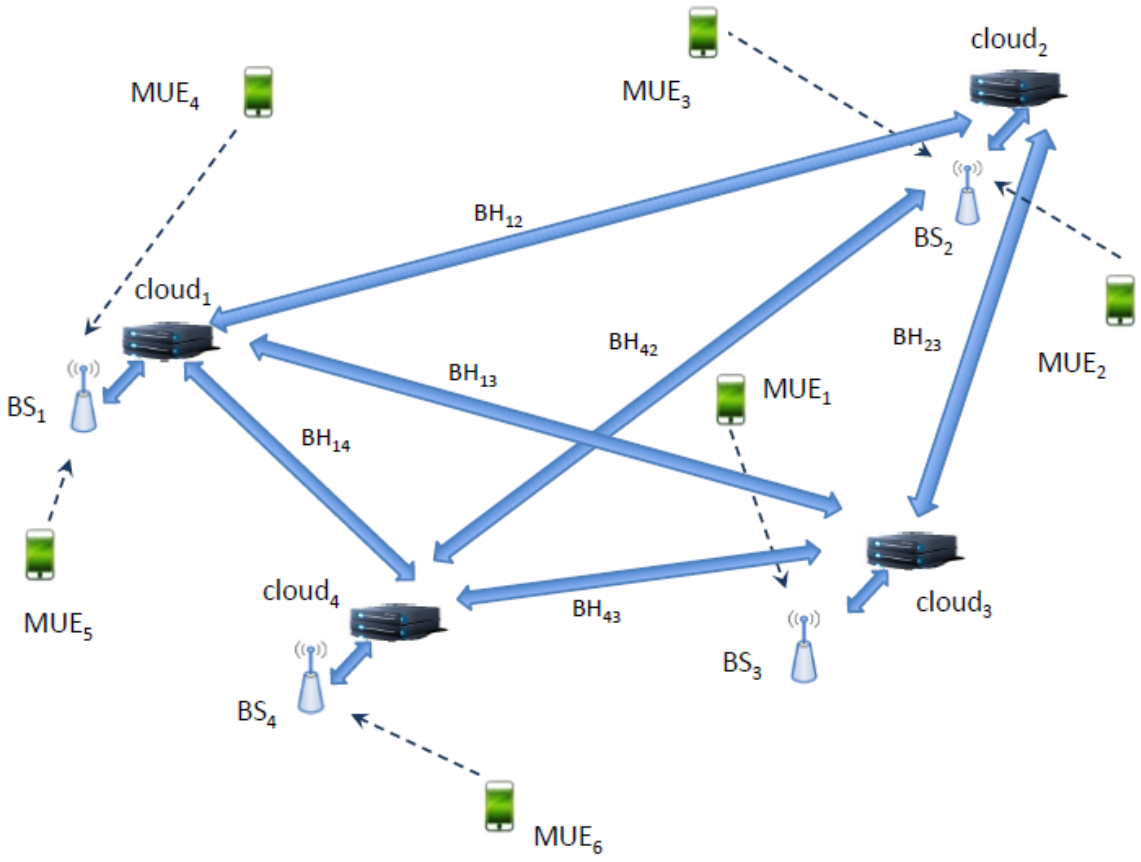


CPU cycles per Tx bits

S. Sardellitti, G. Scutari, S. Barbarossa, "Joint Optimization of Radio and Computational Resources for Multicell Mobile-Edge Computing", IEEE Trans. on Signal and Information Processing over Networks, June 2015

Multiple clouds serving multiple cells

Goal: Joint optimization of radio/computational resources and mobile user-base station-cloud assignment



S. Barbarossa, S. Sardellitti, P. Di Lorenzo, "Communicating while Computing: Distributed Cloud Computing over 5G Heterogeneous Networks", IEEE Signal Processing Magazine, Nov. 2014

Multiple clouds serving multiple cells

Goal: Joint optimization of radio/computational resources and mobile user-base station-cloud assignment

Degrees of freedom:

- Precoding matrix $\mathbf{F}_k$ or, equivalently, covariance matrix $\mathbf{Q}_k$ of each user k

- Number f_{mk} of CPU cycles/sec assigned to k-th user virtual machine on the m-th cloud

- Assignment of each user to a base station and to a cloud: $a_{knm} \in \{0,1\}$

