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EPSRC/MobileVCE Core 5 Programme

The Green Radio Project – An Overview of Outcomes

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Herriot-Watt University

Presentation Outline

1. Introduction
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   - Hardware/Scheduling
6. Integration Outcomes
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7. Sweet-Spot Solutions
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   - SON & Machine Learning
   - Energy Harvesting
8. Competing Research

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Introduction

WP1: Architectures

Continual Interaction with GR2 and Networks Programme

- GR-1.1: Initial Study of Key Metrics and Network Architecture
- GR-1.2 Energy Efficient Architectures
- GR-1.3 Multihop Routing
- GR-1.4 Spectrum Balancing

Time

Outcomes: Deliverables, Papers, Patents

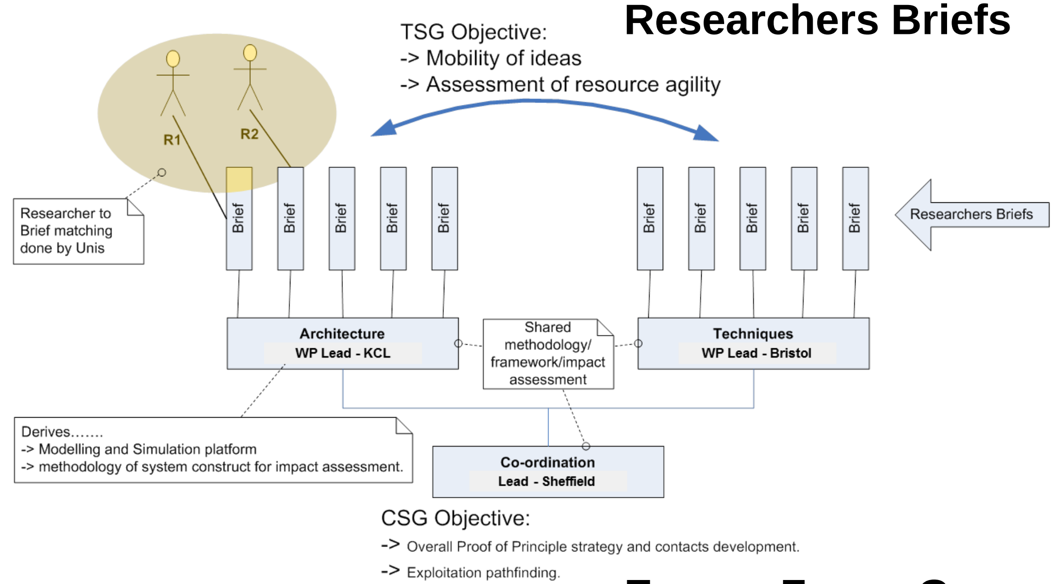
WP2: Techniques

Continual Interaction with GR1 and Networks Programme

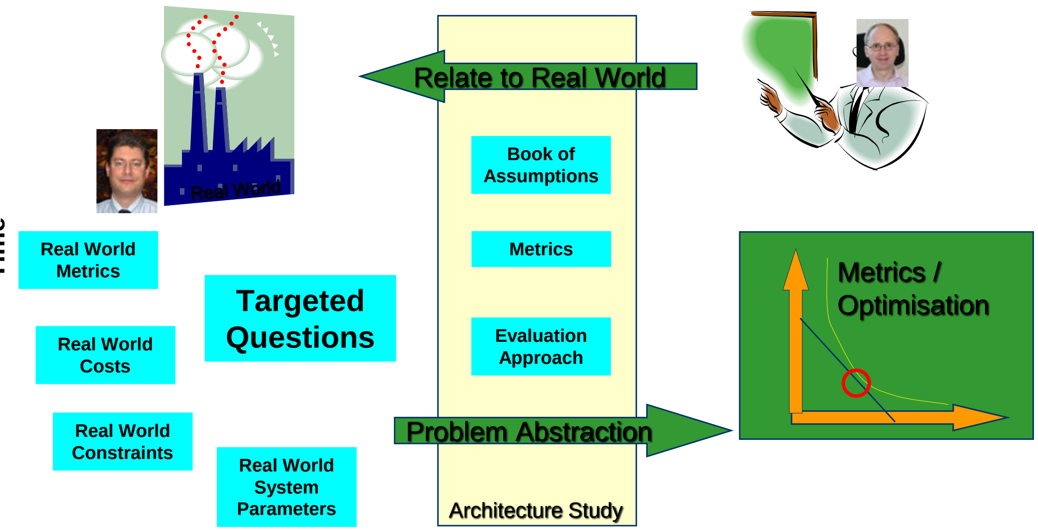
- GR-2.1: Investigation and Evaluation of Techniques for Power Reduction
- GR-2.2: Resource Allocation Techniques
- GR-2.3: Power Efficient Digital Signal Processing
- GR-2.4: Power Efficient Hardware
- GR-2.5: Novel Approaches for Power Reduction

