CROSSFIRE Industrial Dissemination Day

6 July 2015
Castelldefels, Spain
WP1

• Peng Guan (CNRS): Stochastic Geometry Analysis of LTE-A Cellular Networks
• Wei Lu (CNRS): Stochastic Geometry Modeling, Analysis and Optimization of Relay-aided Cellular Networks
• Néstor Hernández (STEINWURF): Throughput, Energy and Overhead of Network Coded Cooperation
• Hisham El Shaer (VODAFONE): Shaping 5G: Downlink/Uplink Decoupling (DUDe)
WP2

- Salvatore Costanzo (UOA): Network Virtualization Component Level Algorithms for Mobility Management and RRM in LTE-A Heterogeneous Wireless Networks
- Giorgos Chochlidakis (KCL): Virtual Network Embedding Solutions for Next Generation Networks
- Georgia Tseliou (UOC): RAN Virtualization in LTE-A Environments
WP3

- Christoforos Vlachos (KCL): Integration of Device-to-Device Communications in Wireless Networks
- Panagiotis Trakas (UOC): Traffic Offloading in Future HetNets
- Georgios Kollias (IQUADRAT): Self Organized Solutions in Future Heterogeneous Cellular Networks
WP4

- Eirini Liotou (UOA): Towards Quality of Experience in Mobile Cellular Networks
MITN – CROSSFIRE
(http://gain.di.uoa.gr/crossfire)

Peng Guan
ESR CNRS-1

7th plenary meeting in Barcelona, July 6, 2015
Stochastic Geometry Analysis of LTE-A Cellular Networks
Motivation

- PPP-based abstraction: modeling the locations of the BSs as Points in a Poisson Point Process (PPP)
  - It is mathematically tractable.
  - It is proven to be capable of accurately capturing the main characteristics of cellular networks.
System Model: PPP-based abstraction

How It Works (Downlink – 1-tier)

- Probe mobile terminal
- PPP-distributed macro base station

Useful link
System Model: PPP-based abstraction

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Useful link
Research Work

- Stochastic Geometry Analysis of LTE-A Cellular Networks
  - Error Performance in Downlink MIMO Cellular Networks
    - Cell Association
    - Arbitrary Fading Channels
  - Multi-Antenna Transmitter and Receiver
  - Computable Mathematical Frameworks
Selected Results: Error Performance

- **PPP-Abstraction vs. Grid**

- **Trends**
Research Work

- Stochastic Geometry Analysis of LTE-A Cellular Networks
  - Coverage and Rate in Downlink MIMO Cellular Networks
    - A Gil-Pelaez Inversion Approach
  - Load Modeling
  - LOS/NLOS Channel Modeling
A *Gil-Pelaez Inversion Approach*

- If SINR can be modeled as follow:

\[
\text{SINR} = \frac{P\gamma_0 r_0^{-\alpha}}{\sigma_N^2 + P\mathcal{I}_{agg}(r_0)}; \quad \mathcal{I}_{agg}(r_0) = \sum_{i \in \Psi(\Lambda)} \gamma_i r_i^{-\alpha}
\]

- The Coverage and Rate can be computed as:

\[
P_{\text{cov}}(T) = \frac{1}{2} - 2\lambda \int_{-\infty}^{+\infty} \text{Im} \left\{ M_{\gamma_0} \left( j \frac{x}{T} \right) \mathcal{F}_{NI}(x) \right\} \frac{dx}{x}
\]

\[
\mathcal{R} = -2\lambda \int_{0}^{+\infty} \text{Im} \left\{ j\mathcal{F}_0(jx)\mathcal{F}_{NI}(x) \right\} dx
\]
Selected Results: A Gil-Pelaez Inversion Approach

- By assuming $\gamma_0 \sim \mathcal{G}(m_0, \Omega_0)$ and $\gamma_I \sim \mathcal{G}(m_I, \Omega_I)$, we have approximation:

\[
P_{\text{cov}}(T) \overset{(a)}{=} \frac{1}{2} - \frac{1}{\pi} \int_0^{+\infty} \frac{1}{x} \text{Im} \left\{ \frac{(1 + \tilde{K}_0 x)^{-m_0}}{2 F_1\left(-\frac{2}{\alpha'}, m_I; 1 - \frac{2}{\alpha'}, jK_I x\right)} \right\} \, dx
\]

\[
\mathcal{R}^{[\infty]}(b) \overset{(b)}{=} \frac{1}{\pi \Gamma(m_0)} \int_0^{+\infty} \frac{1}{x} \text{Im} \left\{ \frac{G_{3,3}^2\left(jK_0 x \left| \begin{array}{cccc} 1 & 1 & 1 & 1\end{array} \right. \end{array} \right)}{2 F_1\left(-\frac{2}{\alpha'}, m_I; 1 - \frac{2}{\alpha'}, jK_I x\right)} \right\} \, dx
\]
Application to MIMO Schemes

- The Gil-Pelaez inversion approach works for many MIMO schemes.

- Open Loop MIMO
  - Spatial Multiplexing and Per-Stream ZF Receiver (ZF)
  - Spatial Multiplexing and Per-stream MRC Receiver (MRC)
  - Orthogonal Space-Time Block Coding (OSTBC)
  - …

- Close Loop MIMO
  - Fixed Rate SVD Multiplexing (SVD)
  - MRC-MRT MIMO (MIMO MRC)
  - Selection Diversity and Combining (SD-MRC)
  - …
Load Modeling

- The probability that on a randomly chosen RB, a BS is inactive (thus non-interfering) is:

\[
\hat{P}_{\text{inactive}}^{(RB)} = \sum_{n=0}^{N_{RB}} \left( 1 - \frac{n}{N_{RB}} \right) \Pr \{ N = n \}
\]

\[
\Pr \{ N = n \} = \frac{3.5^{3.5} \Gamma(3.5+n)(\lambda_{MT}/\lambda_{BS})^n}{\Gamma(3.5)n!(\lambda_{MT}/\lambda_{BS} + 3.5)^{n+3.5}}
\]

- A randomly chosen MT is selected to be served with prob.:

\[
\hat{p}_{\text{select}} = 1 - \left( \frac{3.5}{3.5 + \lambda_{MT}/\lambda_{BS}} \right)^{4.5} \frac{\Gamma[4.5 + N_{RB}]}{\Gamma(4.5)} \left( \frac{\lambda_{MT}/\lambda_{BS}}{3.5 + \lambda_{MT}/\lambda_{BS}} \right)^{N_{RB}}
\]

\[
\times \left\{ \frac{\left( \begin{array}{c}
2F1 \left[ 1, 4.5 + N_{RB}, 1 + N_{RB}, \frac{\lambda_{MT}/\lambda_{BS}}{3.5 + \lambda_{MT}/\lambda_{BS}} \right] \\
\Gamma[1 + N_{RB}]
\end{array} \right)}{\begin{array}{c}
N_{RB} \left( \begin{array}{c}
2F1 \left[ 1, 4.5 + N_{RB}, 2 + N_{RB}, \frac{\lambda_{MT}/\lambda_{BS}}{3.5 + \lambda_{MT}/\lambda_{BS}} \right] \\
\Gamma[2 + N_{RB}]
\end{array} \right)
\end{array} \right. \]

- The load modeling is ready for Multi-tier cellular networks.
Selected Results: Load Modeling

- the more RB, the higher MT selection probability and the higher BS inactive probability (less network interference)

- The higher MT/BS density ratio, the lower MT selection probability and the lower BS inactive probability (more network interference)
Considering the association probability, selection probability and coverage probability, we introduce service success probability:

\[ p_{\text{service}}(\tau_j) = \sum_{j=1}^{K} A_j \times \tilde{p}_{\text{select},j} \times \tilde{p}_{\text{cov},j}(\tau_j) \]
Research Work

◆ Stochastic Geometry Analysis of LTE-A Cellular Networks
  ◆ Modeling, Analysis and Optimization in Multi-Antenna Heterogonous Uplink Cellular Networks
    ◆ New Modeling
    ◆ Multi-Antenna BS: MRC and OC
    ◆ Massive MIMO
    ◆ Interference-Aware (IA) Uplink Power Control
Uplink Modeling

- Using Indicator function to account the geometric constraints introduced by the cell association criterion

\[
y_{k,0} = \sqrt{\hat{P}_{k,0} \rho_0^{-1} \hat{R}_{k,0}^{-\alpha_k}} h_{k,0} x_{k,0} + n_{k,0} + \sum_{\text{MT}_i \in \Phi_{k}^{(MT)} \setminus \text{MT}_0} \sqrt{\hat{P}_{k,i} \rho_0^{-1} D_{k,i}^{-\alpha_k}} h_{k,i} x_{k,i} \mathbb{I} (D_{k,i} > \hat{R}_{k,i}) \\
+ \sum_{k \neq \kappa = 1}^{K} \sum_{\text{MT}_i \in \Phi_{k}^{(MT)}} \sqrt{\hat{P}_{k,i} \rho_0^{-1} D_{k,k,i}^{-\alpha_k}} h_{k,k,i} x_{k,k,i} \mathbb{I} (D_{k,k,i} > \left(\frac{T_k}{T_k} \hat{R}_{k,i}^{\alpha_k}\right)^{1/\alpha_k})
\]
**Selected Results: Uplink Coverage and Rate**

- **Coverage Probability**

- **Rate**
Selected Results: Uplink Massive MIMO

- The trends in massive regime are different if a MRC or a OC demodulator is used at BS.
Two uplink fractional power control mechanisms are studied and compared: interference-unaware and interference-aware.

\[
\mathcal{P}_{MT} = \begin{cases} 
  P_0 R_{MT}^{\alpha}\varepsilon & \text{if } P_0 R_{MT}^{\alpha}\varepsilon \leq P_{\text{max}} \\
  P_{\text{max}} & \text{otherwise}
\end{cases}
\]

\[
\mathcal{P}_{MT} = \begin{cases} 
  P_0 R_{MT}^{\alpha}\varepsilon & \text{if } P_0 R_{MT}^{\alpha}\varepsilon \leq P_{\text{max}} \text{ and } P_0 R_{MT}^{\alpha}\varepsilon \Lambda_{MT}^{-\alpha} \leq P_0^{(I)} \\
  P_0^{(I)} \Lambda_{MT}^{\alpha} & \text{if } P_0 R_{MT}^{\alpha}\varepsilon \Lambda_{MT}^{-\alpha} > P_0^{(I)} \text{ and } P_0^{(I)} \Lambda_{MT}^{\alpha} \leq P_{\text{max}} \\
  P_{\text{max}} & \text{if } P_0 R_{MT}^{\alpha}\varepsilon > P_{\text{max}} \text{ and } P_0^{(I)} \Lambda_{MT}^{\alpha} > P_{\text{max}}
\end{cases}
\]
Conclusion

- Stochastic Geometry Analysis of LTE-A Cellular Networks
  - Error Performance in Downlink MIMO Cellular Networks
  - Coverage and Rate in Downlink MIMO Cellular Networks
  - Modeling, Analysis and Optimization in Multi-Antenna Heterogenous Uplink Cellular Networks
Publications

JOURNAL PAPER


CONFERENCE PAPER


POSTER PRESENTATION

Stochastic Geometry Modeling, Analysis and Optimization of Relay-aided Cellular Networks

Wei Lu, Marco Di Renzo

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Laboratoire des Signaux & Systèmes (L2S)
CNRS – CentraleSupélec – Université Paris Sud
3 rue Joliot-Curie, 91192 Gif-sur-Yvette, France
Outline

- Background of stochastic geometry and Point Process
- Experimental validation of stochastic geometry modeling
- Equivalent-in-Distribution based mathematical analysis
- Dual-hop cooperative relaying in a Poisson field of interferers
- Relay-aided cellular networks
- Cellular networks with simultaneous wireless information and power transfer
Outline

