Green Optical Networks

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Optical Networks Laboratory (ONLab)

- **People**
  - Leader: Prof. Lena Wosinska
    - 2 Faculties
    - 3 Post Docs
    - 4 PhD students

- **Optical core networks**
  - Availability modeling and optimization
  - Network robustness and reliability
  - Fault and attack management
  - Impairment modeling and impairment aware routing
  - Spectrum efficiency: elastic spectrum
  - Filterless and semi-filterless networks
- **Fiber access networks**
  - Hybrid WDM/TDM-PON and long reach PON
  - Techno-economic study
  - Mobile backhaul and converged wireless-optical networks
- **Green networking**
  - Energy aware provisioning
  - Energy efficient network design
  - Energy efficient backhauling strategies

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Acknoledgments

- People
  - Prof. Lena Wosinska (ONLab)
  - Prof. Jens Zander (KTH, COS)
  - Prof. Anna Tzanakaki (AIT, Greece)
  - Prof. Piero Castoldi (SSSUP, Italy)
  - Dr. Luis Velasco (UPC, Spain)
  - Dr. Isabella Cerutti (SSSUP, Italy)
  - Dr. Cicek Cavdar (ONLab)
  - Dr. Amornrat Jirattigalachote (ONLab)
  - Dr. Björn Skubic (Ericsson Research, Sweden)
  - Marc Ruiz (PhD student, ONLab)
  - Sibel Tombaz (PhD student, KTH COS)
  - Ajmal Muhammad (PhD student, ONLab)
- Projects
  - Cost action IC-0804: energy efficiency in large scale distributed systems (http://www.cost804.org/)
  - Building the future Optical Network in Europe (BONE): EU FP7 Network of Excellence (http://www.ict-bone.eu/)
  - Energy-efficient Wireless Networking (eWIN) and Optical Networking Systems (ONS) project: The Next Generation (TNG) Strategic Research Area (SRA) initiative at KTH (http://www.kth.se/en/forskning)
  - Optical Access Seamless Evolution (OASE): EU FP7 Integrated Project (http://www.ict-oase.eu/)

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Agenda

- Motivation
- Energy efficiency in WDM core networks
- Energy efficiency in broadband access
- Conclusions

Energetic issues in ICT

- Energy consumption of ICT already between 2% and 10% in UK (total energy consumption)
- Other countries in similar situations (e.g., Japan)
- 2013 prediction: 15% overall, i.e., worldwide
- Consumption of ICT sector is continuously increasing due to:
  - widespread use and high penetration
  - more and new applications and services, e.g., grid computing, multimedia and on demand services
  - always on: 24x7 from everywhere
- Expected growth rate of ICT energy in excess of 10% per year

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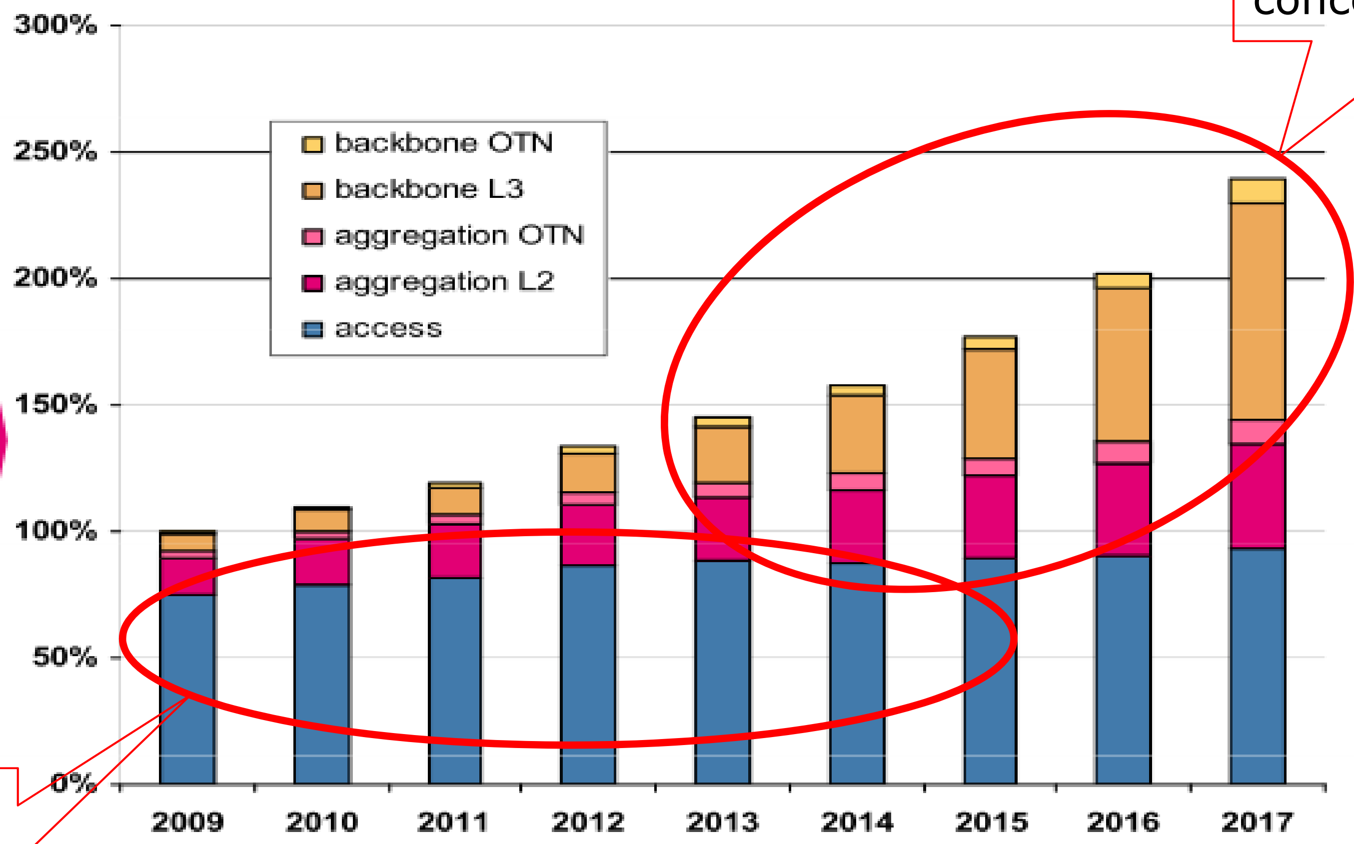
Energy consumption in communication networks

Consumption core segment will be a concern very soon



Consumption access segment relevant immediate future

Source: DTOFC2009

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Energy efficiency in WDM core networks