Each mobile user is served by a single base station and a single cloud, i.e.

$$\sum_{n=1}^{N_b} \sum_{m=1}^{N_c} a_{knm} = 1$$

but the method can be extended

S. Barbarossa, S. Sardellitti, P. Di Lorenzo, "Communicating while Computing: Distributed Cloud Computing over 5G Heterogeneous Networks", IEEE Signal Processing Magazine, Nov. 2014

Multiple clouds serving multiple cells

Problem formulation:

$$\min_{\mathbf{Q},\mathbf{f},\mathbf{a}} E(\mathbf{Q},\mathbf{a}) \triangleq \sum_{k=1}^{K} c_k E_k(\mathbf{Q},\mathbf{a}_k) \qquad (\mathrm{P})$$

weighted sum energy

subject to

i) $g_{knm}(\mathbf{Q}, f_{mk}, a_{knm}) \le L_k, \forall\, k,n,m$ — latency constraint

ii) $\mathrm{tr}(\mathbf{Q}_k) \le P_k, \quad \mathbf{Q}_k \succeq \mathbf{0}, \forall\, k \in \mathcal{I}$ — Tx power constraint

iii) $\mathbf{f} \ge \mathbf{0}, \quad \sum_{k=1}^{K}\sum_{n=1}^{N_b} a_{knm} f_{mk} \le F_m, \quad \forall\, m$ — computing constraint

iv) $\sum_{n=1}^{N_b}\sum_{m=1}^{N_c} a_{knm} = 1,\ a_{knm} \in \{0,1\}, \quad \forall\, k,n,m$ — association constraint

where

$$g_{knm}(\mathbf{Q}, f_{mk}, a_{knm}) \triangleq a_{knm}\left(\frac{c_k}{r_{kn}(\mathbf{Q})} + \frac{w_k}{f_{mk}} + T_{Bmn}\right)$$

$$r_{kn}(\mathbf{Q}) = \log_2 \det\left(\mathbf{I} + \mathbf{H}_{kn}^H \mathbf{R}_{kn}(\mathbf{Q}_{-k})^{-1}\mathbf{Q}_k\mathbf{H}_{kn}\right)$$

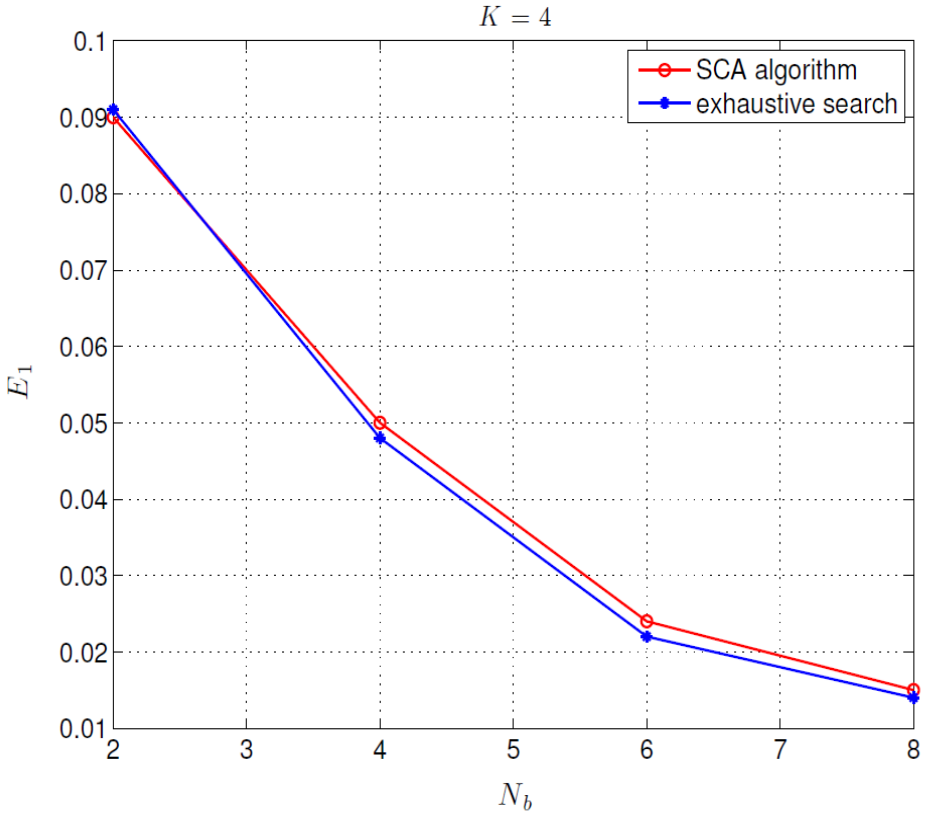
S. Barbarossa, S. Sardellitti, P. Di Lorenzo, "Communicating while Computing: Distributed Cloud Computing over 5G Heterogeneous Networks", IEEE Signal Processing Magazine, Nov. 2014