➢ Stochastic geometry analysis of broadcasting transmission in cellular networks using network coding
➢ Relay-aided millimeter wave cellar networks
Background of Stochastic Geometry

*The database of the actual BS deployments are from Ofcom.
Background of Stochastic Geometry

*The location of the BS deployments are from Ofcom. The building footprints are from Ordnance Survey*
Background of Stochastic Geometry
Background of Stochastic Geometry

(a) London (Vodafone)

(b) London (O2+Vodafone)

(c) Manchester (O2)

(d) Manchester (O2+Vodafone)
Poisson Point Process (PPP) based abstraction model

How It Works (Downlink – 1-tier)

- Probe mobile terminal
- PPP-distributed macro base station
Poisson Point Process (PPP) based abstraction model

How It Works (Downlink – 1-tier)

Probe mobile terminal

PPP-distributed macro base station

Useful link
Poisson Point Process (PPP) based abstraction model

How It Works (Downlink – 1-tier)

- Probe mobile terminal
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Introduction of EiD-based approach

\[ y = \sqrt{E_S} r_0^{-b} \alpha_0 e^{j\varphi_0} s_0 + n_0 + \sum_{i \in \Phi \setminus BS_0 \cap \text{agg}} \sqrt{E_S} r_i^{-b} \alpha_i e^{j\varphi_i} s_i \]

\forall i \in \Phi \setminus BS_0, \ r_i > r_0. \text{ So } i_{\text{agg}}(r_0) \text{ does not follow a common probability distribution. In particular, } i_{\text{agg}}(r_0) \text{ does not follow either a Gaussian distribution, as in AWGN channels, or a symmetric alpha stable distribution, as in ad hoc networks, for which tractable frameworks to the computation of the ASEP exist.}

Is it possible to find a compound Gaussian representation of \( i_{\text{agg}}(r_0) \) for arbitrary values of \( r_0 > 0 \)? \text{ YES!}
Introduction of EiD-based approach

The methodology of the EiD-based approach is summarized as follows:

- Compute the characteristic function (CF) of the aggregate interference
- Find a compound Gaussian series having the same characteristic function as the interference
- Conditioned on the non-Gaussian-distributed random variables
- Compute the ASEP using well-investigated frameworks developed for AWGN channels
- Remove all the conditions
# Introduction of EiD-based approach

<table>
<thead>
<tr>
<th>Setup</th>
<th>( m_0 )</th>
<th>( \Omega_0 )</th>
<th>( Q(\xi) )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SISO (Nak)</td>
<td>( m )</td>
<td>( \Omega/m )</td>
<td>( \mathbb{E}_{\eta_0} \left[ 2F_2 \left( -\frac{1}{b}, m; 1 - \frac{1}{b}, 1; -</td>
<td>\eta_0</td>
</tr>
<tr>
<td>SIMO</td>
<td>( N_r )</td>
<td>( \Omega )</td>
<td>( \mathbb{E}_{\eta_0} \left[ 1F_1 \left( -\frac{1}{b}; 1 - \frac{1}{b}; -</td>
<td>\eta_0</td>
</tr>
<tr>
<td>Spatial Multi.</td>
<td>( N_r )</td>
<td>( \Omega |\eta_0 - \eta_0|^2 )</td>
<td>( \mathbb{E}_{\eta_0} \left[ 1F_1 \left( -\frac{1}{b}; 1 - \frac{1}{b}; -|\eta_0|^2 \Omega \xi \right) \right] - 1 )</td>
<td>A</td>
</tr>
<tr>
<td>OSTBC</td>
<td>( N_r N_t )</td>
<td>( \bar{\beta} \Omega )</td>
<td>( \mathbb{E}_{\eta_0} \left[ 1F_1 \left( -\frac{1}{b}; 1 - \frac{1}{b}; -|\eta_0|^2 \Omega \xi \right) \right] - 1 )</td>
<td>E/A</td>
</tr>
<tr>
<td>ZF Rec</td>
<td>( N_r - N_t + 1 )</td>
<td>( \Omega )</td>
<td>( \mathbb{E}_{\eta_0} \left[ 1F_1 \left( -\frac{1}{b}; 1 - \frac{1}{b}; -|\eta_0|^2 \Omega \xi \right) \right] - 1 )</td>
<td>E</td>
</tr>
<tr>
<td>ZF Pre</td>
<td>( N_t - N_u + 1 )</td>
<td>( \Omega/N_u )</td>
<td>( 1F_1 \left( -\frac{1}{b}; 1 - \frac{1}{b}; -\Omega \xi \right) - 1 )</td>
<td>A</td>
</tr>
</tbody>
</table>
Dual-hop cooperative relaying
## Dual-hop cooperative relaying

### Diversity Order

<table>
<thead>
<tr>
<th>Receiver Interference</th>
<th>Conv. MRC</th>
<th>Conv. SC</th>
<th>Interference-aware MRC</th>
<th>Interference-aware SC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent</td>
<td>$\frac{1}{b_I}$</td>
<td>$\frac{1}{b_I}$</td>
<td>$\frac{2}{b_I}$</td>
<td>$\frac{2}{b_I}$</td>
</tr>
<tr>
<td>Correlated</td>
<td>$\frac{1}{b_I}$</td>
<td>$\frac{1}{b_I}$</td>
<td>$1 + \frac{1}{b_I}$</td>
<td>$\frac{1}{b_I}$</td>
</tr>
</tbody>
</table>

This diversity order hold when the pathloss is modeled by $\kappa r^{2b_I}$
Dual-hop cooperative relaying

- The diversity order depends only on the pathloss exponent of the interfering links
- The spatial and temporal correlation of interference would considerably reduce the performance of interference oblivious receiver
- The interference-aware receiver is capable of achieving higher diversity order
Relay-aided Cellular Networks
Relay-aided Cellular Networks
Relay-aided Cellular Networks

• The interference caused by the relays nodes should be taken into account in the performance analysis and system design

• The performance trends in noise limited regimes is different from its counterpart in interference limited regimes

• The presence of randomly distributed relay nodes may provide negligible gains in the interference limited regimes

• The proposed system-level interference-aware optimized bias coefficient used for one hop or two hop association makes the relay-aided cellular network always outperforms single hop network
SWIPT in Cellular Networks

Energy Harvester

Information Receiver

Time Switcher

Antenna

Energy Harvester

Information Receiver

Power Splitter

Antenna
SWIPT in Cellular Networks

\[ F_c (Q, R) = \Pr \{ Q \geq Q_0, R \geq R_0 \} \]
Future plans

- Broadcasting in cellular network using Random Linear Network Coding (RLNC)
Future plans

Relay-aided indoor-outdoor transmission in millimeter wave frequency band
Related Publications


Related Publications

Throughput, Energy and Overhead of Network Coded Cooperation

Néstor Hernández
Steinwurf ApS
Network Coding Focus Group
Department of Electronic Systems, Aalborg University
Agenda

- Research Outcomes
- Secondment at CNRS - Supélec
- Conclusions
Current situation: Mobile data becoming the dominant factor in current

Goal: Alleviate mobile networks load with multicasting network coding to reduce transmissions

Strategy: Cooperation with mobile clouds interconnected through short range communications, e.g. D2D
Research - Throughput and Energy Gains

In typical network coded cooperation scenarios:

1. Throughput and energy needs to be calculated. When and How do we get gains from using Cooperation with Network Coding?
2. Distributions of RLNC for low field sizes are desirable to be available due to its simplicity on implementation and benefits for particular applications.
3. Typically, optimal strategies cannot be computed due to computational constraints. So, we are interested in analyzing common policies.
Assumptions

Scenario: Transmit RLNC coded packets from a generation of size $g$ and a field size $q$ to $N$ users with different transmission schemes. General conditions are:

1. Scenarios: Broadcast and Cooperation
2. Independent packet erasure rates
3. For cooperation, packets can be recoded among users with mobile connection, which we call the heads. There can be $H$ heads.
Results - Throughput and Energy Ratios

\[ g = 64, \quad q = 2^8, \quad \epsilon = 0.4, N = 50 \]

Throughput rate ratio \( r_t = \frac{T_{s,loc}}{T_{s,cel}} = \frac{R_{s,cel}}{R_{s,loc}} \)

Energy ratio \( r_e = \frac{E_{b,cel}}{E_{b,loc}} \)
Results - Gain Regions

\[ g = 128, \quad q = 2^8, \quad H = 40, \quad N = 50 \]
Results - Optimal Cloud Size

Erasure Cellular: 0.3. Erasure Local: 0.1. Packets: 16. Field Size: 256.0.
Research - Low Overhead Telescopic

In typical network coded cooperation scenarios:

1. Telescopic Codes for short package representations
2. Distributions of these codes under Broadcast and Cloud Cooperation Scenarios
3. Optimal code designs for Low Overhead
Research - Low Overhead Telescopic

Code designs for Broadcast:

(a) Optimal field scheme, \( q^* \)

(b) Overhead mean (%)
Research - Low Overhead Telescopic Code designs for Cloud Cooperation:

(a) Optimal field scheme, $q^*$

(b) Overhead mean (%)
Research - Secondment at CNRS

Objectives:

1. Evaluate Broadcast RLNC in the presence of interference
2. Derive the analytical framework for Broadcast RLNC under an interference
3. Observe the trends: Do we still have gains with Network Coding?
Research - Secondment at CNRS

Scenario:
Stochastic Geometry for Multicast Content Distribution:
1. Interference Computation
2. Trends against interference free broadcast
Research - Secondment at CNRS

Major Results: Gains still hold and even increase for both noise limited and interference limited systems.
Conclusions

1. New in-depth study of the underlying packet distributions to extract key relevant metrics.
2. Gains are achieved by network coded cooperation against its broadcast if cooperation rates are twice fast as the cellular ones.
3. The numbers of heads, data and energy ratios serves as a controlling parameter between a compromise in both throughput and energy
4. For Telescopic Codes, topology plays a key role on the optimal field choice
5. Total Overhead obtained through optimal fields choice permits to reduce by at least a half the total overhead in NC scenarios.
6. For the interference case, NC gains still hold and are being evaluated
Publications


Questions?
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Thank You
Shaping 5G: Downlink/Uplink Decoupling (DUDe)

Hisham Elshaer
Vodafone Group R&D
July 2015
Is there a need for a completely new architecture?

- 1G-4G cellular designs have historically relied on the role of "cells" as fundamentals units within the RAN.

- Recent trends call for a redefinition of the traditional cell-centric architecture.

A given device (human or machine) should be able to communicate by exchanging different information flows through different sets of heterogeneous nodes.

Uplink and Downlink coverage

- UL optimal coverage ≠ DL optimal coverage in HetNets!

- UL and DL cell association should be decoupled!
Device-centric architectures: Downlink/Uplink Decoupling (DUDe)

- Cell centric → Device centric
- UL and DL from different nodes!
- UL cell association → Pathloss
- DL cell association → DL RSRP
- This creates the shaded region where a UE is associated to the Scell in the UL and to the Mcell in the DL.

Atoll and Simulation setup

- Atoll: Multi-technology radio planning tool.
- It uses a high resolution 3D ray tracing propagation model that takes into account clutter, terrain and building data. (Highly realistic!)