- WDM networks represent important step towards energy efficiency
  - lower per-bit switching cost (O-E-O not needed)
- Different green efforts in different contexts
  - Design of energy efficient WDM core networks
    - Protection
    - Quality of transmission
  - Green WDM core network provisioning
    - Power aware RWA solutions
    - Power awareness and resiliency

Sleep mode concept

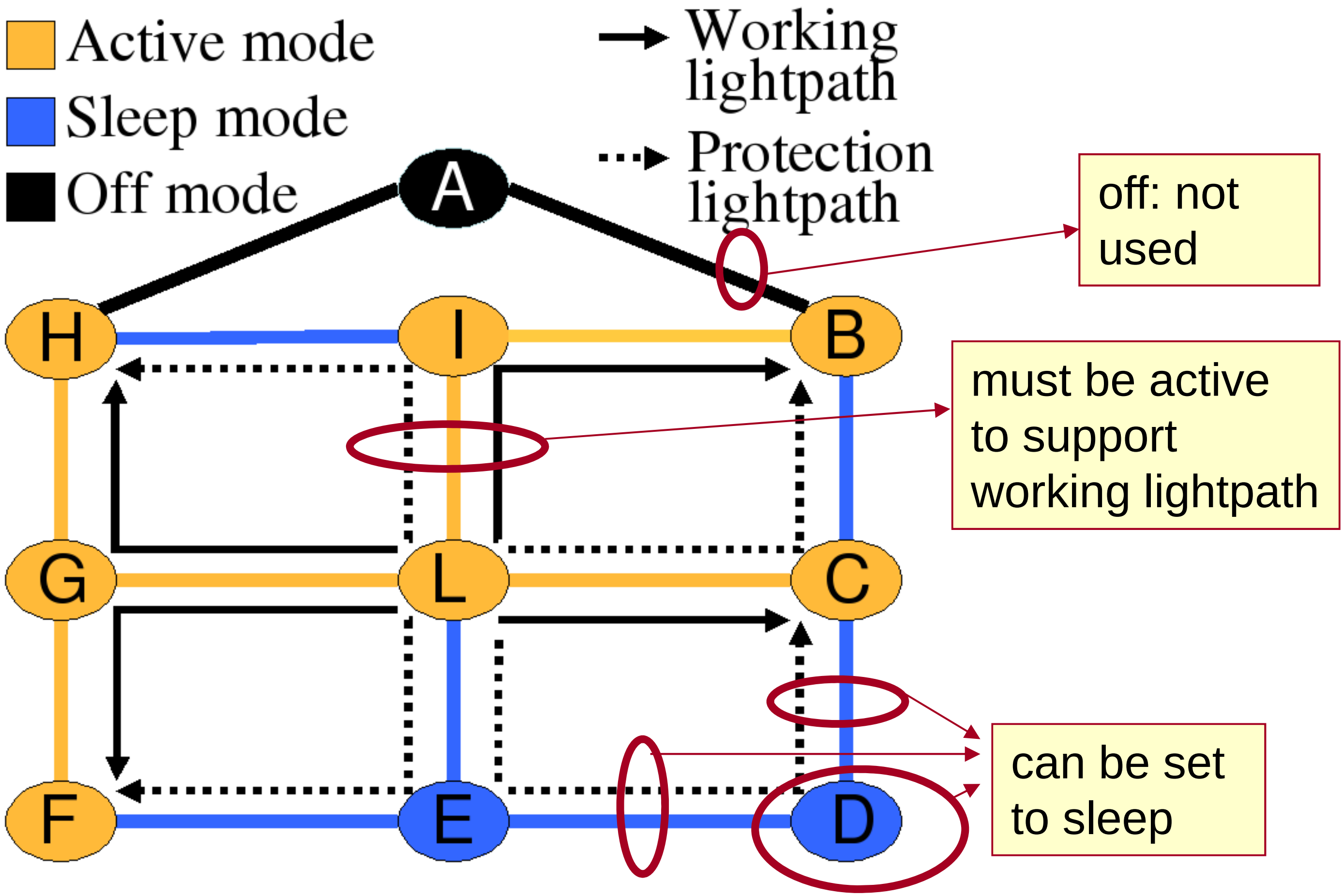
- Sleep mode in the optical network devices
  - low-power inactive state from which devices can be suddenly waken-up
  - not yet available in most network devices, but advocated by current efforts from standardization bodies, e.g., Energy star(*)
- Devices will be in different operational modes
  - Off: null power consumption - disconnected
  - Sleep: negligible amount of power - promptly switchable to active mode
  - Active: power consumption - constant amount + portion traffic load dependent
- Exploit sleep mode to support both *primary* and *protection* resources

(*) Energy Star, "*Small network equipment*," http://www.energystar.gov/index.cfm?c=new specs.small network equip.

Protection and energy efficiency

- Dedicated Path Protection: for each working lightpath one dedicated (link/node) disjoint protection lightpath

- Intuition: use the sleep mode option for backup resources
  - e.g., amplifiers, optical switches
- Objective: reduce the total power consumption for optical circuit switching layer



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Possible solutions

- Problem can be formulated as integer linear programming (*ILP*)(*) where:
  - a set of pre-computed paths are used for routing
  - wavelength conversion is assumed to be available at each node

- Problem can be also solved using a design *heuristic* based on Surballe algorithm(**) where:
  - all connection are ordered by their increasing estimated power consumption
  - starting from first in the list, connections are provisioned in the network
  - weight of each link/node are varied according to their use

(*) A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, "Energy-efficient WDM network planning with dedicated protection resources in sleep mode," in Proc. **IEEE Globecom**, 2010

(**) P. Monti, A. Muhammad, I. Cerutti, C. Cavdar, L. Wosinska, P. Castoldi, A. Tzanakaki, "Energy-Efficient Lightpath Provisioning in a Static WDM Network with Dedicated Path Protection," in Proc. **IEEE ICTON**, 2011

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Possible strategies

- MP-S: design at minimum power with devices in sleep mode
- MP-S can be compared to:
  - MP: design at minimum power with devices without sleep mode enabled
  - MP with sleep mode: MP design in which devices can be set to sleep mode
  - MC: design at minimum cost in terms of wavelengths requirement and minimum energy consumption
    - i.e., CAPEX minimization
    - second objective function can be power minimization ($\xi > 0$)