Time

Researchers Briefs



Energy Focus Group



Energy Metrics

Book of Assumptions v2, and TR-GR-0071 Baseline RAN

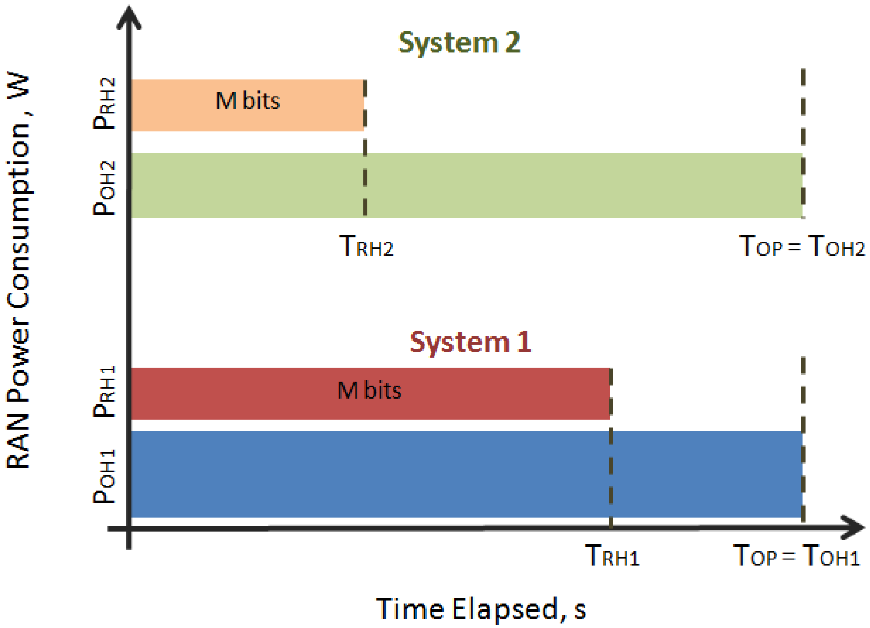
Energy (E) = Power (P) x Time (T):

$$E = P_{RH}T_{RH} + P_{OH}T_{OH}$$

ECR = Energy (E) / M bits delivered:

$$ECR = \frac{E}{M} = \frac{P_{RH}\frac{M/T_{OH}}{M/T_{RH}} + P_{OH}}{M/T_{OH}} = \frac{P_{RH}\frac{R}{C} + P_{OH}}{R}$$

where ***R*** is the *offered* ***traffic rate***, and ***C*** is the achievable ***system throughput***. ***R/C*** can be seen as the system ***load***, ***L*** (proportion of transmit period to total operational period).



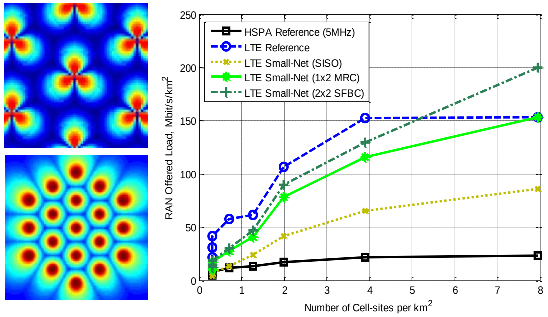
ECG = Sys 2 Energy (E2) / Sys 1 Energy (E1):

$$ECG = \frac{E_2}{E_1} = \frac{P_{RH,2}T_{RH,2} + P_{OH,2}T_{OP}}{P_{RH,1}T_{RH,1} + P_{OH,1}T_{OP}} = \frac{P_{RH,2}\frac{R}{C_2} + P_{OH,2}}{P_{RH,1}\frac{R}{C_1} + P_{OH,1}} = \frac{P_{RH,2}L_2 + P_{OH,2}}{P_{RH,1}L_1 + P_{OH,1}}$$

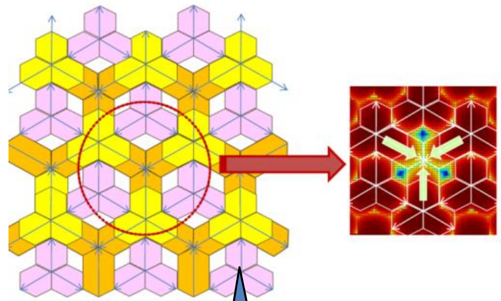
ERG = (1 – 1 / ECG) x 100%:

$$ERG = (1 - \frac{P_{RH,1}L_1 + P_{OH,1}}{P_{RH,2}L_2 + P_{OH,2}}) \times 100\%$$