- Simulation deployment: Small cell testbed in London.
- Simulations are based on user distributions based on live traffic measurements.
- We study the improvement in the Uplink by DUDe.
DUDe: Differences in the coverage area

- Femto–Baseline (20dBm): DL RSRP association
- Pico–Baseline (30dBm): DL RSRP association
- DUDe: path loss association

- Green $\rightarrow$ Mcell Uplink coverage
- Red $\rightarrow$ Scell Uplink coverage

- Big differences between DUDe and the other 2 cases!
DUDe: Uplink throughput gain

- 5\textsuperscript{th} percentile:
- DUDe achieves a gain of:
  - 200% over Femto–Baseline.
  - 100% over Pico–Baseline.
- The gain is even more in the 50\textsuperscript{th} percentile.
- The gains result from:
  - higher coverage of Scells $\rightarrow$ better distribution or UEs.
  - UEs have higher SINR $\rightarrow$ Higher MCS and throughput.
DUDe: Outage rate

- High traffic demand scenario.
- Min throughput demand per UE: 1Mbps.
- Outage: UEs that cannot get 1Mbps.

- Outage in Mcell layer for Femto–Baseline and Pico–Baseline is over 90% (congestion!)
- Outage in DUDe is below 10% for Scell and Mcell layers.
- Much more efficient distribution of UEs!
Connecting in the UL to a nearby Scell has 2 effects:

- Max. Tx. Power (No power control)
  This means higher received SNR.

- Fixed Rx SNR (Full PL compensation)
  This means a reduction of the Tx power of the devices as shown in the figure

- Average Tx power reduction by:
  2.3 dB at 50% and 3 dB at 95%.
DUDe analysis using Stochastic geometry

- The locations of Mcells, Scells and devices are modeled according to independent homogeneous Poisson Point Processes ($\phi_M$, $\phi_S$, $\phi_d$) with intensity ($\lambda_M$, $\lambda_S$, $\lambda_d$) respectively.
- UL association: PL based. DL association: DL Received power based.
- We derive the probability of association for 4 cases:
  - Case 1: UL & DL = Mcell $\rightarrow$ $\Pr(Case\ 1) = \frac{\lambda_M}{\lambda_M + \lambda_S}$
  - Case 2: DL=Mcell & UL=Scell $\rightarrow$ $\Pr(Case\ 2) = \frac{\lambda_S}{\lambda_M + \lambda_S} - \frac{\lambda_S}{\lambda_S + \frac{P_M}{P_S}^{2/\alpha} \lambda_M}$
  - Case 3: DL=Scell & UL=Mcell $\rightarrow$ $\Pr(Case\ 3) = 0$
  - Case 4: DL=Mcell & UL=Scell $\rightarrow$ $\Pr(Case\ 4) = \frac{\lambda_S}{\lambda_S + \frac{P_M}{P_S}^{2/\alpha} \lambda_M}$

$PM$: Mcell Tx power
$PM$: Scell Tx power
$\alpha$: PL exponent

DUDe analysis using Poisson Point Process

• We plot the association probability for 3 cases:
  a. Atoll experimental setup
  b. PPP model
  c. Regular grid model

• The plot shows that the association probability depends mainly on the density of deployment and not the process used to generate it.
We introduce the cell load and backhaul capacity in the cell selection criterion.

We use the Shannon formula for UL capacity:

\[ C_{ij}^{\text{Access}} = \text{BW} \log_2(1 + \text{SINR}_{ij}) \]

The cell association criterion is given by:

\[ s(i) = \arg \max_{j \in B} \frac{C_{ij}^{\text{Max}}}{E[N_j] + 1}, \text{ where } C_{ij}^{\text{Max}} = \min\{C_{ij}^{\text{Access}}, C_j^{bk}\} \]

Load aware DUDe

• In this result we use an interference aware power control algorithm:
\[ P_{UE} = \min\{P_{MAX}, 10 \log_{10}(M) + P_0 + \alpha L, I_0 + L_S + 10 \log_{10}(M)\} \]

• This introduces a balance between 5\textsuperscript{th} and 50\textsuperscript{th} percentile UEs.

• 5\textsuperscript{th} percentile → DUDe-Load > DUDe by (15%)
• 50\textsuperscript{th} percentile → DUDe-Load > DUDe by (20%)

• Optimized PC algorithm is crucial for UL performance.

Security Classification: C1 Public
DUDe: Architecture considerations

Reference Architecture as used to today in 3GPP.

NAS-Decoupling with RAN Anchor Point.

NAS-Decoupling with Core Network Anchor Point.

AS-Decoupling with RAN Anchor Point.

Security Classification: C1 Public
Is DUDe possible in LTE?

1. Centralized processing (CRAN)
2. Shared Cell-ID.
3. Dual Connectivity

Security Classification: C1 Public
Exploitation plans

- DUDe was part of a SI on Small cells in Re. 12.
- It was deprioritized!

- We are working on creating consensus among the different vendors and operators about DUDe.

- We co-authored a paper with Ericsson about DUDe.

- Plans of inclusion in future standardization of 4G and 5G.
Conclusions

• Downlink/Uplink Decoupling (DUDe) is a promising candidate for future 4G and 5G!
• It shows gains of 2x and 3x in the 5th and 50th percentiles respectively.
• Theoretical analysis based on stochastic geometry confirms the experimental trends.
• DUDe-Load shows an improvement in performance.

Future work

• Study the mix of DUDe and mmWave frequencies.
• Introduce Quality of Experience (QoE) as an association criterion in DUDe and as a benchmark.
# Papers & Patents

## Papers

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Conference/Journal</th>
<th>Year</th>
<th>Notes</th>
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<tbody>
<tr>
<td>H. Elshaer, N. Scully, L. Anaya</td>
<td>&quot;CARRIER AGGREGATION MODE SELECTION&quot;</td>
<td>GB 1412266.7.</td>
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<tr>
<td>H. Elshaer, N. Scully, L. Anaya</td>
<td>&quot;RESOURCES MANAGEMENT FOR INTER-ENODEB CARRIER AGGREGATION.&quot;</td>
<td>GB 1412264.2</td>
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<td>H. Elshaer, N. Scully, L. Anaya</td>
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<td>GB 1412265.9</td>
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<td>H. Elshaer, E. Bouton, F. Boccardi, I. Thibault</td>
<td>&quot;UL Cell Selection criterion for nodes with different MIMO configuration&quot;.</td>
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<td>GB 1420131.3.</td>
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</tr>
</tbody>
</table>

## Patents

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
<th>Patent Number</th>
</tr>
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<tbody>
<tr>
<td>H. Elshaer, F. Boccardi, M. Dohler and R. Irmer</td>
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<td>Arrangement for choosing transceiver nodes in a Mobile Telecommunications Network</td>
<td>GB 1417366.0.</td>
</tr>
</tbody>
</table>

Security Classification: C1 Public
Thank you!
Early Stage Researcher UOA-1

Salvatore Costanzo
University of Athens

CROSSFIRE Industrial Dissemination Day
6 July 2015, Castelldefels, Spain
Outline

- Contribution in WP2
  - RAN Infrastructure Virtualization
  - SDN-based resource sharing
  - QoE-aware SDN network management

- Future plans
Network virtualization component level algorithms for mobility management and RRM in LTE-A heterogeneous wireless networks

Objectives:

- Proposal of novel network virtualization component level algorithms for mobility management and RRM
- Proposal of analytical/system-level simulation methodologies towards validating the performance of network virtualization component level algorithms for mobility management and RRM
- Proposal of novel technical features or improvements on the LTE-A system to support future network virtualization, advanced mobility management, and enhanced RRM in heterogeneous deployments.
NV for mobility management

- SDN-based architecture for enabling on-the-fly leasing of the physical networking infrastructure from other mobile network operators:
  - Objective: virtually increasing the base station density of a mobile network operator
  - Leasing conditions related to the network status of the involved operators:
    - e.g. when additional base stations are needed for traffic offloading
    - e.g. when link quality improvements can be achieved
NV for mobility management

Move from operator-limited cellular access model
NV for mobility management

Operator A

Operator B

SDN Controller

To physically nearest-base-station model

Operator A

Operator A

Operator B

Operator B
Multi-tenant RAN architecture
Signaling flow
Simulation results

Need of fair Handover triggering algorithm

<- Home Operator

<- Host Operator
NV for RRM
SDN-based resource sharing*

- Objective: RAN and spectrum sharing strategies to improve resource efficiency utilization in heterogeneous deployed environments:
  - enable flexible spectrum sharing among heterogeneous transmission points
  - dynamic increase the network capacity of certain cells and better serve the user traffic requirements in real time

*joint research activity UoA-NEC
FDD/TDD Elastic RAN

- **An SDN-based framework for elastic resource sharing in integrated FDD/TDD LTE-A HetNets:**

  - **Scenario:** multi-tier networks of macrocell and pico base stations wherein different transmission modes are employed, i.e. FDD and TDD

  - **SDN Controller:**
    - provides open access at certain TDD hot spots
    - re-configures the TDD small-cells
Preliminary results

NV for QoE-aware *
network management

*joint research activity UoA-NEC
QoE Aware Flexible Network Management

- **OTT providers**:  
  - specify requirement via A-CPIs

- **SDN controller**:  
  - periodically interacts with 3GPP OAM sub-system  
  - Instructs Pico eNB via D-CPI

- **QoE assessment function working at the pico-eNB**:  
  - monitor QoE related KPIs like MOS  
  - report KPIs to the SDN controller  
  - handle Adaptive TD-reconfiguration function
Signaling flow
QoE Triggering Algorithm

An outage is considered when 
\[ \text{Prob}(MOS \leq MOS_{V_{oIP\text{thresh}}}) > Thr \]

MOS outage triggers SDN virtual cell function:

---

**Algorithm 1: QoE Assessment Function**

```plaintext
1: for \( c \in C \) do
2:   for \( u=1:U \) do
3:     for \( f=1:F \) do
4:       Calculate \( MOS(f) \) according to the E-Model
5:       \( MOS_{dist}(f) = \text{CalcDistFunc}(MOS(f), MOS_{Thr}(f)) \)
6:       if \( MOS_{dist}(f) \leq 0 \) then
7:         Add \( f \) to \( G_{0mos} \)
8:       end if
9:       if \( 0<MOS_{dist}(f) <1.5 \) then
10:      Add \( f \) to \( G_{1mos} \)
11:      Update \( P_{G1} \)
12:     end if
13:     if \( 1.5 < MOS_{dist}(f) < 2.5 \) then
14:      Add \( f \) to \( G_{2mos} \)
15:      Update \( P_{G2} \)
16:     end if
17:     end for
18:     if \( u,c < \gamma_{\text{thresh}} \) then
19:       Add \( u \) to \( U_{lowSINR} \)
20:     end if
21:   end for
22:   if \( P_{G0} = P_{G0_{out}} \) for \( t=\Delta T \) then
23:     if \( P_{G1} = P_{G1_{out}} \) \&\& \( P_{G2} \neq P_{G2_{out}} \) for \( t=\Delta T \) then
24:       Invoke SDNVirtualCellFunc(\( G1, U_{lowSINR} \))
25:     end if
26:     if \( P_{G2} = P_{G2_{out}} \) \&\& \( P_{G1} \neq P_{G1_{out}} \) for \( t=\Delta T \) then
27:       Invoke SDNVirtualCellFunc(\( G2, U_{lowSINR} \))
28:     end if
29:     if \( P_{G1} = P_{G1_{out}} \) \&\& \( P_{G2} = P_{G2_{out}} \) for \( t=\Delta T \) then
30:       Invoke SDNVirtualCellFunc(\( G1, G2, U_{lowSINR} \))
31:     end if
32:   end if
33: end for
```
Simulation Results

- 15% lower Outage Prob. than static conf. 1 scenario
- 10% lower Outage Prob. than the AC scenario

- 15% lower PLR than static conf. 1 scenario
- 10% lower PLR than the AC scenario
Current an Future Plans

- Slicing and RAN network virtualization:
  - solutions for enabling OTT application providers to deploy customized services and more efficient resource management solutions in isolated slices.