Multiple clouds serving multiple cells

Proposed solution: Successive Convex Approximation (SCA)

Comparison between relaxed problem and exhaustive search

Average energy consumption vs. number of base stations N_b



Note:

- Losses wrt exhaustive search are very small

- Dense deployment yields a considerable energy saving

Merge mmWaves and MEC

Shortcomings:

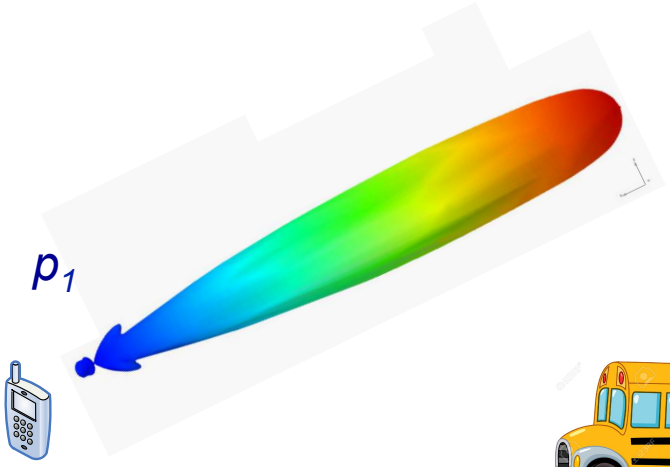
- Channel intermittency due to obstacles
- Interference from users transmitting from similar angles (e.g., canyon crowd)
- Large attenuation over long distance links

Proposed approach

- Overbook resources to meet latency constraints on average, depending on probabilities of blocking events
- Use multi-link communications whenever possible

S. Barbarossa, E. Ceci, M. Merluzzi, E. Calvanese-Strinati, "Enabling Effective Mobile Edge Computing Using Millimeter Wave Links", ICC 2017

Example: Single user / Multi-link to 2 radio access points

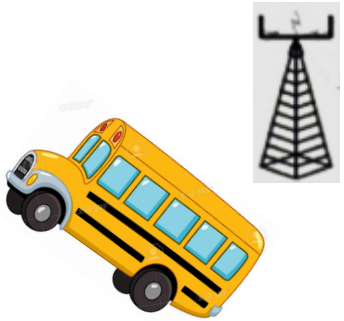


mobile user transmits to RAP_1

with probability $\mathbb{P}_1$

using power p_1

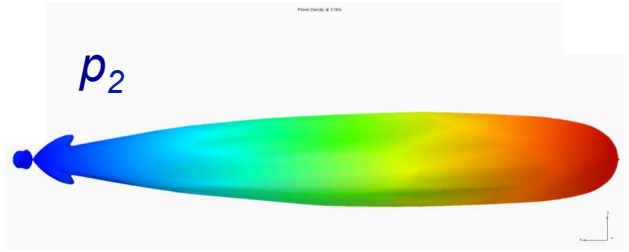
Example: Single user / Multi-link to 2 radio access points