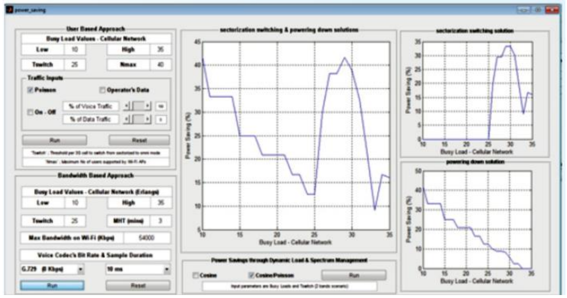
Architectures



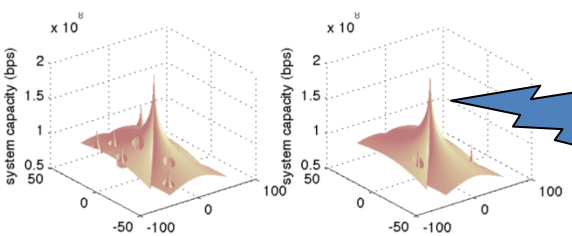
Cell Size



Cell Expansion / Sleep Mode



Traffic Off-loading to Wi-Fi



Femto Cells

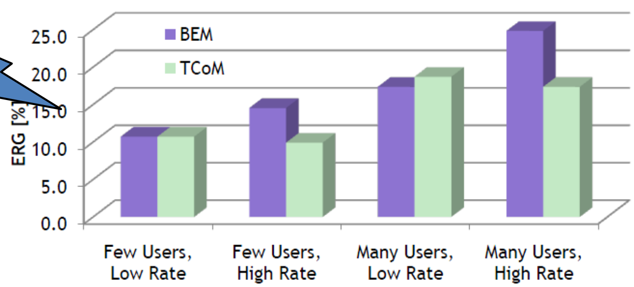
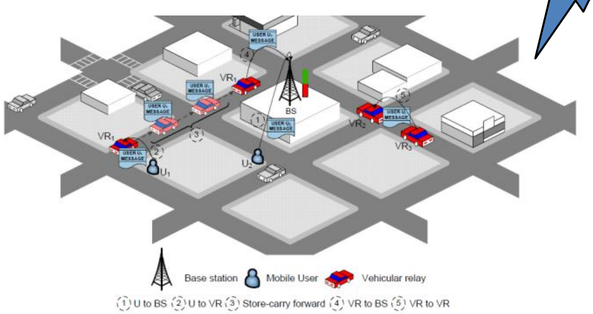
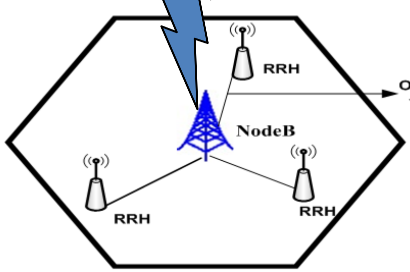


Fig 1. Theoretical gains from manipulating bandwidth

Bandwidth Expansion for High User Density



Mechanical Relaying



1. Distributed antenna system with 3 RRH in a single cell

Distributed Antenna System For Cell Edge Users

Techniques

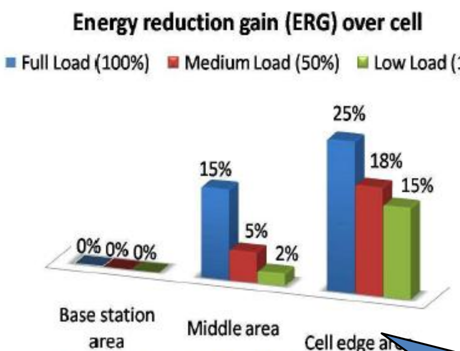


Fig. 1: Average ERG for R-NC vs. HARQ in downlink LTE-A with different traffic load

Random Network Coding

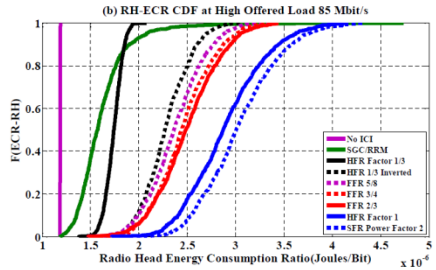
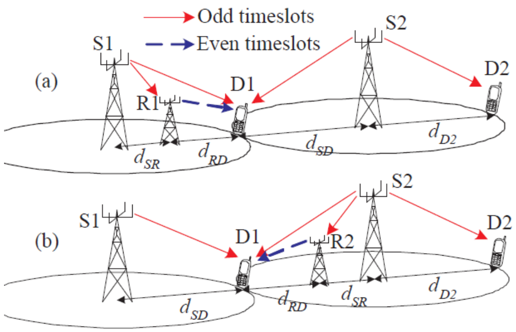
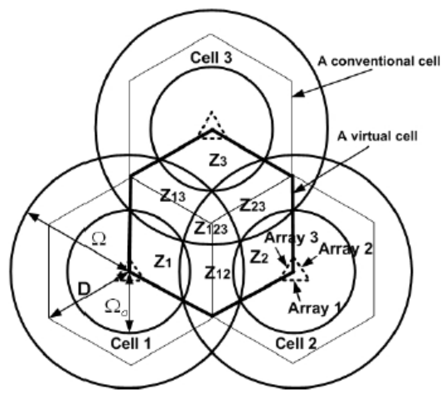