- Enhanced Mobility Management and RRM in multi-tenant scenarios:
  - NV-driven Handover solution for multi-tenant base stations
  - Radio Resource Sharing solution in shared RAN
Thanks
for your attention!
Publications


Virtual Network Embedding solutions for Next Generation Networks

Giorgos Chochlidakis and Vasilis Friderikos

King’s College London
Strand WC2R 2LS, London, UK

7th CROSSFIRE plenary meeting
6-9/07/2015, UOC, Barcelona, Spain
Ericsson’s estimates for future mobile networks

Mobile Subscriptions (2014-2020)

All Device Types

Split per Device

Figure 1: Estimates for future mobile subscriptions.
## Why Network Virtualization?

### Motivation
- Limited resources
- Increasing demand
- Flat charging models
- Inflexible architectural model
- Need for virtualization of resources.

### Benefits
- Higher utilization of resources
- Scalable and flexible architectural design
- Higher manageability of the network
- Energy efficient
- Higher margin and more competitive market.
VNE Algorithms

Deeply studied area

Progress on fixed networks can be used for mobile networks

Algorithms for efficient mapping of VNet in terms of reliability, stability, load balancing etc.

However, the mobility has not yet been considered.
The Impact of Mobility

- How can the mobility affect the mapping procedure?
- What is the gain if we take it into account?
- Which is the optimal mapping algorithm then?
- Comparison of results

Figure 3: VNE and mobility.
Algorithm 1: Mobility Agnostic Heuristic Algorithm

INPUTS: Graph $G = (V, E)$, number of tenants $U$, virtual network requests $Q$, classes of flows $K$, set of paths $P$, set of demands $d$, set of capacities $C$

OUTPUTS: Set of mapped substrate paths for every virtual network request

1: for $u = 1$ to $U$ do
2:   sort (descending) demands $d^{uq}$ $\forall q \in Q, k \in K$
3:   for $q = 1$ to $Q$ do
4:     for $k = 1$ to $K$ do
5:       $p = 1$
6:       repeat
7:         if path $\pi_{kp}$ not congested then
8:           map path $\pi_{kp}$ to request $q$
9:           decrease available capacity of path $\pi_{kp}$
10:          flag = 1
11:         end if
12:       $p = p + 1$
13:       until flag = 1 or $p > P$
14:       flag = 0
15:     end for
16:   end for
17: end for

---

We define the following variables:

- $G = (V, E)$: undirected planar tree-like graph
- $\pi_{kp}$: set of substrate paths from source to AP $k$
- $r_{kji}$: set of substrate paths from AP $k \in K^{uq}$ to AP $j \in T$
- $U$: set of different tenant’s set of virtual network requests
- $Q^u$: set of virtual network requests of tenant $u \in U$
- $K^{uq}$: set of classes of flows that have to be served by $q \in Q^u$
- $d_{kq}^u$: set of demands for class of flows $k \in K^{uq}$ of tenant $u \in U$ and virtual network request $q \in Q^u$

$$z^n_{kp} = \begin{cases} 
1, & \text{if node } n \in \pi_{kp} \\
0, & \text{otherwise}
\end{cases}$$

$$l^n_{kji} = \begin{cases} 
1, & \text{if node } n \in r_{kji} \\
0, & \text{otherwise.}
\end{cases}$$
Integer Programming Algorithm

Then, we define the following boolean variables:

\[ x_{kp}^{uq} = \begin{cases} 1, & \text{if } \pi_{kp} \text{ is assigned to } k \in K^{uq} \\ 0, & \text{otherwise} \end{cases} \quad (1) \]

\[ y_{kji}^{uq} = \begin{cases} 1, & \text{if } r_{kji} \text{ is assigned to } k \in K^{uq} \\ 0, & \text{otherwise} \end{cases} \quad (2) \]

The total routing cost \( \phi \) can be written as:

\[ \phi = \sum_{u \in U} \sum_{q \in Q^u} \sum_{k \in K^{uq}} \sum_{p \in P} d_{k}^{uq} \pi_{kp} x_{kp}^{uq} \quad (3) \]

The total mobility cost \( M \) can be written as:

\[ M = \sum_{u \in U} \sum_{q \in Q^u} \sum_{k \in K^{uq}} \sum_{j \in T} \sum_{i \in I} h_{kj} d_{k}^{uq} r_{kji} y_{kji}^{uq} \quad (4) \]
Problem's Constraints

\[ \text{minimize} \quad T = M + \Phi \quad (5) \]

subject to

\[
\begin{align*}
\sum_{u \in U} \sum_{q \in Q^u} \sum_{k \in K^{uq}} \left( \sum_{p \in P} d_k^{uq} x_{kp}^{uq} z_{kp}^{uq} + \right. \\
\sum_{j \in J} \sum_{i \in I} h_{kj} d_k^{uq} y_{kji}^{uq} l_{kji}^{uq} \right) & \leq C_n, \quad \forall n \in V \\
T_{un} & \leq T_{un+1}, \quad \forall u, q, k, p, i \\
\sum_{j \in J} \sum_{i \in I} y_{kji}^{uq} & = \mathbb{1}(h_{kj}), \quad \forall u, q, k \\
\sum_{p \in P} x_{kp}^{uq} & = 1, \quad \forall u, q, k \\
x_{kp}^{uq}, y_{kji}^{uq} & \in \{0, 1\}, \quad \forall u, q, k, p, i
\end{align*}
\]
Total cost comparison

- Comparison to existing VNE algorithms [1].
- No gain at fixed-network scenario.
- As mobility increases, the gain increases linearly.
- Mapping forwarding paths reduces the overall cost.
- Significant impact of mobility effect.

Figure 4: Objective function’s value over percentage of migrating flows.

---

Acceptance rate comparison

- Heuristic’s worst case is 2 times worse than optimal solution.
- In high congestion the proposed algorithm performs better.
- Mobility consideration decongests the VNets.
- Lower congestion means higher acceptance rate.

Figure 5: Acceptance rate over the average node capacity.
Comparison to other solutions (low congestion scenario)

Figure 6: Average slack versus percentage of migrating flows.

Figure 7: Worst routing cost versus percentage of migrating flows.

---

Proposed linear-integer programming algorithm

We define the following variables:

- $G = (V, E)$: undirected planar tree-like graph
- $\pi_{kp}$: set of substrate paths from source to AP $k$
- $r_{kji}$: set of substrate paths from AP $k \in K^{uq}$ to AP $j \in T$
- $U$: set of different tenant’s set of virtual network requests
- $Q^u$: set of virtual network requests of tenant $u \in U$
- $G^u_{qu} = (V', E')$: set of virtual network requests
- $K^{uq}$: set of classes of flows that have to be served by $q \in Q^u$
- $h_{kj} \in H$: the handover matrix
- $d^u_k$: set of demands for class of flows $k \in K^{uq}$ of tenant $u \in U$
- virtual network request $q \in Q^u$
- $z^u_{kp} = \begin{cases} 1, & \text{if node } n \in \pi_{kp} \\ 0, & \text{otherwise} \end{cases}$
- $l^u_{kji} = \begin{cases} 1, & \text{if node } n \in r_{kji} \\ 0, & \text{otherwise}. \end{cases}$

Figure 8: IEEE ICC ’15 presentation - June 9 2015, London UK.
Low Latency VNE

The delay function can be modelled as:

\[ F_l(T_l, C_l) = \frac{1}{C_l - T_l}, \]  

(11)

We approximate the non-linear function as:

\[ f_l(T_l, C_l) = g_l T_l + b_l, \ \forall T_l \in [n\omega, (n + 1)\omega], \]  

(12)

where

\[ \omega = \frac{C_l - \epsilon}{a}, \]  

(13)

is the stepsize for each linear piece,

\[ g_l = \frac{1}{C_l - (n+1)\omega} - \frac{1}{C_l - n\omega}, \]  

(14)

is the gradient of the linear piece for \( T_l \in [n\omega, (n + 1)\omega] \),

\[ b_l = \frac{1}{C_l - n\omega} - g\omega. \]  

(15)
Problem’s formulation

\[
\Gamma(x) = \sum_{r v k j p} a_r x_{v k j p}^r \sum_l z_{k j p l} (\delta_l + f_l(T_l, C_l))
\]  

(16)

Based on the above definitions the mathematical program can be formulated as follows:

\[
\min \Gamma(x)
\]  

(17)

s.t.

\[
\sum_{r v k j p} x_{v k j p}^r z_{k j p l} \leq C_l \quad \forall l \in L
\]  

(18)

\[
\sum_p x_{v k j p}^r = h_{v k j} d_{v k j}^r \quad \forall r \in R, v \in V, k \in K, j \in J
\]  

(19)

\[
x_{v k j p}^r \geq 0 \quad \forall r \in R, v \in V, k \in K, j \in J, p \in P.
\]  

(20)
We calculate the problem’s Lagrange function

\[
\mathcal{L}(x, \lambda, q) = \Gamma(x) + \sum_l \lambda_l (T_l - C_l)
\]

\[
+ \sum_{rvk_j} q_{rvk_j}^r \left( h_{vkj} d_{vkj} - \sum_p x_{vkjp}^r \right) - \sum_{rvkj} h_{vkj} d_{vkj} - \sum l \lambda_l C_l,
\]  

\[
(21)
\]
Lagrangian relaxation

\[ \frac{\partial \mathcal{L}(x, \lambda, q)}{\partial x_{ro}^r_{vo}k_{ko}j_{jo}p_{po}} = a_r \left( \sum_l z_{ko}j_{jo}p_{pol}(\delta_l + \frac{\lambda_l}{a_r}) \right) + gl \sum_{rvkjp} \left( \frac{a_r + a_{ro}}{a_{ro}} \right) z_{kjpl}x_{vkjp}^r + b_l - \frac{q_{ro}^{r_{vo}}k_{ko}j_{jo}}{a_r} \] (22)

and

\[ \frac{\partial^2 \mathcal{L}(x, \lambda, q)}{\partial (x_{ro}^r_{vo}k_{ko}j_{jo}p_{po})^2} = \sum_l 2a_{ro} (z_{ko}j_{jo}p_{pol})^2 gl. \] (23)
Projected subgradient method

\[
x^{(\kappa+1)}_o = \left[ x^{(\kappa)}_o - \beta^\kappa_x \left( \frac{\partial^2 \mathcal{L}}{\partial x^2_o} \right)^{-1} \frac{\partial \mathcal{L}}{\partial x_o} \right]^+, \quad (24)
\]

\[
\lambda^{(\kappa+1)}_l = \left[ \lambda^{(\kappa)}_l - \beta^\kappa_l \frac{\partial \mathcal{L}}{\partial \lambda_l} \right]^+, \quad \text{and} \quad (25)
\]

\[
q^{(\kappa+1)}_o = \left[ q^{(\kappa)}_o - \beta^\kappa_q \frac{\partial \mathcal{L}}{\partial q_o} \right]^+, \quad (26)
\]

\[
x^{\kappa}_{proj} = \left( \mathbf{I} - \mathbf{A}_{eq}^T (\mathbf{A}_{eq} \mathbf{A}_{eq}^T)^{-1} \mathbf{A}_{eq} \right) \mathbf{x}^\kappa + \mathbf{A}_{eq}^T (\mathbf{A}_{eq} \mathbf{A}_{eq}^T)^{-1} \mathbf{b}_{eq}. \quad (27)
\]
Numerical results

Figure 9: Convergence of proposed algorithm for different values of link capacities.

Figure 10: Ratio of two services’ delays versus maximum link utilization.
A Robust Virtual Network Embedding Solution

- Shortest path approach
- Parameters (i.e. VNet requests) are subject to uncertainty
- Adjustable robustness
- Conservatism vs Utilization

Figure 11: Violation probability against different values of $\frac{\Gamma_i}{|J_i|}$
Secondment to Steinwurf Aps, Aalborg, Denmark for the period May 1 - July 31 2015

- Attendance of offered courses on network coding by Aalborg University.
- Training activities and skills improvement.
- Research-friendly environment with highly-skilled staff.
- The main objective is a joint work at the end of the secondment.