Performance results: ILP formulation

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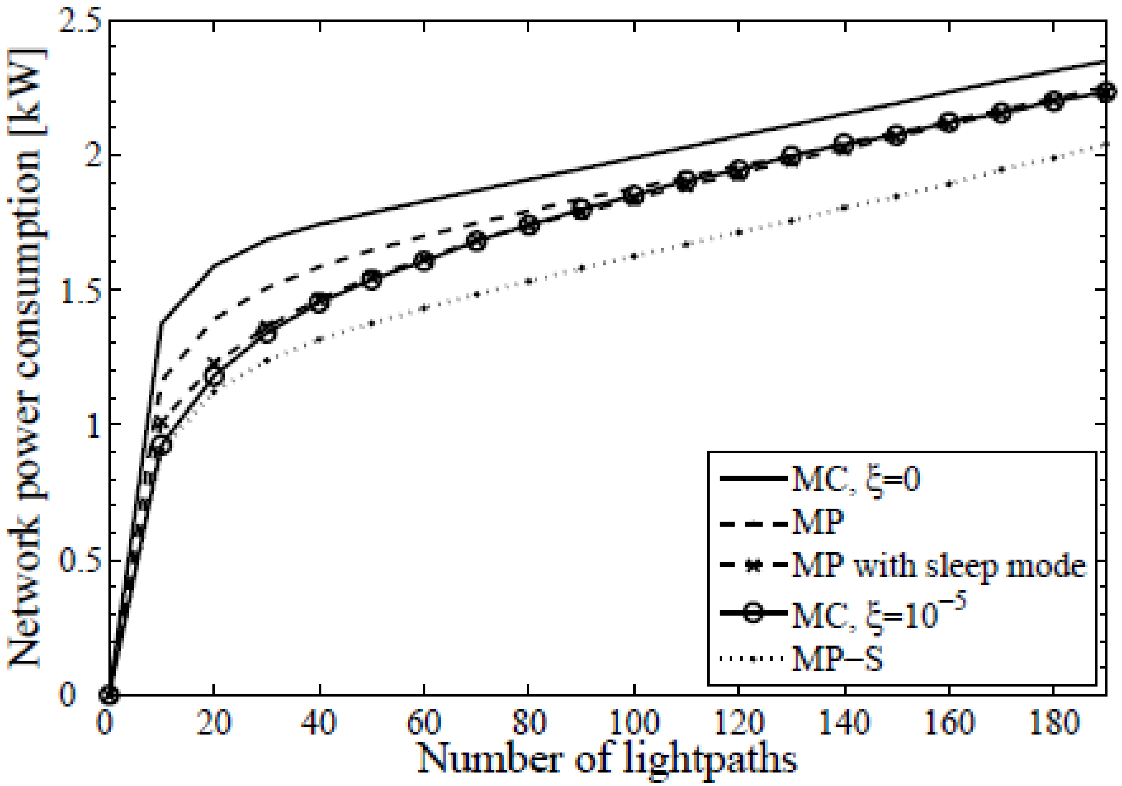
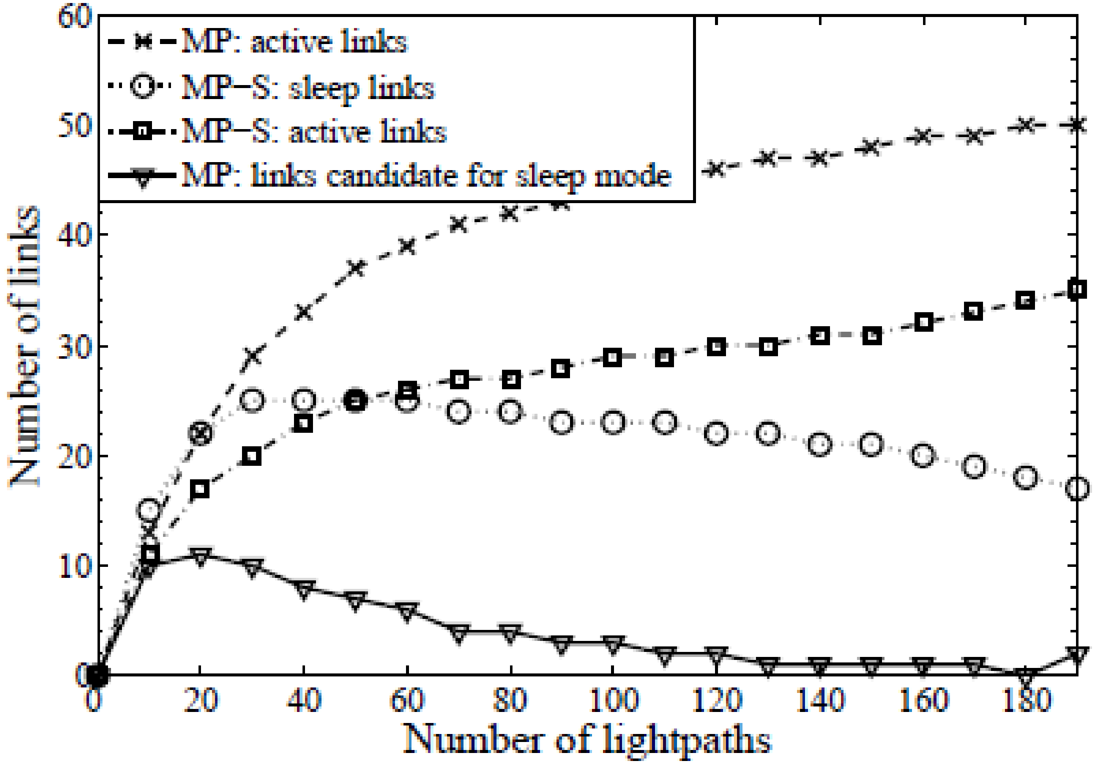
Network power consumption



MP-S saves 25% compared to MC, 15% to MP, and 10% compared to MP with sleep mode support

Number of links in sleep mode



Number of links in sleep mode increase significantly with MP-S, while number active links decrease

A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, “Energy-efficient WDM network planning with dedicated protection resources in sleep mode,” in Proc. **IEEE Globecom**, 2010