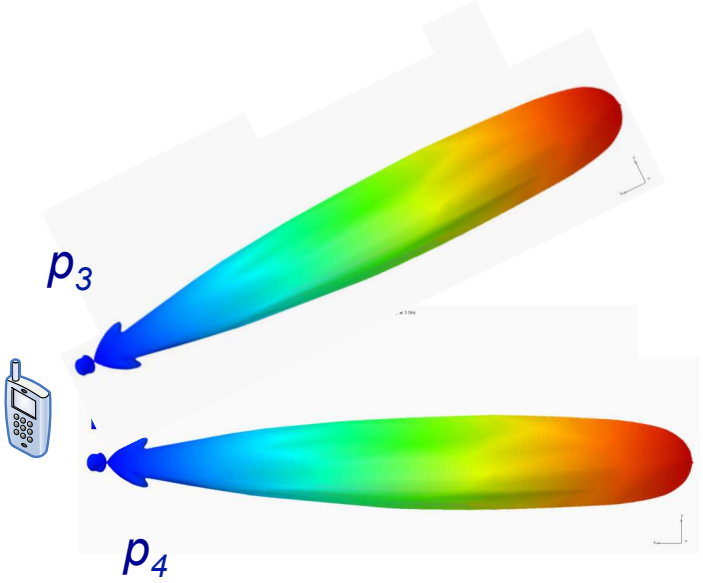
mobile user transmits to RAP_2

with probability $\mathbb{P}_2$

using power p_2



Example: Single user / Multi-link to 2 radio access points



mobile user transmits to both RAP_1 and RAP_2

with probability $\mathbb{P}_3$

using power p_3 and p_4

Problem formulation: min *average* transmit power consumption subject to *average* rate

Example: 2 access points

$$\min_{\boldsymbol{p}} \ \sum_{i=1}^{4} \mathbb{P}_i \, p_i, \ \text{s.}t.$$
$$i) \ \sum_{i=1}^{4} \mathbb{P}_i \log(1 + a_i p_i) \geq \bar{R}_{min}$$
$$ii) \ p_i \geq 0, i = 1, \ldots, 4;$$
$$iii) \ p_i \leq P_T, i = 1, 2; p_3 + p_4 \leq P_T,$$

where $\mathbb{P}_i$ is the probability of having link *i* on

Solution

$$p_i = \left[\beta - \frac{1}{a_i}\right]_0^{P_T}, i = 1, 2 \qquad p_i = \left[\frac{\beta \mathbb{P}_i}{\mathbb{P}_i + \nu_3} - \frac{1}{a_i}\right]_+, \ i = 3, 4$$

where

$$\beta = \exp\left(\frac{c}{2 - P_{I_1} - P_{I_2}}\right)$$

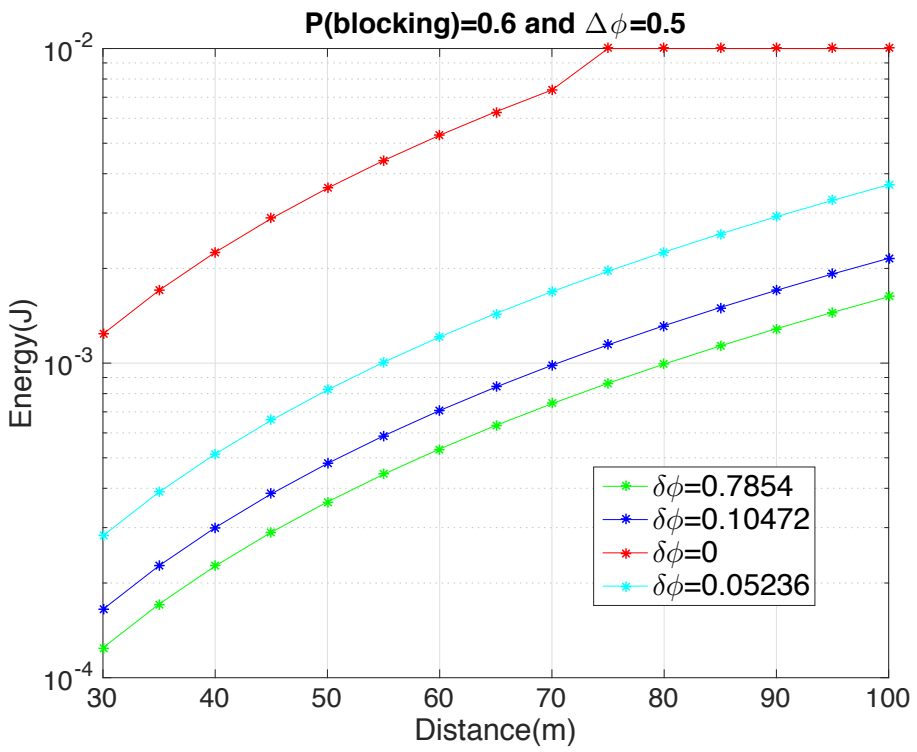
if optimal powers do not reach the power budget