Figure 12 : Steinwurf ApS, Niels Jernes Vej 10, Denmark, 9220 Aalborg, Denmark.
Public Talks

Figure 13: Presentation for the open day as part of CROSSFIRE’s dissemination activities.

Figure 14: A talk about CROSSFIRE project to IEEE student congress hosted by Kings College London.
Accepted for Publication


[3] G. Chochlidakis and V. Friderikos, “Robust Virtual Network Embedding for Mobile Networks”, IEEE PIMRC ’15, 30 August - 2 September, Hong Kong, P.R. China

Acknowledgements

This work has received funding from the European Unions Seventh Programme for research, technological development and demonstration under grant agreement No 317126, as a part of the Marie Curie Initial Training Networks (ITN) CROSSFIRE\textsuperscript{1} project.

\textsuperscript{1}http://mitn-crossfire.eu/
Thank you for your time

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RAN Virtualization in LTE-A Environments

Georgia Tseliou
Marie Curie Early Stage Researcher

Plenary Meeting, Barcelona, Spain

6.7.2015
Outline

- Introduction

- Research Work
  - Main accomplishments
  - Plans

- Conclusions

- Activities
Business Trends – Multi-tenancy
Required for Profitability

Developed Asia Pacific mobile carrier 'end of profit'

mounting cash pressure

End of profit

Cumulated Revenue (Traffic)

Urban Sub-urban Rural-like areas

- Low profitability sites
- 50% revenue ≈ 10% sites
- 50% sites take less than 10% revenue
- Top 30% sites ≈ 80% revenue.
Placing virtualization context into the network

- ‘edge’ vs. ‘cloud’
  - Push intelligence out to the edge OR optimize resource utilization by centralizing workloads?

- Focus on how to enhance the traditional macro-cellular system through virtualization

- Centralization of functionalities of BS exploits the reality that BS are not 100% loaded all the time
Why to modify the network?

- MVNOs over-purchase resources in order to guarantee available resources for peak traffic.
- Traffic fluctuations along time.
- Static contracts for allocating resources:
  - on-demand mechanisms requiring no-human intervention
  - re-configure resources within short time scales
- Goal: maximize use of the wireless resources without compromising the quality of the provided services.
RAN Reconfiguration in LTE-A

- Management & provision of services do not match requirements by end-user applications
- Heterogeneous & denser deployments pose technical challenges
- LTE-A does not allow multiple service providers to share underlying physical resources
- Heterogeneous virtual networks cannot coexist in isolation within the same infrastructure
Beyond SoA

Map virtual path requests to substrate physical topology using Radio Resource Management

RENEV fills the gap in existing SoA by extending virtualization to geographical dimension

Resources nEgotiation for Network Virtualization (RENEV) Algorithm (Proposal within CROSSFIRE)
## Key Virtualization features by RENEV

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstraction</td>
<td>resources into a pool, delivered on demand</td>
</tr>
<tr>
<td>Isolation</td>
<td>reserved portion of resources</td>
</tr>
<tr>
<td>Customization</td>
<td>operators conquer different part of the shared resources according to the actual requirements</td>
</tr>
<tr>
<td>Resource Utilization</td>
<td>efficient use of physical radio resources with rational signalling burden</td>
</tr>
</tbody>
</table>
Resources Negotiation for Network Virtualization (RENEV)

- Address traffic dynamics considering the service requirements & mobile operator resources.
Multitenant capacity Slicing (MuSli*)

- Each tenant queries & requests spare capacity to the Shared RAN based on policies & without human intervention.
- Objective: To achieve a good trade-off between Number of served requests vs. service quality violation.
- Question: How to improve RB allocation among MVNOs with predicted future information?

Dynamic capacity negotiation: the Shared RAN can provide means to allocate available spare capacity to the Tenants.

* Work performed during my secondment at NEC Labs Europe Ltd.
Multitenant capacity Slicing (MuSli)

- Future information improves the served requests - SLA violation trade-off

Multi-tenant Slicing into different traffic slices considering the forecasted traffic
Multitenant capacity Slicing (MuSli)
Research Plans

- Small cell decomposition: virtualization functional splits
- ETSI NFV Use case #6: Virtualization of the Mobile Base Station
- Study of alternative splits is related to associated requirements on the transport network for supporting the fronthaul link between the virtual network function & physical components

* Various possible LTE base station decompositions*

* Small Cell Forum, Virtualization for SCs: Overview, Issue date: 09.06.2015
Conclusions

- **RENEV**
  - coordination between BSs (baseband part) results in higher resource utilization

- **MuSli**
  - Prediction of resources enhances the capacity negotiation from a shared RAN to multiple tenant operators

- **NFV**
  - As an increasing set of functions are implemented as a virtual network function, the transport requirements in terms of bandwidth and latency become more onerous
Industrial Benefits & Exploitation

- Multiple virtual entities under the same infrastructure
  - sharing capacity

- Dynamic capacity distribution (SW-based, on demand)
  - Instead of purchasing new network nodes

- Easier management and investment of NFV

- Moldable infrastructure
  - deploy functions on demand
  - more automated -> simpler, more economic
Activities (February 2015 – present)

- Publications:
  - Public Talk scheduled for the end of July (TBD)
Questions?
Remarks?
Thank you

Georgia Tseliou
Marie Curie Early Stage Researcher
Open University of Catalonia (UOC)
gtseliou@uoc.edu
Research Overview-Industrial Day
July 2015-Barcelona

Rudraksh Shrivastava
Supervisor: Dr. Konstantinos Samdanis
Network Research Division
NEC Laboratories Europe
Outline

- Introduction
- Work update
- Virtual Cell Concept for TD-LTE
- SDN-based Virtual Cell Framework for Enhancing the QoE in TD-LTE Pico Cells
- Result Analysis'
- Conclusion
TD-LTE Deployment Status

LTE TDD investments worldwide
Commercial network deployments, trials, studies

40 commercial LTE TDD systems in 27 countries

49 more LTE TDD commercial networks in deployment or planned

© Global mobile Suppliers Association (GSA)

Data source:
GSA’s Evolution to LTE report
September 17, 2014

Countries with commercially launched LTE TDD networks
Countries with LTE TDD studies, trials, deployments
Virtual Cell Concept For TD-LTE

- An idea for efficient resource management
- Enables UE to share sub-frames from configurations used by neighboring eNBs
- Enables real time adaptation to the varying traffic conditions
- Exploits spatial as well as time domain for load balancing
- Improved resource flexibility when neighboring cells use a different UL/DL configuration
- Utilization of UL/DL resources occurs at different times

Virtual cell example with a UE utilizing resources from both eNBs
Impose a challenge for admission control and load balancing

Applications with specific UL/DL needs may suffer congestion

Resources may exist, but on another slot, in opposite transmission direction

Cell seems congested due to inefficient resource utilization
TD-LTE Frame Arrangement Scenarios

**Static config. 1** - All eNBs employ the same UL/DL configuration with a subframe ratio of 60% DL and 40% UL

**Cell Specific Adaptive Reconfiguration** - The UL/DL subframe ratio is dynamically selected from the set of seven potential TD-LTE frame configurations

- The selection of a suitable UL/DL configuration for individual cells is based on estimations of the uplink and downlink traffic demands

**Virtual Cell Configuration** -

- Perform locally a cell specific adaptive reconfiguration
- Utilizes resources from more than one eNB
- Virtual cells are created by the SDN controller, which may optionally enforce an UL/DL reconfiguration to a specific cell to secure adequate resources for the virtual cell region
Result Analysis’ (1)

- 25% improvement in the low SINR users’ throughput in DL and around 20% in the UL compared to the Cell Specific Adaptive Reconfiguration

- 35% and 30% compared to Static Cong. 1, in the DL and UL respectively

- Resolves the pseudo congestion problem

10% improvement in mean users’ throughput in the DL and around 6% in the UL compared to the Cell Specific Adaptive Reconfiguration

~16% and 12% improvement compared to the Static Config. 1 in DL and UL respectively
25% improvement in the low SINR users’ delay in DL and around 20% in the UL compared to the Cell Specific Adaptive Reconfiguration

35% and 30% compared to Static Cong. 1, in the DL and UL respectively

Provides Enhanced flexibility

10% improvement in mean users’ delay in the DL and around 6% in the UL compared to the Cell Specific Adaptive Reconfiguration

~16% and 12% improvement compared to the Static Config. 1 in DL and UL respectively

- LTE-A HetNet with FDD macro and TD pico cells
- Dynamic UL/DL re-configuration in TD pico cells to meet the real time traffic demands
- A multi-tenant scenario with common infrastructure provider and multiple FDD/TDD operators
- Infrastructure leased to the FDD/TDD operators based on SLAs
- Frequency band allocation to FDD/TDD systems depends on
  - Geographic location
  - SLAs between infrastructure provider and the FDD/TDD operators
- Two operators scenario
  - Operator A- FDD with Network virtualization (NV) aware eNB
  - Operator Z- TDD eNB with NV aware eNB
SDN based Network Architecture & Management (1)

Different Control Applications for FDD and TDD modes

Multitenant manager (MTM)
- Manage multitenant policies
- HO decisions towards pico eNB
- Instructions to MTA with real time info. to enable efficient resource sharing

Resource Transfer Agent (RTA)
- Implements resource transfer procedures
- Collect resource request information from tenant operators
- Periodically update RRM module about the network state

Multi tenant agent (MTA)
- Performs dynamic slice re-configuration
- Enable delivery of packets from users to the appropriate VeNB
Scheduler Agent

- Cooperation between RTA & MTA
- Provides MAC layer abstraction to the tenant operator

VeNB

- Pool of software apps. emulating upper layers of protocol stack
- Managed by a different tenant operator
- Logically connected to the core network of the tenant operator
Evaluated Scenarios

**FDD macro eNB**
- FDD baseline scheme-macro eNB system with no SDN-based framework
- FDD with SDN scheme- FDD macro eNB system with the proposed SDN-based framework
- Similar performance of both schemes above the target delay threshold of 0.1 s

**TDD pico eNB**
- No sharing of resources with the FDD system and no re-configuration of the TDD frames
- SDN-based elastic resource sharing with the FDD system and no re-configuration of the TDD frames
- SDN-based elastic resource sharing with the FDD system and re-configuration of the TDD frames
Results Analysis’

~ 21% delay improvement in FDD macro cells compared to the baseline scenario where no SDN based sharing is applied.

Higher delay experienced in TD-pico cells compared to no sharing fixed TD case due to resource sharing with FDD macro cells.

Improved TD system performance when resource sharing is enabled with dynamic frame reconfiguration in TD-pico cells.
Virtual Cell Framework for QoE Aware Flexible Network Management

QoE assessment function
- Resides at the pico eNB
- Works in cooperation with Adaptive TD-reconfiguration function

OTT-app providers specify their requirement via A-CPIs

SDN controller acquires global network view by on-demand or periodically interacting with 3GPP OAM sub-system

D-CPI
- Communicates instructions from SDN controller to the Pico eNB
- Monitor QoE related KPIs like MOS of different apps, and directly feeds it to the SDN controller
Evaluated Schemes

Simulation parameters as per 3GPP specification [TR 36.814] were used

A cluster of seven outdoor TD-LTE pico cell hotspots

Evaluated three schemes namely:

- **Static Configuration (SC)**- All eNBs have same and static config. 1 as per the 3GPP configuration modes

- **Cell Specific Adaptive Reconfiguration (AC)**-Dynamic TDD frame re-configuration to best match the UL/DL traffic need given the 7 UL/DL configurations

- **Virtual Cell Configuration (proposed framework)**-
  - Similar UL/DL frame adaptation mechanism as the AC but
  - Additionally serves users by employing virtual frame configuration to match the real time UL/DL traffic needs
Increase in traffic leads to higher PLR and delay while causing throughput degradation.