Figure 4. Radio Head Energy Performance

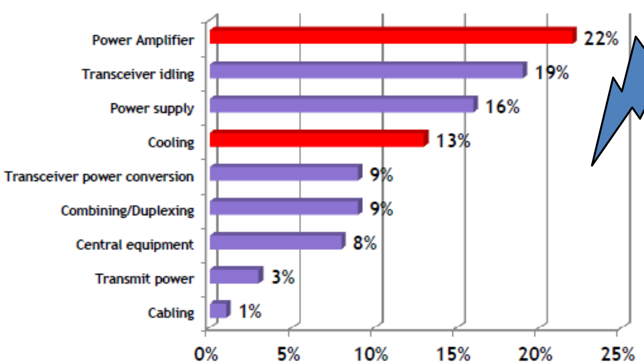
EE Scheduling



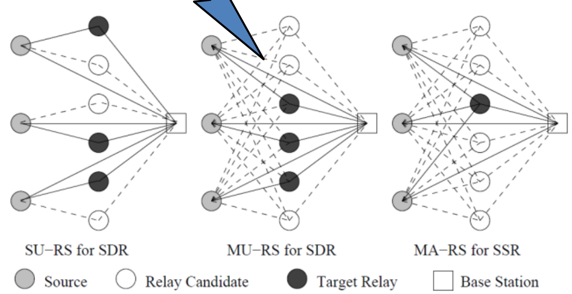
Interference Cancellation



CoMP



Power Amplifier Efficiency



Cooperative Relaying and Backhauling

Framework Documents

Register of Technologies

Colour Key
RF
Op

ARM Themes
- Theme 1 Architectures
- Theme 2 Relaying
- Theme 3 Hardware
- Theme 4 Scheduling

Tracks	Technical Approach	# Res'	RF ERG%	OP ERG%	Average ERG%
Cell Deployment	1. Cell Topology	5	90	60	51, 27
	2. Macro/Femto		46	66	
	3. DAS vs. nonDAS		9	-9	
	4. Network Coding		37	5	
	5. Femto vs. WiFi		75	15	
Frequency Management	6. Spectrum Management	2	70	50	70, 46
	7. Energy Aware N/W Selection		-	42	
Multihop Relaying	8. Multihop in LTE-A	6	45	40	64, 37
	9. Mechanical Relaying		80	-	
	10. Scheduling for MH Relay		89	53	
	11. Power Aware Routing		75	30	
	12. PHY Cooperation		90	-	
	13. WiFi Cooperation		37	0	
	14. N/W Coding for MH Relay		30	63	
BS Radio Efficiency	15. PA Efficiency	2	-	33	98, 33
	16. Antenna Efficiency		98	-	
Interference Management	17. Beamforming	2	94	63	69, 31
	18. Distributed Interf. Cancel^n		83	22	
	19. MIMO Interf. Cancel^n		30	9	
Scheduling + RRM	20. Multiuser Diversity	4	56	-	50, 7, 28
	21. Link Adaptation		72	-	
	22. Dynamic RRM		64	-	
	23. EESB/BEM Scheduler		40	2, 30	
	24. PF Energy Scheduler		33	12, 26	
	25. eNodeB Coop Scheduling		45	-	
	25. TD Sleep Modes		39	-	

Framework Documents

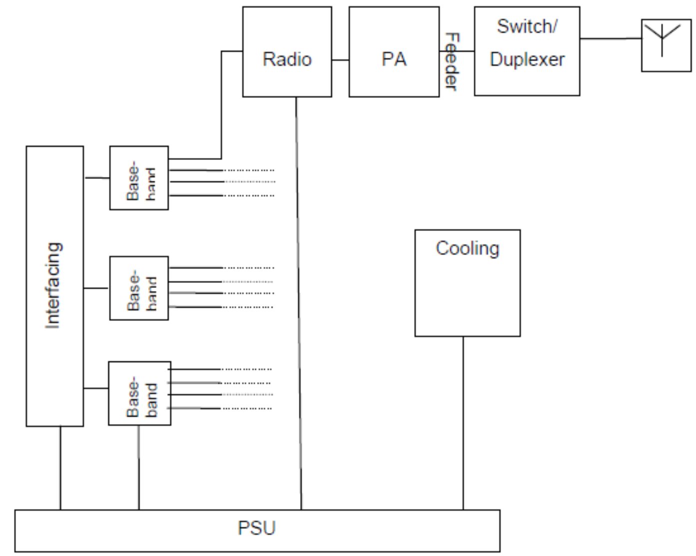
Book of Assumptions v2, and TR-GR-0013 BS Efficiency

Developed base-station **Operational (OP)** power consumption model that is a function of:

- **Radiohead (RH)** power (Load ***L*** dependent)
- **Overhead (OH)** and **Backhaul (BH)** power (Load independent)

$$P_{OP} = N_a[\frac{P_{TX}}{\mu} L + (P_{OH} + P_{BH})]$$

No. Antennas (N_a) | **Radiohead** ($\frac{P_{TX}}{\mu} L$) | **Overhead & Backhaul** ($P_{OH} + P_{BH}$)

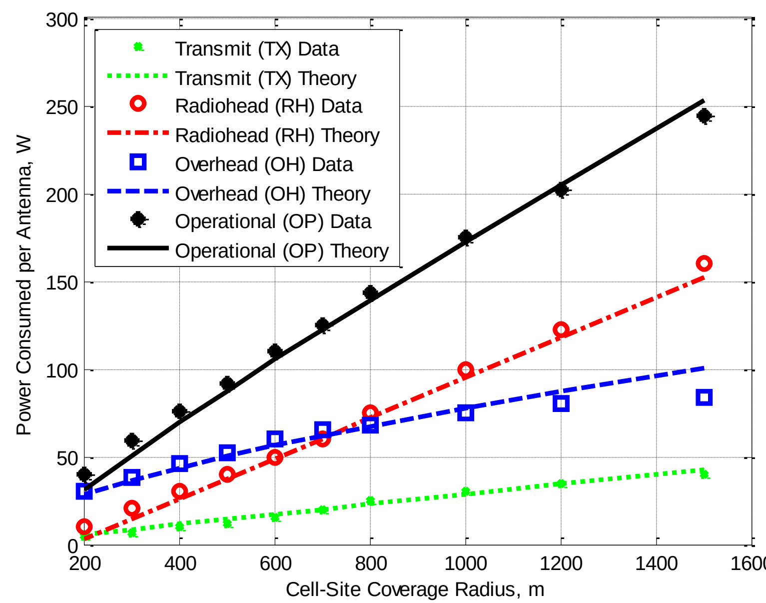


There is a relationship between the BS coverage radius and the power consumption of the BS:

- Power amplifier efficiency decreases with BS size
- Overhead power varies slowly with BS size
- Backhaul power is roughly constant

This yields an approximate empirical formula between operational power and coverage radius (***r***):

$$P_{OP} \approx N_a[0.1rL + (r^{0.62} + P_{BH})]$$



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Thematic Deliverables

mobile vce : research innovation application :

Key Observations from The Architecture Theme

- There are significant energy gains of 40-60% reported from *traffic off-loading* in outdoor, indoor and enterprise scenarios.
- There are also significant energy gains of up to *50% from spectrum balancing*.
- Results indicated that the *LTE system is more efficient than the HSPA* standard by 10-50%.
- The use of *omni-directional antenna cells* in place of tri-sectored ones can save 60-80% energy under low offered traffic load conditions.
- *Network coding* found to be less promising with only small operational energy gains reported.
- Distributed Antenna System (DAS) and Network MIMO can give operational ERGs up to 59% in *planned hotspot areas close to the cell edge*.

Key Observations from The Relay/Multihop Theme

- *Scheduling in relay-aided networks* achieves operational energy savings up to ~50%.
- Mechanical relaying achieves *>80% ERG for RF* but the gains depend on the elasticity of the service traffic. Mechanical relaying allows BS to be powered down.
- *Routing in multi hop* wireless networks using cooperative diversity produces operational energy savings of up to 50%.
- *Random Network Coding in relay-aided cellular networks* outperforms the HARQ-based scheme and gives operational energy savings of ~30% and 40% for relay-assisted and single-hop scenarios.

Thematic Deliverables

Key Observations from The Hardware/Scheduling Theme

- A narrowband Class-J prototype PA operating at ~2GHz with a 140MHz bandwidth delivered a peak output power in excess of 10W with an *efficiency of 74%.*
- A multi-channel PA covering *1.6GHz to 2.2GHz* delivered a peak output power in excess of 10W with an efficiency of 55%.
- Antenna efficiency of 95% for air-gap dielectric but the bandwidth < whole LTE band; a lower antenna efficiency of *90% for air-gap dielectric can cover the LTE band*.
- Energy efficient scheduling achieves RF ERGs from 40% to 70%, these gains reduce to ~ 30% when RH only is considered but *gains are eroded to 5-10% when BS overheads* are considered.
- EE scheduling algorithms had a *low energy cost* when implemented compared to other BS processes.
- The potentially high ERGs for radio heads available from energy efficient schedulers may be *inhibited by the constraints of current PA technology* (i.e. when input signal to PA is low)

Integration Studies

	ERG [%]	Antenna	PA	Multi-hop Relaying	BS Coop	R-NC	Interference cancellation	Packet Scheduling
Antenna	18							
PA	33							
Multi-hop Relaying	50							
BS Coop	59							
R-NC	40							
Interference Cancelation	22							
MH Scheduling	53							

Full benefit of both techniques
Less than the cumulative benefit of the two
One gain or the other
Unknown interaction on gains