Numerical results: Statistically dependent blocking events

Average energy consumption vs. distance

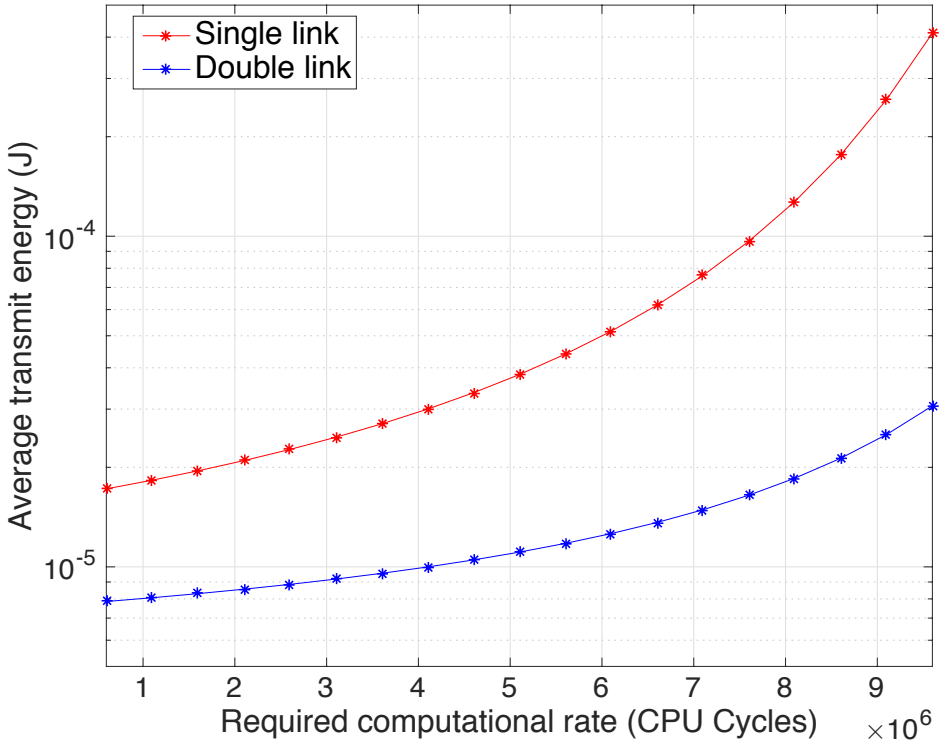
- RAP angular spread $\delta\phi$

- obstacle shadowing angle $\Delta\phi$



S. Barbarossa, E. Ceci, M. Merluzzi, "Overbooking Radio and Computation Resources in mmW-Mobile Edge Computing to Reduce Vulnerability to Channel Intermittency", EUCNC 2017

Numerical results: Average energy vs. computational load (independent blocking events)



S. Barbarossa, E. Ceci, M. Merluzzi, E. Calvanese-Strinati, "Enabling Effective Mobile Edge Computing Using Millimeter Wave Links", ICC 2017

Multi-user / Multilink

Problem formulation

$$\min_{\boldsymbol{R},\boldsymbol{f}} \sum_{k=1}^{K}(1-P_{I_k})\,\frac{1}{a_k}\,\left(2^{R_k}-1\right)$$

min average power

$$\text{s.t. } \frac{c_k}{(1-P_{I_k})\,R_k}+\frac{w_k}{f_k}\leq \Delta_k,\ \forall k$$

latency constraint

$$R_k \geq 0,\ \forall k$$

non-negative rate

$$R_k \leq \log_2(1+a_k P_T),\ \forall k$$

lower rate limit

$$\sum_{k=1}^{K} f_k \leq f_S;$$

overall computing rate

$$0 \leq f_k \leq f_S,\ \forall k$$

individual rate limits

Multi-user / Multilink

Solution:

Optimal computation rate: $f_k = \dfrac{\sqrt{w_k\,\gamma_k}}{\sum_{k=1}^{K}\sqrt{w_k\gamma_k}}\,f_S$