28% reduction in delay compared to the SC scenario.

20% in comparison with the AC scenario.

15% Lower Packet Loss Rate compared to the SC scenario.

10% Lower Packet Loss Rate than the AC scenario.
Results Analysis’ MOS Outage Probability

- Probability of having VoIP flows with MOS lower than 3.5
- 15% Lower Outage Probability compared to the SC scenario
- 10% Lower Outage Probability than the AC scenario
Conclusion

Presented an overview of the research work done

Virtual cell concept that enables users to dynamically and adaptively use subframes from neighboring eNBs was introduced

Discussed a Novel SDN-based framework for elastic resource sharing in LTE-A TDD/FDD HetNets with multiple network operators

QoE-centric SDN-based framework that enables QoE-aware network management for OTT mobile services

Provide network operators to

- Flexibly and efficiently manage the network in real time
- Enhance resource usage efficiency

The concept of QoE-centric SDN-based framework that increases user satisfaction in TD-LTE networks with picocells
Thank You!

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Empowered by Innovation

NEC
On the Integration of Device-to-Device Communications in Wireless Networks

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CROSSFIRE’s Industrial Dissemination Day,
Barcelona, Spain

6th July 2015
Outline

1. Overview on Device-to-Device (D2D) communications
2. Robust Randomized Resource Allocation for D2D Communications
3. Resource-aware Load Balancing (LB) Optimization in D2D-based Cellular Networks
4. Optimal Virtualized Resource Slicing for D2D Communications
Main D2D characteristics

In this emerging communication paradigm, two close-ranged UEs are eligible to connect directly and communicate with each other by utilizing either the cellular spectrum (i.e. inband) or the unlicensed spectrum (i.e. outband), unlike the traditional communication via the BS.

- Close proximity.
- Frequency reuse gain.
- Traffic offloading.
- Power saving.
- Higher data rates.

Figure 1: Cellular (A) vs D2D (B) data path.
Overview on Device-to-Device (D2D) communications

D2D Classification

D2D communications

- Inband D2D
  - Underlay
  - Overlay
- Outband D2D
  - Controlled
  - Autonomous

Figure 2: D2D communications taxonomy.
Robust Randomized Resource Allocation for D2D Communications

System model (1/2)

Assumptions

1. Underlay DL scenario.
2. D2D & CUs uniformly distributed.
3. Fractional Frequency Reuse (FFR)\(^1,2\)
   - FRF = 1 for inner users
   - FRF = 3 for outer users
4. Fixed D2D transmission power.

---


Figure 3: System model of D2D as an underlay to cellular network.
Figure 4: CU and D2D UEs available resource pools.
Robust Randomized Resource Allocation for D2D Communications

Randomized algorithm proposal

Allocate $C$ orthogonal resources to CUs

Random resource allocation for each D2D pair / cell (location dependent)

Update available resources’ pool for each cell

Estimate Aggregate Throughput ($AT_k$)

Iterative Algorithmic Block ($K$ iterations)

Choose RA corresponding to maximum $AT$

Figure 5: Algorithmic block representation.
Robust Randomized Resource Allocation for D2D Communications

Results (1/2)

Figure 6: Mean Aggregate System Throughput comparison with fixed number of D2D pairs.

* 1: random allocation, 2: strict-FFR based allocation, 3: differentiated FFR allocation, 4: proposed scheme

Results acquired after 1000 algorithmic iterations:

1. 9.8% performance gain compared to the baseline study.
2. 12.5% improvement of baseline study’s worst case.
3. D2D rate performance significantly increased.
Robust Randomized Resource Allocation for D2D Communications

Results (2/2)

Figure 7: Aggregate System Throughput behaviour for different number of D2D pairs.

1. Proportional increase with the number of D2Ds.
2. Main difference/gain observed for high density scenarios.
3. 14.5% highest achieved improvement compared to the baseline work.
Robust Randomized Resource Allocation for D2D Communications

Concluding remarks

- Low-complexity iterative randomized algorithm.
- After a round of $K = 100$ iterations, almost 99% of best performance solution ($M$) is achieved.
- Robust to uncertainty scenarios.
- System throughput improvement.
- Add-on feature in FFR-based wireless systems.
Seven-hexagonal cell scenario.
D2D uniformly distributed.
Single BS-D2D link association.
Fixed D2D link range.
Same RA rationale as before.

Figure 8: Different BS-control scenarios considering crossing D2D links.
Path-loss:

\[ PL_{b,n_i} = 36.7 \log_{10} r_{b,n_i} + 40.9 + 26 \log_{10}(f_c/5), \]

where \( n_i \): node \( i \) of a D2D link.

Cost of D2D link \( l \) connected to BS \( b \):

\[ c_{lb} = \frac{PL_{b,n_1} + PL_{b,n_2}}{2}. \]

BS-D2D link association indicator:

\[ y_{lb} = \begin{cases} 
1, & \text{if link } l \text{ connected to BS } b \\
0, & \text{otherwise.} 
\end{cases} \]
Problem Formulation:

\[
\text{min } \sum_{l \in L} \sum_{b \in B} c_{lb} y_{lb} \\
\text{s.t. } \sum_{b \in B_l} y_{lb} = 1, \ \forall l \in L \\
\sum_{l \in L} y_{lb} \leq K_b, \ \forall b \in B \\
y_{lb} \in \{0, 1\}, \ \forall l \in L, \forall b \in B.
\]

Figure 9: Normalized cost comparison for cost minimization IP solver and CbH algorithm.
Resource-aware LB Optimization in D2D-based Cellular Networks
Optimization framework – Joint connectivity cost & RB reuse

Definition:

\( \rho_{br} \): index that captures how many times a resource \( r \) is assigned by the base station \( b \).

Problem Formulation:

\[
\min \left\{ \sum_{l \in L} \sum_{b \in B} c_{lb} y_{lb} + \sum_{b \in B} \sum_{r \in R} \rho_{br} \tau_{br} \right\}
\]

s.t.
\[
\sum_{b \in B_l} y_{lb} = 1, \quad \forall l \in L
\]
\[
\sum_{l \in L} y_{lb} \leq K_{b}, \quad \forall b \in B
\]
\[
\sum_{r \in R} \tau_{br} \leq K_{b}, \quad \forall b \in B
\]
\[
\sum_{r \in R} \tau_{br} \geq \sum_{l \in L} y_{lb}, \quad \forall b \in B
\]
\[
y_{lb}, \tau_{br} \in \{0, 1\}, \quad \forall l \in L, \forall b \in B, \forall r \in R.
\]

Figure 10: Normalized utilization balancing comparison for optimal allocation of RBs.
Resource-aware LB Optimization in D2D-based Cellular Networks
Optimization framework – Joint interference-aware and LB optimization

Definition:
$\vartheta_{lb}$: penalty factor that represents the number of interferers for D2D link $l$.

Problem Formulation:

$$\min \left\{ \sum_{b \in B} \left( \sum_{l \in L} y_{lb} \right)^2 ; \sum_{l \in L} \sum_{b \in B} \vartheta_{lb} y_{lb} \right\}$$

s.t. $\sum_{b \in B_l} y_{lb} = 1, \forall l \in L$

$\sum_{l \in L} y_{lb} \leq K_b, \forall b \in B$

$y_{lb} \in \{0, 1\}, \forall l \in L, \forall b \in B$.

Figure 11: Weighted sum method simulation with variant weight values for $f_1$ and $f_2$ objectives.
Concluding remarks

- Single BS-D2D link association.
- Set of linear integer programming settings.
- Cell association with respect to cost, RB reuse and network load is provided.
- Efficient balance of the emerging D2D links.
Radio resource management undergoes significant changes.

Network Virtualization (NV) has emerged as a principal concept to overcome the complexity of current network operation.

Virtual resource allocation approaches are expected to become popular for future mobile network architectures.

... but, what about D2D?
We consider:

- Random distribution of D2D and cellular users in hexagonal cell.
- BS is assumed to be shared by $N$ InPs.
- UL scenario and respective interference is taken into account.
- Resource pool is sliced for the different InPs (slices).
- In our case, we assume one InP ($N = 1$) and two slices.

Figure 12: An example that shows an NVS-compatible sub-optimal resource assignment case. Dashed lines represent the existed interference.
Path-loss:

\[ PL_{D2D} = 148 + 40 \log_{10} d \]  
\[ PL_{CU} = 128.1 + 37.6 \log_{10} d \]

where \( d \): distances in meters.

Binary decision variable:

\[ y_{ink} = \begin{cases} 
1, & \text{if D2D link } i \text{ of InP } n \text{ utilizes RB } k \\
0, & \text{otherwise}.
\end{cases} \]

RB \( k = k_d \) is allocable to a D2D link \( i \) of InP \( n \) if:

\[ \gamma_{inkd} = \frac{g_{inkd} P_d}{\sum_{k \in \mathcal{R}} y_{ink} g_{nk}^{ci} P_c + W + I} \geq \gamma_t \]

Similarly, the SINR threshold (\( \gamma_t \)) needs to be satisfied also for the cellular transmissions:

\[ \frac{g_{nk}^{cb} P_c}{\sum_{i \in \mathcal{I}} \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{R}} y_{ink} g_{nk}^{ib} P_d + W + I} \geq \gamma_t \]

Achievable D2D rate:

\[ r_{ink} = B_{RB} \log_2 (1 + \gamma_{ink}) \]
Optimal Virtualized Resource Slicing for D2D Communications
Optimization framework – D2D resource allocation

Single RB sharing:

\[
\begin{align*}
\max & \quad \sum_{i \in I} \sum_{n \in N} \sum_{k \in R} r_{ink} y_{ink} \\
\text{s.t.} \quad & \sum_{i \in I} \sum_{n \in N} \sum_{k \in R} y_{ink} g_{ink}^h P_d \gamma_t \leq -\left( \tilde{\gamma}_t (W + I) - g_{n k c}^b P_c \right), \\
& \forall c \in C, \quad k_c \in R \\
& \sum_{i \in I} \sum_{n \in N} y_{ink} = 1, \quad \forall i \in I \\
& \sum_{i \in I} \sum_{k \in R} y_{ink} \leq U_n, \quad \forall n \in N \\
& y_{ink} \in \{0, 1\}, \quad \forall i \in I, \quad \forall n \in N, \quad \forall k \in R
\end{align*}
\]  

\[ (7) \]

Multiple RB sharing:

\[
\begin{align*}
\max & \quad \sum_{i \in I} \sum_{n \in N} \sum_{k \in R} r_{ink} y_{ink} \\
\text{s.t.} \quad & \sum_{i \in I} \sum_{n \in N} \sum_{k \in R} y_{ink} g_{ink}^h P_d \gamma_t \leq -\left( \tilde{\gamma}_t (W + I) - g_{n k c}^b P_c \right), \\
& \forall c \in C, \quad k_c \in R \\
& \sum_{i \in I} \sum_{n \in N} y_{ink} \geq 1, \quad \forall i \in I \\
& \sum_{n \in N} \sum_{k \in R} y_{ink} \leq \Gamma, \quad \forall i \in I \\
& \sum_{i \in I} \sum_{k \in R} y_{ink} \leq U_n, \quad \forall n \in N \\
& y_{in(k-1)} - y_{ink} + y_{ink} \leq 1, \quad \forall m \in \{k + 1, \ldots, |R|\} \\
& y_{ink} + y_{in(k+m)} \leq 1, \quad \forall m \in \{\Gamma, \ldots, |R|\} \\
& \sum_{m \in M} y_{inm} \geq l \cdot s_{ink}^l, \quad M = \{k, \ldots, k + l - 1\} \\
& \sum_{n \in N} \sum_{k \in R} s_{ink}^l = 1, \quad \forall i \in I \\
& y_{ink} \in \{0, 1\}, \quad \forall i \in I, \quad \forall n \in N, \quad \forall k \in R \\
& s_{ink}^l \in \{0, 1\}, \quad \forall i \in I, \quad \forall n \in N, \quad \forall k \in R, \quad \forall l \in L
\end{align*}
\]  

\[ (8) \]
Optimal Virtualized Resource Slicing for D2D Communications

Results (1/2)

- Maximum assignable number of RBs is four ($\Gamma = 4$).
- ORS outperforms HRS in a mean percentage of less than 15%.
- >27% D2D sum-rate improvement compared to investigated NVS heuristic solutions.