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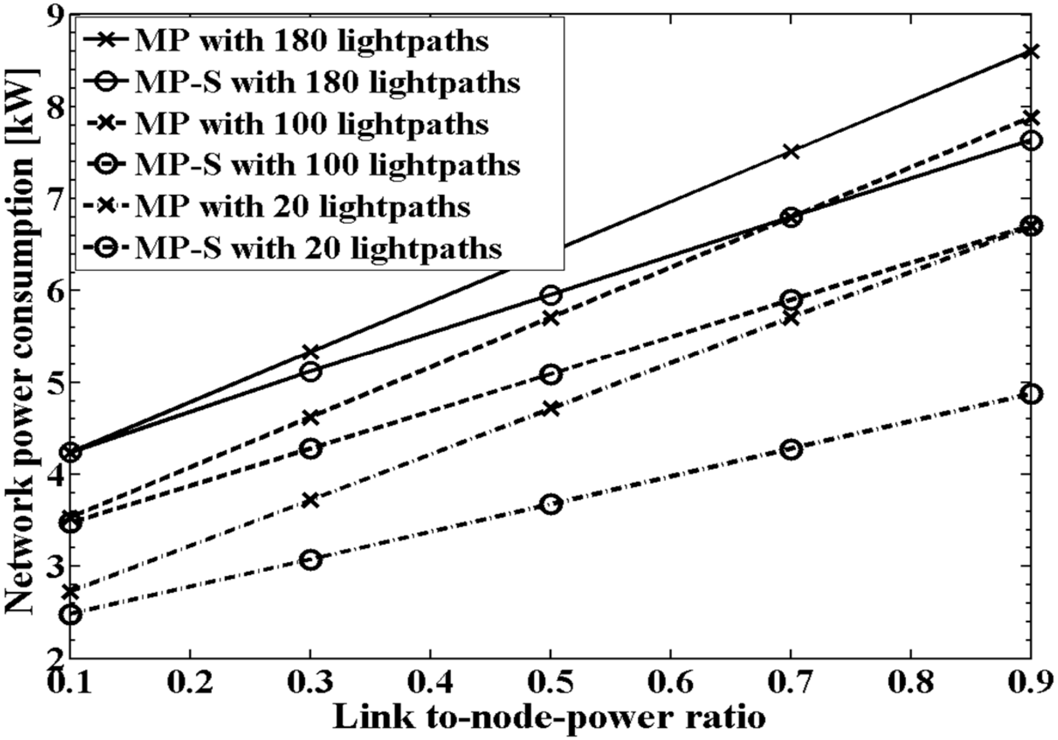
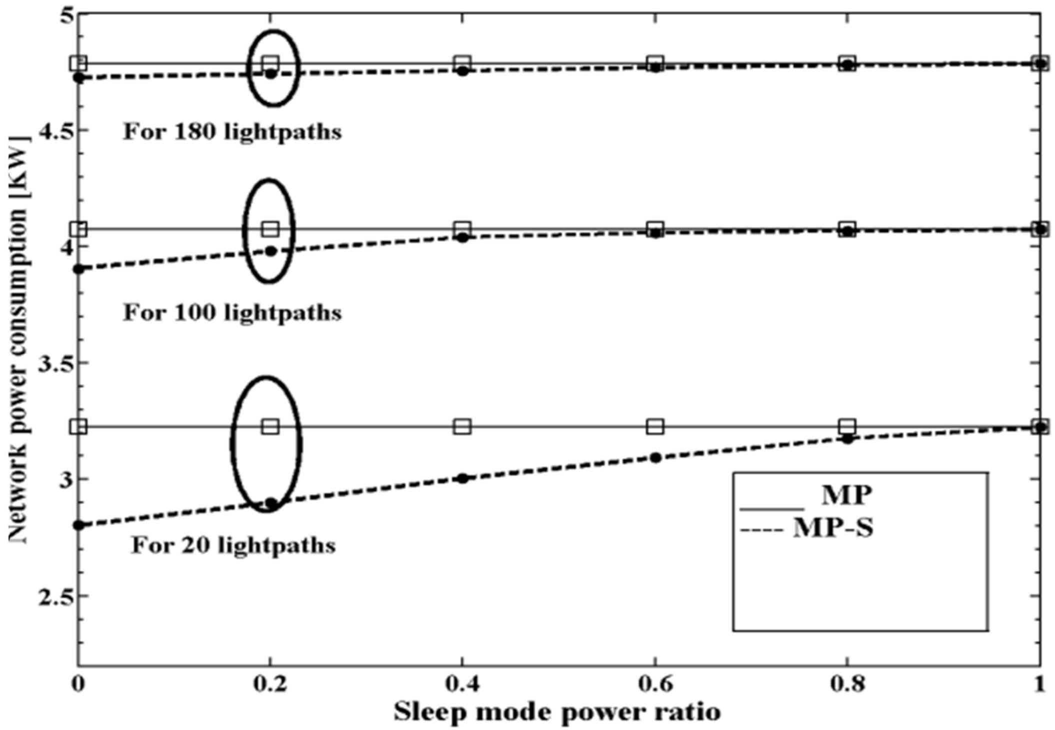
Benefits of sleep mode: sensitivity analysis with heuristic

Link to node power ratio



MP-S potentially effective when link consumption close to the power consumed by the nodes, and when the number of lightpath requests is relatively low

Impact of sleep mode power



Savings more significant when links in sleep mode are consuming a negligible amount of power with respect to the active links

P. Monti, A. Muhammad, I. Cerutti, C. Cavdar, L. Wosinska, P. Castoldi, A. Tzanakaki, ”Energy-Efficient Lightpath Provisioning in a Static WDM Network with Dedicated Path Protection,” in Proc. **IEEE ICTON**, 2011

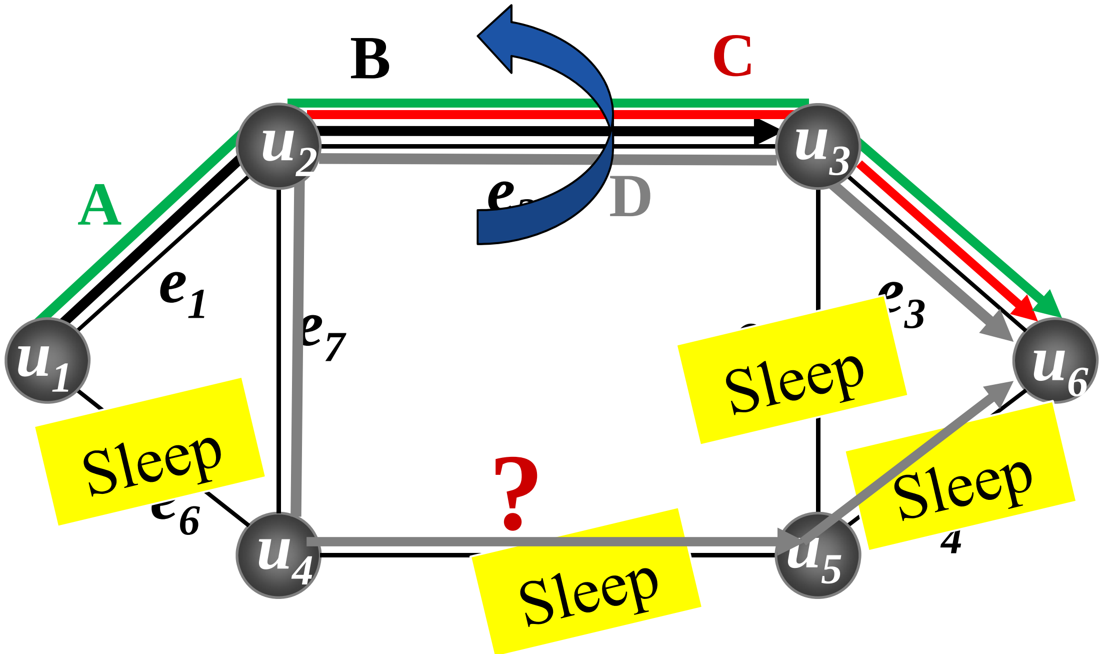
Energy efficiency and optical signal quality guarantee