Wide area (Macro) Integration

Interaction Matrix

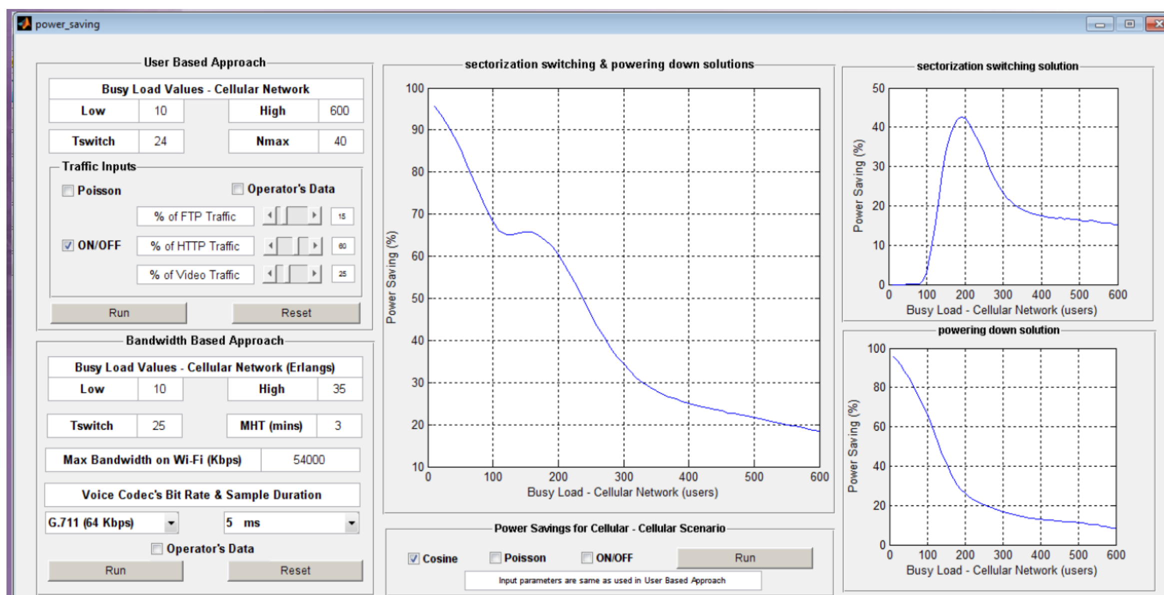
K number of Integrated techniques

$$ERG_{total} = 1 - \left(\prod_{i=1}^{K} ECG_i \right)^{-1}$$

Energy Consumption Gain

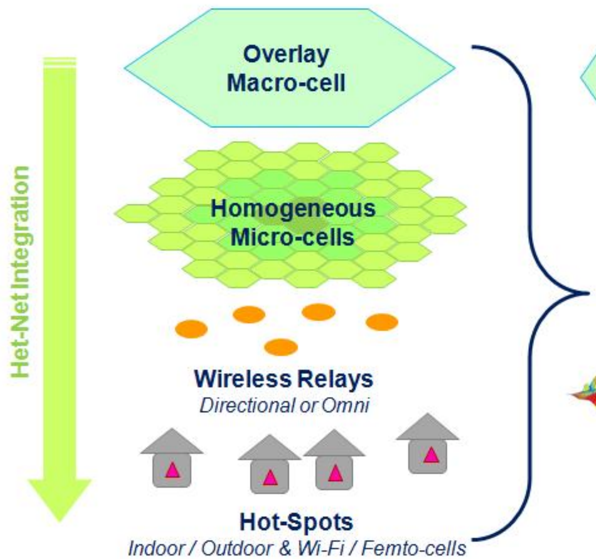
Enterprise

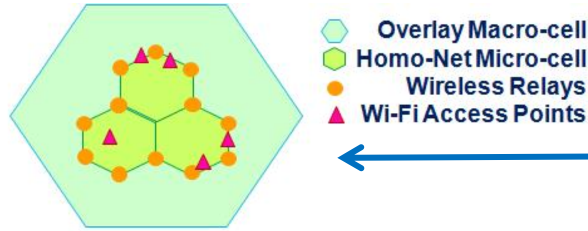
3G to WiFi Off-Load

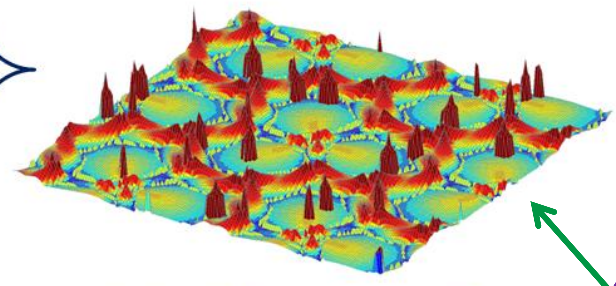


VCESIM: Dense Urban Hetnets

Version 2.1 Released (April 2012), in Deliverable-GR-0016





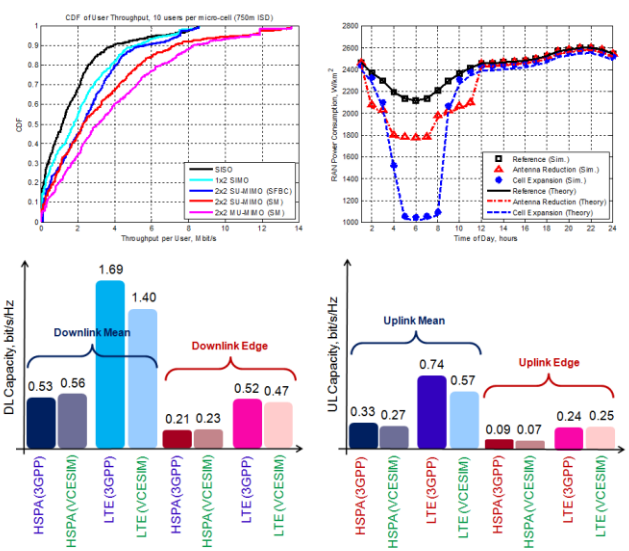


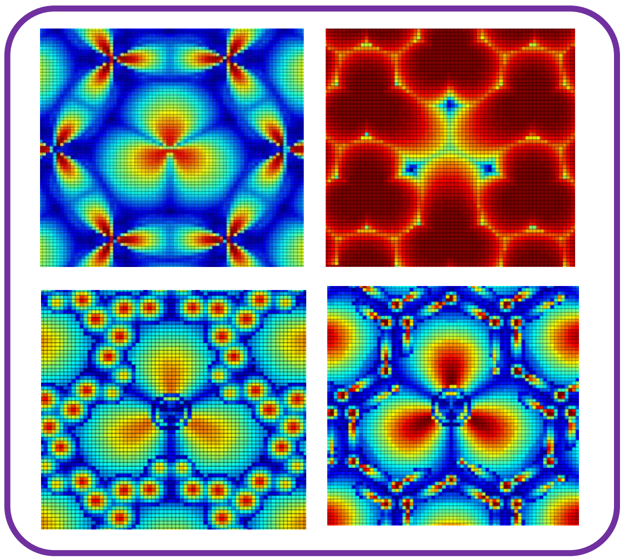
Het-Net with Relays and Indoor Wi-Fi

Heterogeneous RAN (wrap around)
2-hop RS, 802.11n AP, Femto-BS, Macro/Micro-BS, DAS/RRH