Figure 13: Sum-rate estimation for varying number of D2D links. Maximum bound of $\Gamma = 4$ is set for this realization.
Figure 14: Average received signal-to-interference-plus-noise ratio for cellular uplink in relation to high congestion levels.

- \( \frac{\text{# D2D users}}{\text{# Cellular users}} > 50\% \).
- ORS and HRS achieve less interference to/from the BS.
- >23% better performance compared to randomized NVS-C technique.
1/5/2015 - present: Secondment to Steinwurf, Aalborg, DK.

Work basis: Investigation of D2D communications as a helper to offload traffic for the cellular BS.

Main objective: Integration of Network Coding (NC) notion to apply for efficient, broadcast-based content delivery without the need to erase existing data from already cached users.

Main idea: Based on NC, we focus on linearly combining the downloaded fragments (packets) of data of each user’s device with its corresponding user pool in vicinity in order to avoid deleting already stored files.
Accepted:


[3]. C. Vlachos and Vasilis Friderikos, ”Optimal Virtualized Resource Slicing for Device-to-Device Communications”, in 2015 IEEE Global Communications Conference (GLOBECOM), San Diego, CA, USA, December 2015.

Poster:

[1]. C. Vlachos and Vasilis Friderikos, ”Integrating Device-to-Device (D2D) Communications in 5G Networks”, in OFCOM’s ”5G and Future Technology” event, London, UK, March 2015.

Submitted:

Any questions?

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Traffic Offloading in future HetNets

Crossfire
7th Plenary Meeting

UOC – 2
Panagiotis Trakas
ptrakas@uoc.edu
Outline

• Activities
• Publications – Submissions
• Current work
• Planning – Future Work
• Conclusions
Activities

• Participation at the IEEE ICC 2015 conference in London (08-12/06/2015)

• Scheduled public talk in the end of July at the premises of the Open University of Catalonia (UOC)
Publications

Panagiotis Trakas, Ferran Adelantado, Christos Verikoukis, “A novel learning mechanism for traffic offloading with Small Cell as a Service,” IEEE International Conference on Communications (ICC 2015). (presented)
Submissions


Fig. 2: Traffic served by the SC cluster vs total offered load for $MSP_1$

Fig. 3: $MSP_1$ throughput vs total offered load

Fig. 4: $MSP_1$ profit vs total offered load
Current Work – Scenario

- A future 5G scenario, which is described by:
  - Heterogeneous networks that operate in microwave and mmWave bands.
  - Heterogeneous traffic: Demand for differentiated services at random locations.
  - QoE and QoS requirements with high throughput and low delay that cannot be guaranteed by 4G/LTE-A
  - Traffic offloading from MSPs to SCOs
Scenario Description – Stakeholders

**MSP**
- Sub-6GHz eNB
- **mmWave** HeNBs
- Ideal backhaul connection for eNB and some of the HeNBs
- mmW multihop backhaul for the rest of the HeNBs

**SCO**
- **mmWave** small cells that are either directly connected to NTPs or one hop away from them.
- Licensed spectrum
- Subscribers
- Offloads MSP’s traffic

7th Plenary Meeting, Barcelona, Spain
Scenario Description – Users

- Set of services with different QoS requirements
- User’s Utility=QoE=MOS, which should be described by a convex function according to the IQX hypothesis \([1]\).

**Pricing**: Use of static pricing. That is, a particular price (euro/MB), for a particular service and class of this service (e.g. 720p or 1080p video streaming are priced differently)

Problem Statement

• The **objective** in this scenario is the maximization of the stakeholders’ profits (MSP and SCO), while guaranteeing the users’ QoE.

• Hence, the **problem** is **where** should the users be connected (MSP’s BSs or offloaded to the SCO’s ones) in order to achieve the **objective**.
Planning – Future Work

• Completion of current work and submission to ICC 2016, and IEEE transaction by Dec 2015
• Secondment in NEC for the period Sep-Dec 2015
  – Collaboration for new subject
  – Paper submission to Globecom 2016, and IEEE transaction by Jun 2016
• Writing of thesis
Conclusions

• The direction of my research has been towards future mobile communication scenarios/trends in the field of traffic offloading.

• Regarding the use of the research findings in industrial environments, they could be used for:
  – Network planning in case of small cell densification investments,
  – Traffic offloading strategies, both for typical MSPs as well as newcomers/third parties (SCOs).
Thank you!

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Marie Curie Early Stage Researcher
Open University of Catalonia (UOC)

ptrakas@uoc.edu
“Self Organized Solutions in Future Heterogeneous Cellular Networks”

Georgios Kollias
Iquadrat
Outline

• Introduction
• Main accomplishments
• Conclusions
• Current Work
• Activities
Introduction

- Exponential increase in demands
  
  ![Graph showing exponential increase in mobile data traffic from 2014 to 2019.](chart)

  **Source:** CISCO - Global Mobile Data Traffic Forecast Update, 2014–2019

- HetNets
Motivation - Challenges

• Challenging Mobility Management in HetNets.
• Fixed values for Time-to-Trigger and Hysteresis Margin degrade Handover (expressed in Radio Link Failure, Handover Failure and Ping-Pong rates).

• Study how Handover performance is affected by the location of small cells and Handover parameters (TTT, speed).
Handover Performance in LTE-A HetNets Through Inter-Site Distance Differentiation

CAMAD 2014

Scenario - System Model

\[
R_{SS_t} \geq R_{SS_s} + H
\]

\[
P_{T_t} - A_{0_t} - \alpha_t 10 \log_{10} d_t \geq P_{T_s} - A_{0_s} - \alpha_s 10 \log_{10} d_s + H
\]

\[
R_1 \approx \left( \frac{D}{10^{\frac{-2(\gamma - 0.1H)}{\alpha_s}} - 1} \right) \cdot \left( \cos(\Theta_i) \pm \sqrt{\cos(\Theta_i)^2 + 10^{\frac{-2(\gamma - 0.1H)}{\alpha_s}} - 1} \right)
\]

\[
R_2 \approx \left( \frac{D}{10^{\frac{-2(\gamma + \frac{Q_{out} - N}{10})}{\alpha_s}} - 1} \right) \cdot \left( \cos(\Theta_i) \pm \sqrt{\cos(\Theta_i)^2 + 10^{\frac{-2(\gamma + \frac{Q_{out} - N}{10})}{\alpha_s}} - 1} \right)
\]
Handover Performance in LTE-A HetNets Through Inter-Site Distance Differentiation
CAMAD 2014

Results

- $P_{\text{HO}}$ rises with Inter-Site Distance, because of the increase in the actual coverage area of the small cell.

- $P_{\text{RLF}}$ rises when the coverage area of the small cell is big enough. In our case, when $D>160\text{m}$. Note that SINR depends on both RSS from source cell and received Interference.
The Impact of Inter-Site Distance and Time-to-Trigger on Handover Performance in LTE-A HetNets
ICC 2015

Motivation - Challenges

• Challenging Mobility Management in HetNets.
• Values for Time-to-Trigger and Hysteresis Margin shouldn’t be selected on a cell type or a cell-pair basis.
• Maintain at most 2% Radio Link Failures per executed Handover.

• Derive closed-form expressions for the different HO performance metrics as a function of inter-site distance and speed of UEs.
The Impact of Inter-Site Distance and Time-to-Trigger on Handover Performance in LTE-A HetNets
ICC 2015

Scenario - System Model

$R_\theta$ defines the small cell radius

$$R_\theta = 10 \frac{\gamma - 0.1H}{a_t} (D^2 + 2R_\theta D\cos(\theta_{inner}) + R_\theta)^{\frac{a_s}{2a_t}}$$

$r_\theta$ defines the HOF circle

$$r_\theta = 10 \frac{\gamma + 0.1Q_{out}}{a_t} (D^2 + 2r_\theta D\cos(\theta_{inner}) + r_\theta)^{\frac{a_s}{2a_t}}$$

$S_\theta$ defines the radius of the outbound HO

$$S_\theta = 10 \frac{-\gamma + 0.1H'}{a_s} (D^2 + 2S_\theta D\cos(\theta_{inner}) + S_\theta)^{\frac{a_s}{2a_t}}$$
The Impact of Inter-Site Distance and Time-to-Trigger on Handover Performance in LTE-A HetNets
ICC 2015

Results

- \( P_{\text{HO}} \) increases with maximum allowed entry angle and falls with maximum HOF angle.

- For a given \( v \) and \( T \), with maximum allowed entry angle rises when \( D \) grows (resulting in \( R \) increase).

- Tightly coupled with \( R \) (coverage area) and \( r \) (HOF area).

- \( P_{\text{HOF}} \neq 0 \) if
  \[
  \frac{R-r}{T} \leq v \leq \frac{R+r}{T}
  \]
  or
  \[
  \frac{vT}{1+\beta} \leq R \leq \frac{vT}{1-\beta}, \quad \beta = \frac{r}{R}
  \]
Motivation - Challenges

• Booming demands of cellular users.
• Densification of networks.
• Usage of short-range communications.
• Creation of clusters in a distributed-centralized manner.
• Cluster-Heads with good connection with the overlaid base station.
• Reduction of resources’ utilization.
• Increases in achieved capacity.
Scenario

Scenario without and with clustering where Cluster-Heads are serve both DL and UL demands of cluster-members.
System Model

Number of resources required in DL per subframe.

\[ N_{k}^{DL} = \sum_{i \in \mathcal{C}^k} R_{i}^{DL} \Phi_{i}^{k} + \sum_{c_{u} \in \mathcal{C}^{k}} \sum_{i \in c_{u}} R_{i}^{DL} \Phi_{h_{u}i}^{k} \]

Number of resources required in UL per subframe.

\[ N_{k}^{UL} = \sum_{i \in \mathcal{C}^k} \alpha_{i} R_{i}^{DL} \Phi_{i}^{k} + \sum_{c_{u} \in \mathcal{C}^{k}} [\alpha_{h_{u}} R_{h_{u}}^{DL} \Phi_{h_{u}}^{k} + \sum_{i \in c_{u} \setminus h_{u}} R_{i}^{DL} (\alpha_{i} \Phi_{h_{u}i}^{k} + \phi_{h_{u}i} + \alpha_{i} \phi_{ih_{u}})] \]

Total amount of resources required per subframe.

\[ N_{k}^{T} = N_{k}^{DL} + N_{k}^{UL} \]

\[ = \sum_{i \in \mathcal{C}^k} R_{i}^{DL} (\Phi_{i}^{k} + \alpha_{i} \Phi_{i}^{k}) + \sum_{c_{u} \in \mathcal{C}^{k}} \sum_{i \in c_{u} \setminus \{h_{u}\}} R_{i}^{DL} (\phi_{h_{u}i} + \alpha_{i} \phi_{ih_{u}} + \alpha_{i} \phi_{h_{u}i}^{k} + \Phi_{h_{u}}^{k}) \]
• Less than 40% DL spectrum is utilized for 55 UEs with Clustering.
• DL spectrum utilization decreases by 70%.