Energy-Aware Routing

+

transmission impairments

Impairment and Energy Aware RWA Mechanism



- Longer paths: worse attenuation levels
- Denser fiber links: higher XPM and cross talk levels

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Problem objective and solution

- Objective: find a design approach for energy efficient optical networks with signal-quality guarantee accounting for the *trade-off* between energy saving and impairment-aware network planning

- Solution: problem formulated as mixed integer linear programming (MILP) (*)
    - accounts for, in a linearized form, the impact of linear and non linear optical impairment as a constraint(**)
    - using a set of pre-computed paths for routing
    - wavelength conversion is assumed to be available at each node

(*) C. Cavdar, M. Ruiz, P. Monti, L. Velasco, L. Wosinska, "Design of Green Optical Networks with Signal Quality Guarantee," in Proc. **IEEE ICC**, 2012

(**) M. Ruiz, L. Velasco, P. Monti, L. Wosinska, "A Linearized Statistical XPM Model for Accurate Q-factor Computation," in **IEEE Communication Letters**, 2012

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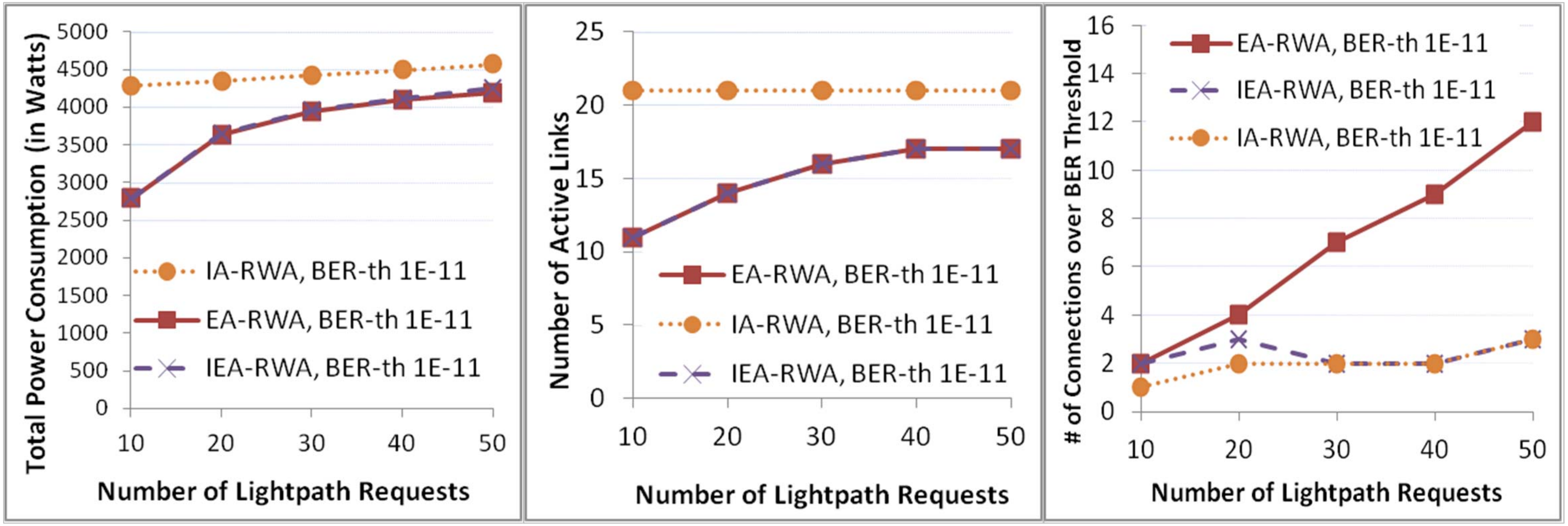
IEA-RWA performance evaluation



- IEA-RWA and EA-RWA achieve same total power consumption reduction (up to 35%) compare to IA-RWA
- IEA-RWA and EA-RWA comparable fiber usage performances, IA-RWA activates all the fibers
- IEA-RWA provides signal quality levels close to IA-RWA while minimizing total power consumption

C. Cavdar, M. Ruiz, P. Monti, L. Velasco, L. Wosinska, ”Design of Green Optical Networks with Signal Quality Guarantee,” in Proc. **IEEE ICC**, 2012

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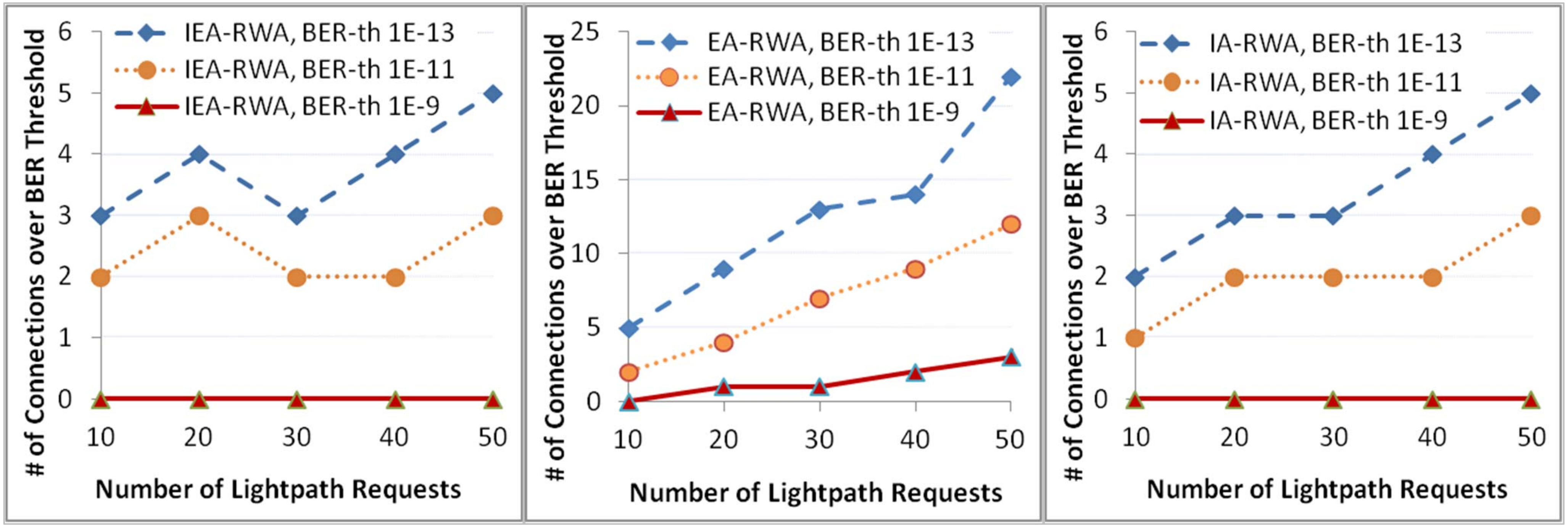
Impact of signal quality