Optimal communication rate: $R_k = \dfrac{c_k}{(1-P_{I_k})\left(\Delta_k - \sqrt{\frac{w_k}{\gamma_k}}\sum_{k=1}^{K}\sqrt{w_k\gamma_k}/f_S\right)}$

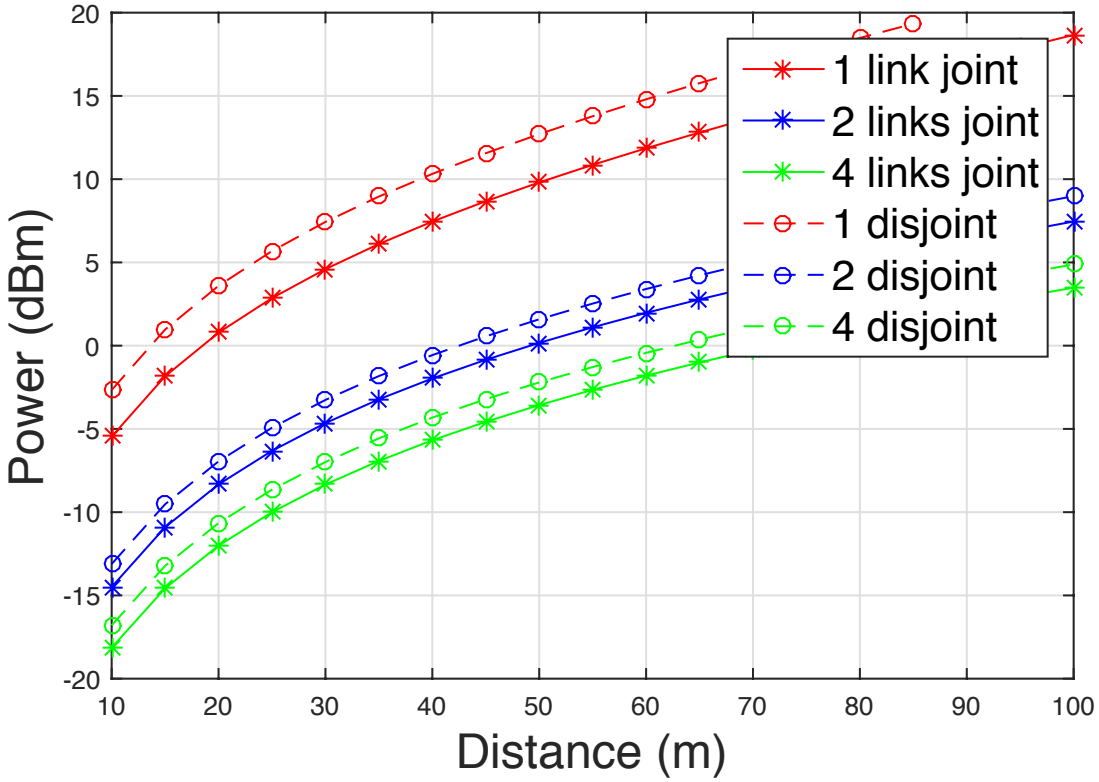
Note: Optimal computation rate does not coincide with proportional allocation

$$f_k = \frac{w_k}{\sum_{k=1}^{K} w_k}\,f_S$$

S. Barbarossa, E. Ceci, M. Merluzzi, "Overbooking Radio and Computation Resources in mmW-Mobile Edge Computing to Reduce Vulnerability to Channel Intermittency", EUCNC 2017

Multi-user / Multilink

Numerical results



S. Barbarossa, E. Ceci, M. Merluzzi, "Overbooking Radio and Computation Resources in mmW-Mobile Edge Computing to Reduce Vulnerability to Channel Intermittency", EUCNC 2017

Conclusions

- Mobile edge-computing enables joint optimization of radio and computing resources, depending on channel state, backhaul state, and application parameters
- Optimal association of mobile users to base stations and clouds provides a mechanism for optimal instantiation of virtual machines and represents a new way to handle handover
- Non-convex offloading problems have been efficiently solved by using a new class of SCA-based algorithms converging to stationary solutions of the original problem
- mmW channel intermittency can be counteracted by resource overbooking based on knowledge (estimation) of blocking probability
- Incorporation of online distributed learning mechanisms in mobile devices (task profilers) as well as in the edge of the network
- Extension to coded caching & coded computing

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