• UL utilization increases to 35%.
• Near optimal performance of CORE for DL and acceptable for UL.
• Around 50% gains in spectrum utilization.
In a scenario where 80% of UEs are cell edge and hotspot users, 50% of cluster-head users are outside hotspot areas and closer to the overlaid base station.
Conclusions – Industrial Impact

• Proved the dependence of Handover performance on Inter-Site distance in a multi-tier deployment

• Derive closed-form expressions for the different HO performance metrics as a function of inter-site distance and speed of UEs.

• Set a strategy for selected the proper Time-to-Trigger value according to operators’ policies

• Achieve gains in spectrum utilization after adopting the idea of clustering among users with good connection to the overlaid base station and users will lower quality links.
Current Work

- Introduce parameters related to energy.
- Study the impact of mobility on the clustering formation.
Activities

- ICC participation (London, June 8-12th)
- CTTC Seminar entitled "LTE Release 13 and road to 5G"
- Public Talk (King’s College, London March 2015)
- Secondment in London
Publications

• “Handover Performance in LTE-A HetNets Through Inter-Site Distance Differentiation”, G. Kollias, F. Adelantado, J. Varadakas, and K. Ramantas, (CAMAD 2014’ published)

• “The Impact of Inter-Site Distance and Time-to-Trigger on Handover Performance in LTE-A HetNets” G. Kollias, F. Adelantado, C. Verikoukis, (ICC 2015’ published)

• “CORE: A Clustering Optimization algorithm for Resource Efficiency in LTE-A Networks”, G. Kollias, F. Adelantado, K. Ramantas, C. Verikoukis, (Globecom 2015’ accepted)
Thank you for your kind attention!

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Towards Quality of Experience in Mobile Cellular Networks

CROSSFIRE Industrial Dissemination Day

Eirini Liotou
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The CROSSFIRE architecture
WP4 contribution

- Understand what influences the QoE of mobile users
- Devise new, QoE-centric mechanisms in the network
- Exploit QoE-awareness to share the network resources more efficiently
- Propose an architecture that realizes QoE monitoring and QoE management
- Focus on LTE/LTE-A
WPi=1,2,3 interactions with WP4

- **WP1**: Model the aggregate network interference in heterogeneous cellular networks, investigate performance of various transmission schemes & propose new solutions
  - Focus on PHY-related QoE metrics

- **WP2**: Propose architectures based on infrastructure and resource sharing, using NFV, SDN, etc.
  - Exploit proposed architectures for achieving better QoE
  - Propose new system/business models that leverage QoE opportunities

- **WP3**: Evaluate D2D with traffic offloading, explore new cell selection algorithms, study techno-economic implications
  - SON techniques as a way to increase the QoE
QoS in LTE/LTE-A is provisioned via the concept of virtual bearers. They define how UE data are treated across the network (guidelines).

9 QoS class identifiers (QCI):
- Allocation & retention priority (ARP)
- Guaranteed & Maximum bit rate (GBR, MBR)
- Packet delay & packet error rate upper bounds
An operator’s perspective: The need for QoE

The degree of delight or annoyance of the user of an application or service

Customer Experience Management

Quality evaluation & control

Automate service configuration, analytics
Reduce / prevent customer churn
Better customer care & support, troubleshooting

Drive business operations
Enable strategic business decisions
Build “ELAs”

Business strategy (QoBiz)

Network efficiency

The overall acceptability of an application or service, as perceived subjectively

Avoid under-engineering
Proactively predict / prevent problems
Reactively improve the QoE

Avoid over-engineering
Reduce energy consumption
Save spectrum resources
What influences QoE?

**Mobile networks**
- Wireless aspects
- User mobility
- Transient loss of connectivity
- Session establishment delay
- Accessibility & Coverage
- Device battery consumption
- Security & Privacy
- Network heterogeneity

**QoS**
- Quality of Service

**GoS**
- Goodput

**QoR**
- Quality of Experience

**Network**

**Context**
- Communication task
- Equipment
- Customer support
- Green
- Business
  - Location
  - Social & cultural context
  - Task type
  - Urgency
  - Intentions
  - Charging policy
  - Costs
  - Business model
  - Company image, brand
- Equipment
  - HW & SW, OS
  - Ease of services’ setup
  - Type & characteristics
- Customer support
  - SLAs
  - Customer care
- Green
  - Quality assurance guarantees
  - Energy savings
  - Eco-friendly

**Human**
- Psychophysics & Physiology
  - Realization & Perception
- Cognitive science
  - Cognition & Judgment
- Psychology & Sociology
  - Demographic profile
  - Psychology & Emotional state
  - Experiences, Expectations
  - Role & social factor
- Decision science
  - Interpretation, Expression & Description

**QoE score**

**CROSSFIRE Industrial Dissemination Day: 6 July 2015, Castelldefels, Spain**
Towards QoE provisioning

**OBJECTIVE:**
Enable a QoE-centric network management framework to:

1. Monitor the end-users’ QoE
2. Enhance their experience
3. Improve the network’s efficiency (spectrum, energy)

How can QoE be measured?

 ➤ The answer is via: QoE modelling!

QoE Modelling

Subjective
- Controlled experiments
- Real service evaluation
- Streaming/Download Crowdsourcing

Objective
- Media-layer
- Packet-layer
- Parametric

In-service
Post-service
Full Reference
Reduced Reference
No reference
Examples of objective models

- **VoIP:** \( R = 94.2 - [0.024d + 0.11(d - 177.3)H(d - 177.3)] - [11 + 40 \ln(1 + 10p)] \)
  - {\text{packet loss rate, delay}}

- **YouTube (TCP):** \( QoE = 3.5 \times e^{-(0.15L + 0.19)N} + 1.5 \)
  - {\text{duration of stalls, } \# \text{ of stalls}}

- **HTTP Adaptive Streaming (TCP):** \( QoE = 0.003 \times e^{0.064t} + 2.498 \)
  - {\text{time on highest quality level}}

- **Real-time video (UDP):** \( V_q = 1 + I_{\text{coding}} \times I_{\text{transmission}} \)
  - {\text{FR, BR, PLR}}

- **FTP:** \( QoE = \alpha \log_{10}(\beta R) \), \( 10 \text{kbps} < R < 300 \text{kbps} \)
  - {\text{data rate}}
## Which are some key QoE KPIs?

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Quality Influence Factors</th>
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<tbody>
<tr>
<td>Video specific</td>
<td>Frame Rate</td>
<td>Transport / Network</td>
<td>Round trip / one-way delay</td>
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<td></td>
<td>Video bit rate</td>
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<td>Jitter</td>
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<td></td>
<td>Video content</td>
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<td>Packet loss ratio</td>
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<td></td>
<td>Terminal type</td>
<td></td>
<td>Delay burstiness distribution</td>
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<tr>
<td></td>
<td>Display size, type and resolution</td>
<td></td>
<td>Loss burstiness distribution</td>
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<td></td>
<td>Codec type and implementation</td>
<td></td>
<td>Bottleneck bandwidth</td>
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<tr>
<td></td>
<td>Video resolution and video format</td>
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<td>Congestion period</td>
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<tr>
<td>Video on Demand</td>
<td>Number of stalling events</td>
<td>Physical</td>
<td>SNR / SIR / SINR</td>
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<tr>
<td></td>
<td>Duration of stalling events</td>
<td></td>
<td>Bit rate</td>
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<td></td>
<td>Total video duration</td>
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<td>BLER</td>
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<td></td>
<td>Initial delay (start-up delay)</td>
<td></td>
<td>Outage probability</td>
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<tr>
<td></td>
<td>Time on highest layer (HAS)</td>
<td></td>
<td>Packet / Symbol / Bit Error Probability</td>
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<td></td>
<td>Number of switches (HAS)</td>
<td></td>
<td>Outage capacity</td>
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<td></td>
<td>Altitude (HAS)</td>
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<td>Ergodic capacity / throughput</td>
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<td>Diversity order / coding gain</td>
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<td>Area spectral efficiency</td>
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<td>Energy efficiency</td>
</tr>
</tbody>
</table>
How can the QoE KPIs be monitored?

Industry exploitation scenarios

1. Integrate QoE into existing or emerging mechanisms (to increase QoE)
   – QoE-driven D2D communications
2. Exploit QoE awareness to save network resources
   – QoE-aware Interference Management
3. Preserve the QoE level in a specific situation of interest
   – QoE-aware Admission Control
4. Proactively ensure the end-user QoE (knowing what really influences it)
5. Exploit QoE results to devise more meaningful network mechanisms
6. Create new business (and system) models
   – An SDN QoE-Service where telecom/network providers cooperate with OTTs
   – The notion of “experience packages”
Scenario 1: 
QoE-driven D2D communications (1/2)

- QoE awareness can control the operational mode of users in LTE-A:
  - Drive cellular ⇔ Device-to-Device (D2D) mode transitions
- Enhance QoE, ↑ throughput, offload network, ↓ power, allow for profits

Scenario 1: QoE-driven D2D communications (2/2)
Scenario 2: QoE-aware Interference Management (1/2)

- QoE awareness can drive a Power-Controlled Interference Management scheme in femto-overlaid LTE-A

- How: Reduce HeNB’s transmit power, with no loss in femto-UEs’ QoE, provided that this is optimal

Scenario 2:
QoE-aware Interference Management (2/2)
Scenario 3: QoE-aware Admission Control (1/2)
Scenario 3:
QoE-aware Admission Control (2/2)

An SDN QoE-Service for dynamically enhancing the performance of OTT applications (1/3)

- OTT providers gain momentum while MNOs not in the revenue loop
- OTT applications are treated as best-effort by the MNOs though!
- With SDN, MNOs can expose their network assets to OTTs
- An SDN-based “QoE-Service” can trigger network programmability to meet the requirements of OTT on-demand services or of premium users
An SDN QoE-Service for dynamically enhancing the performance of OTT applications (2/3)

- The QoE-Service requests KPIs
- The SDN controller translates these requests into monitoring commands
- The MNO collects the requested data from appropriate nodes and reports back to the controller
- The collected data are modelled into QoE by the QoE-Service
- QoE policies are triggered by the QoE-Service and applied by the SDN controller

* ACK: Dimitris Tsolkas, IEEE QoMEX 2015 presentation
An SDN QoE-Service for dynamically enhancing the performance of OTT applications (3/3)

- The QoE-Service requests KPIs
- The SDN controller translates these requests into monitoring commands
- The MNO collects the requested data from appropriate nodes and reports back to the controller
- The collected data are modelled into QoE by the QoE-Service
- QoE policies are triggered by the QoE-Service and applied by the SDN controller

What/How many KPIs
Which applications
MNO-specific
Monitoring periodicity
Signaling overhead
A QoE modelling problem
Decision problem

Note: Different business models can be defined

The notion of “experience packages”

- Step 1: Match a user to a suitable profile
- Step 2: Derive the application/service unique characteristics and requirements
- Step 3: Deduce the context of the current session
- Step 4: Build “experience packages” when delivering a service. This decision is a compromise between the requirements derived from steps 1-3 and the actual capabilities of the network

Conclusions

- The integration of QoE is essential for mobile operators
- QoE-modeling & awareness is a challenging requirement
- New metrics for quality monitoring are necessary
- Novel QoE-driven network management open up new possibilities
- Quality consistency and user/service differentiation are important
- Context awareness will be a key point for ensuring QoE in the future
- SDN may be the key for QoE enhancement/differentiation
Thank you!

Q&A

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CROSSFIRE Industrial Dissemination Day: 6 July 2015, Castelldefels, Spain