- EA-RWA shows the worst performance in terms of blocked connections
- EA-RWA shows some blocking already with low BER-th values and up to 46% of blocked requests with stringent BER-th requirements
- IEA-RWA and EA-RWA perform very similarly for all BER-th value

C. Cavdar, M. Ruiz, P. Monti, L. Velasco, L. Wosinska, "Design of Green Optical Networks with Signal Quality Guarantee," in Proc. **IEEE ICC**, 2012

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Energy efficiency in WDM core networks

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  - lower per-bit switching cost (O-E-O not needed)
- Different green efforts in different contexts
  - Design of energy efficient WDM core networks
    - Protection
    - Quality of transmission
  - Green WDM core network provisioning
    - Power aware RWA solutions (energy vs. blocking)
    - Power awareness and resiliency (energy vs. blocking)

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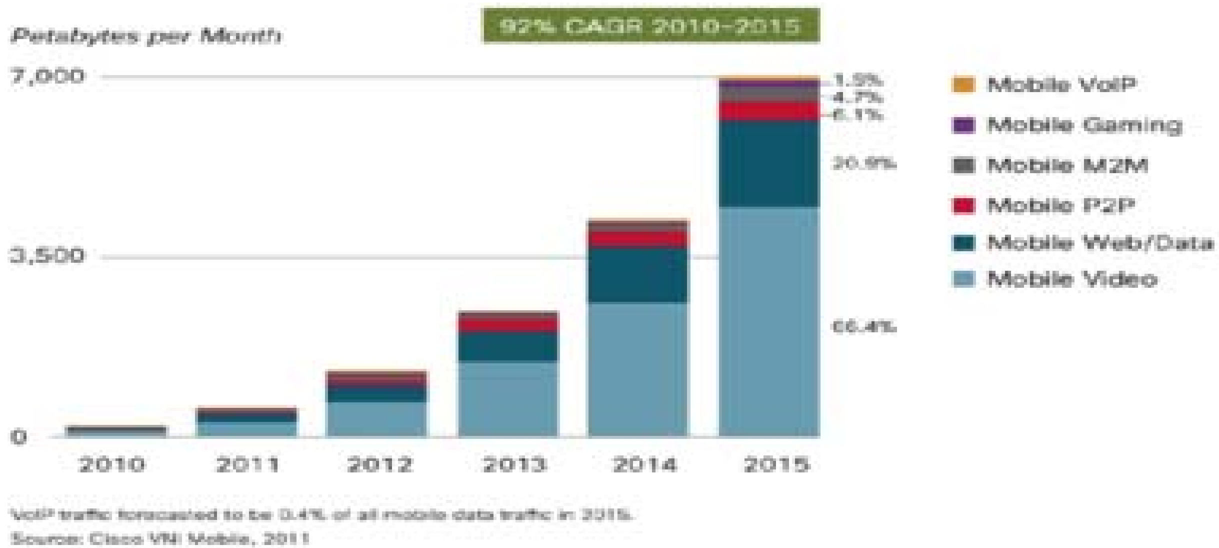
Why energy efficiency is needed in broadband access?

- Mobile broadband data usage has experienced a dramatic growth



- Energy prices increases (expected: 3x in 7 years)
  - more and more challenging operational cost for operators
- Power consumption increases 2x every 5 years
- So far, mobile networks design strategies have ignored energy
  - Optimized for spectral efficiency, capacity, not energy

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How to achieve energy efficiency in mobile broadband access?

- Reducing the power consumption of the main consumer, i.e., the base station
  - more power efficient hardware (e.g., power amplifier)
  - using more advanced software (e.g., adapting power consumption to traffic)
- Intelligent deployment strategies
  - smaller cell sizes (advantageous path loss)
  - heterogeneous deployments:
    - capacity provided by macro base stations
    - coverage provided by Pico/Micro

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HetNet deployment

- HetNets are an alternative to macro densification
- The rationale is to tailor the network deployment to the expected traffic levels, i.e., selectively add high capacity only where it is needed
- Most studies consider only the aggregated power consumption of the base stations
- Contribution of the backhaul to the total network power is omitted/neglected

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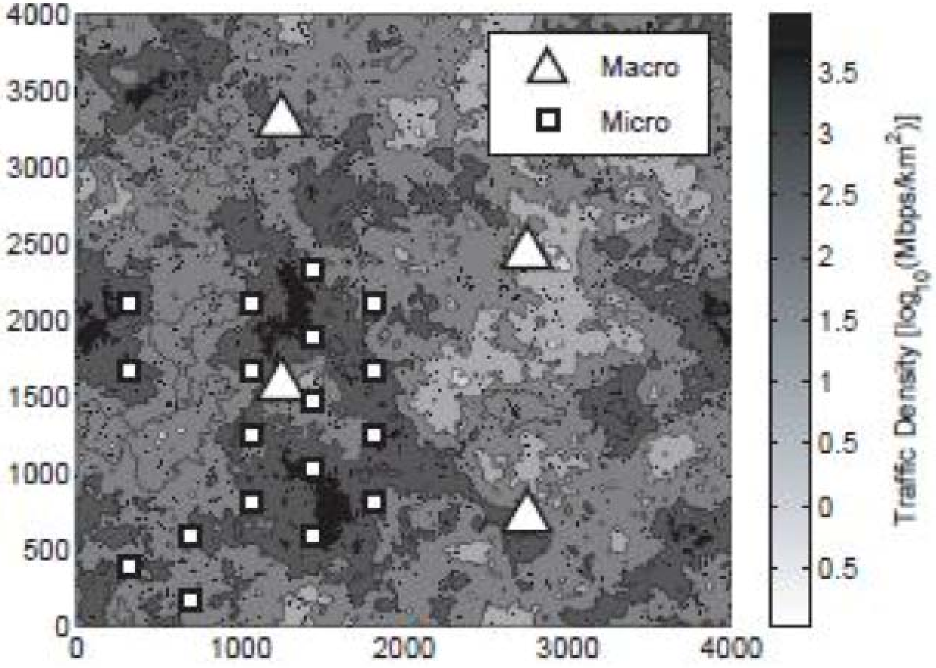
Case study: impact of backhauling