Dynamic Base-stations
Antenna beam tilt/pan/fan, Sleep Mode Management and Cell Expansion

Transmit Efficient Techniques
Interference avoidance, MIMO, Mechanical relaying, CoMP,





Integration
Dynamic Programming, Self-Organizing-Network (SON)

Geographic Specific Test Case
London Traffic and RAN model

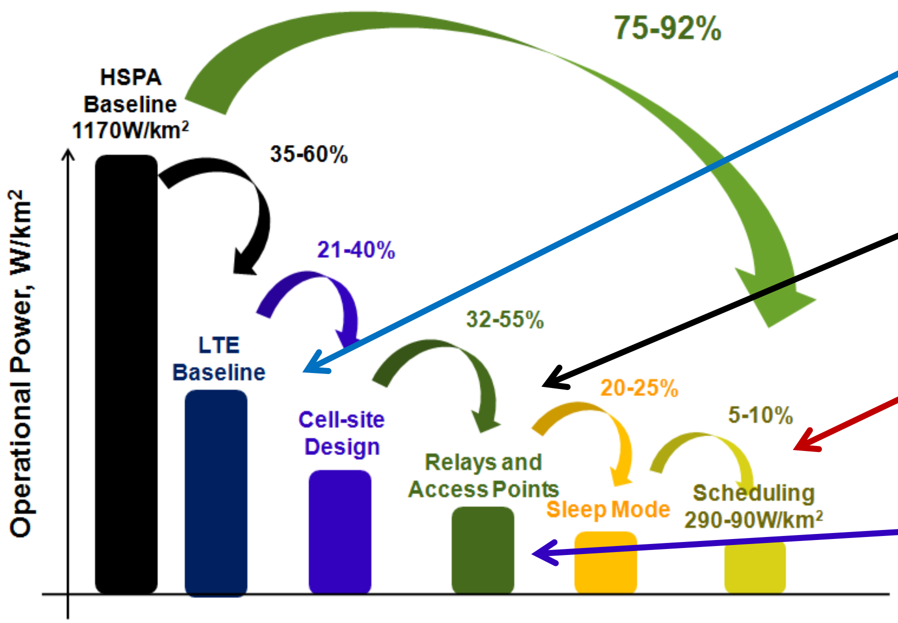
Integration Results

Deliverable D-GR-0013 (Dec. 2011)

- **Stage 1: Multiple Access**
  LTE is 1.5x more spectrally efficient than HSPA and results in a 35%-60% energy saving.

- **Stage 2a: Green Architecture and Techniques**
  Architecture and Hardware: fewer BSs with relays and APs saves 50% energy. Dynamic BSs that can expand and contract saves 40% energy. Hardware improvements save 5% energy.
  Transmission Techniques: Mechanical Relaying (Store-Carry-Forward) saves up to 26% energy. Energy Aware Scheduling and Interference Avoidance saves up to 10% energy.

- **Stage 3: Integration of GR Research under VCESIM**
  Integration of Architecture and Techniques into a Green RAN saves **75-92%** energy.



Integration
Dynamic Cells, Sleep Mode, Interference Avoidance, Relaying, Indoor Network

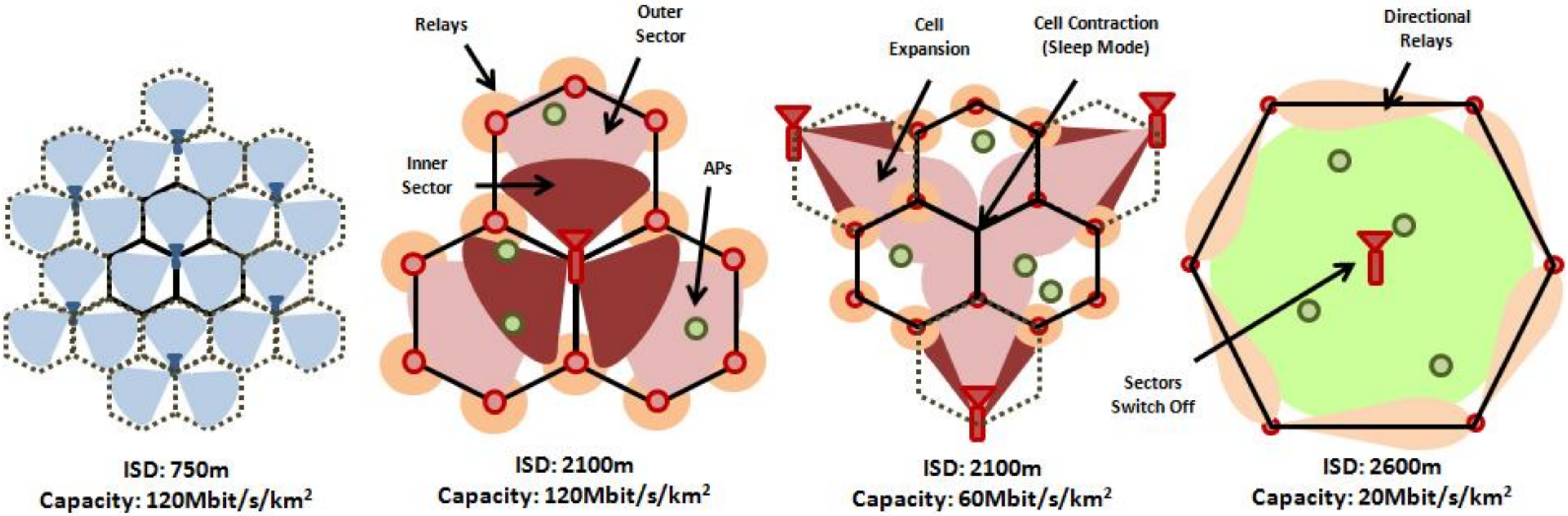
Mechanical Relaying, Wi-Fi offloading.