Cost effective network deployment for an area of 4 × 4km with different Hetnet scenarios



- Each BS type is assumed to have
  - maximum supported throughput s_{max} [Mbps/km2]
  - maximum range δmax [km]
- Number of base stations required is determined sequentially
- Macro base stations are deployed first to provide coverage

K. Johansson, "Cost effective deployment strategies for heterogeneous wireless networks," *Ph.D. dissertation*, Sweden, November, 2007, KTH Information and Communication Technology

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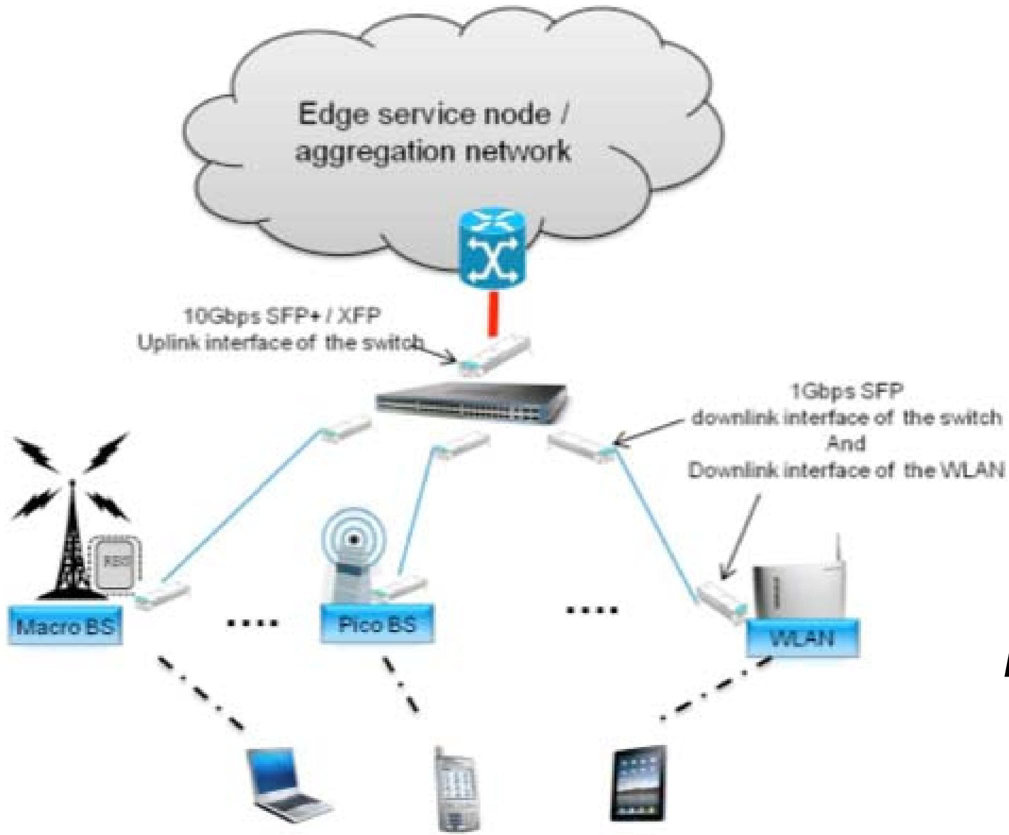
Fiber-based star backhaul topology: power model



$$P_{tot}^{FIB} = \sum_{i=1}^{m} N_i P_i + P_{bh}^{FIB}$$

$$P_i = a_i P_{tx} + b_i + c_i$$

$$P_{bh}^{FIB} = \left\lceil \frac{1}{C_{switch}^{MAX}} \left(\sum_{i=1}^{m} C_i \right) \right\rceil P_s + \left(\sum_{i=1}^{m} N_i \right) P_{dl} + N_{ul} P_{ul}$$

S. Tombaz, et al., “Impact of Backhauling Power Consumption on the Deployment of Heterogeneous Mobile Networks,” *in Proc.* ***IEEE GLOBECOM***, 2011