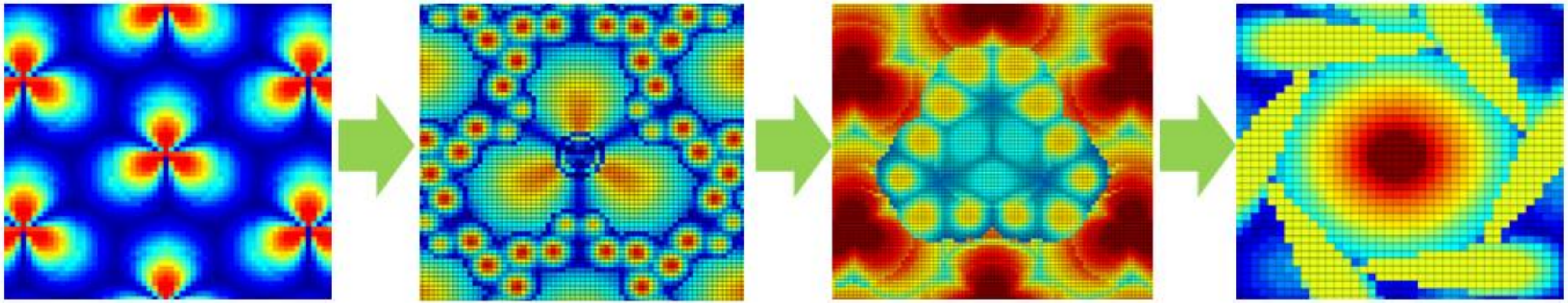
Hardware and Energy Efficient Scheduling

Femto-cell Deployment and 2 Layer Het-Nets

Dynamic Green LTE-A RAN

*Integration Study: **D-GR-0013 (Dec. 2011)***





HSPA/LTE Reference

Green LTE-A RAN (High Load 87% ERG to Low Load 92% ERG)
Also reduces 39-75% OPEX

Sweet-Spots ⇒100x

Integration (Dynamic Programming & Re-Deployment): 87-92%

No Overhead (Cloud RAN): < 91-95%

At most 95% OP ERG can be achieved with no over-head power consumption. (TR-GR-0098)

Integration with SON & FlexNetwork (Machine-Learning): > 89-94%

At least 94% OP ERG can be achieved by using machine intelligence methods – SON. (TR-GR-0114)

Energy Harvesting (Solar Power) >99.9% OP grid-ERG?

Can potentially improve grid ERG by up to 100% with 4x3m solar panel per sq. km. High CAPEX and Embodied Energy. (TR-GR-0071)

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Competing Research

mobile vce : research innovation application :

	MVCE GR	EARTH	OPERA-Net	GSMA MEE	Cool Silicon	GREEN-T	Green-Touch
Region & Duration	UK 2009-12	Europe 2010-12	Europe 2008-11	Global 2011	Global 2012/13	Europe 2011-14	Global 2010-15
Target Research	4G LTE-A	Mobile Networks	GSM	Mobile Networks	ICT	4G LTE-A	ICT
Target ERG	99%	50%	N/A	10-25%	50%	N/A	99.9%
Achieved ERG	<92%	In progress	53%	In progress	Too early	Too early	>97% (Mostly in Core)

Integrated Cross-Layer Solution (Architecture, Techniques and Hardware)

Single Set of Techniques (Multi-Hop Relaying and RF Circuit Design)

Bit-Interleaved Passive Optical Network

Observations from GR

Key Observations

- One solution does not cure all
- Integration of solutions is key
- Different load demands need different RAN configurations (in quasi real-time)
- Overhead and Backhaul energy consumption are limiting factors

Big Ticket Items

- Cell deployment
- Relaying
- Sleep modes

Polarised Trends

– Fewer large, high capacity cells augmented with relays
– Many small cells, heterogeneous deployments
– Femtocell/WiFi off-loading

Thank you &
Questions

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