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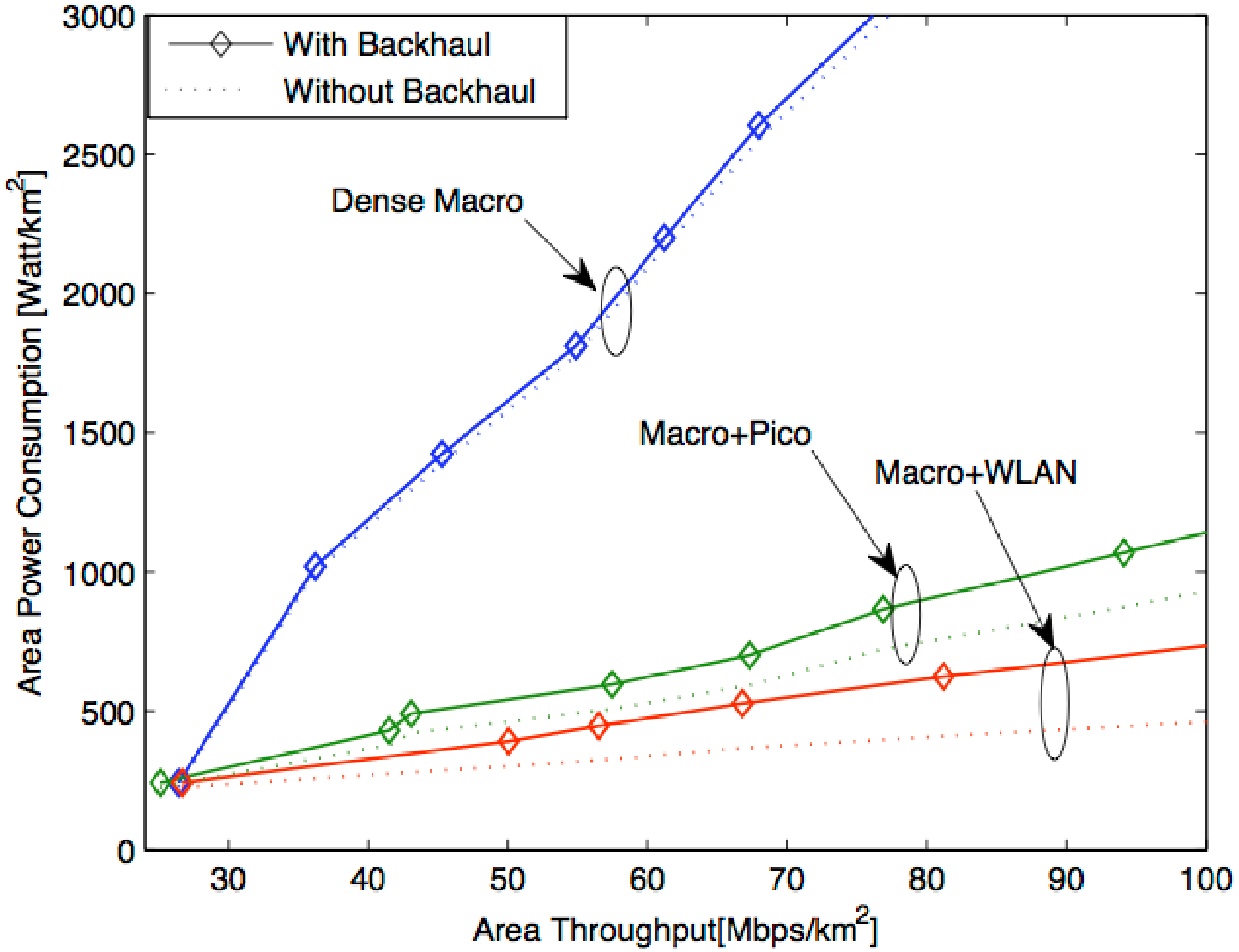
Impact of backhauling in HetNet deployment



S. Tombaz, et al., "Impact of Backhauling Power Consumption on the Deployment of Heterogeneous Mobile Networks," *in Proc.* ***IEEE GLOBECOM***, 2011

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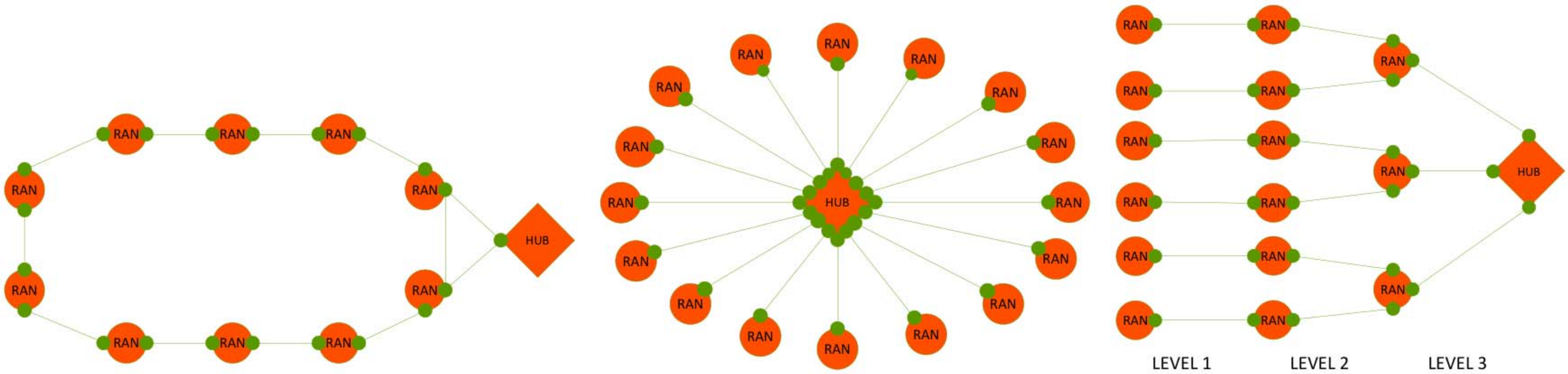
A better understanding is necessary

- Important to understand of how different architectural and technological options for backhaul affect the total backhaul power consumption
- Analysis of the power consumption for todays HetNet deployment scenarios including the effect of backhaul for
  - microwave-based architectures
  - fiber-based architectures

Mobile backhaul architectures



- Traffic backhauled through a *hub* node connected to an area aggregation point, i.e., *sink* node
- Multiple hubs, function of topology and architectural choice
- If multiple backhaul links originates or terminate at a node, *switch* is needed
- *Ring*: good for resiliency, latency might me an issue, limited number of sites because of capacity issues
- *Star*: simplest one, might have LOS limitation for MW links
- *Tree*: sensitive to faults to feeder links, better delay than ring

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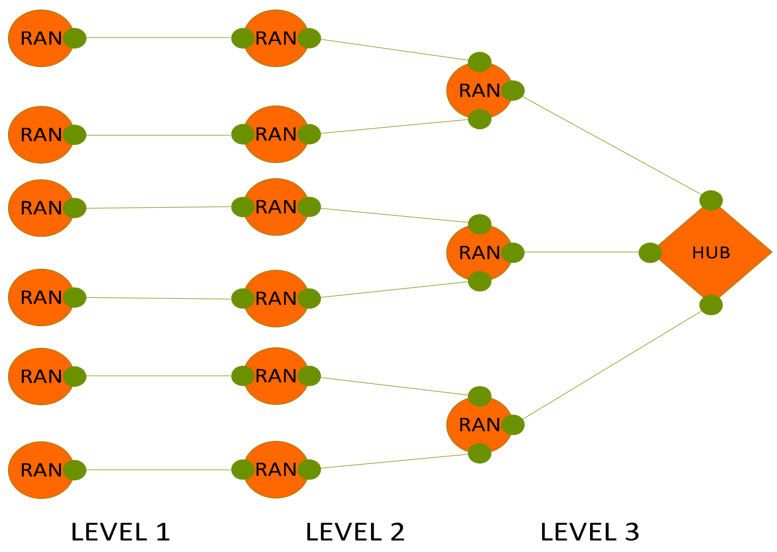
MW-based backhaul power model

$$P_{tot}^{MW} = \sum_{i=1}^{m} N_i P_i + P_{bh}^{MW}$$

$$P_i = a_i P_{tx} + b_i$$

$$P_{bh}^{MW} = P_{\text{sink}} + \sum_{j=1}^{N_{BS}} P_j^{MW}$$

$$P_j^{MW} = P_{j,agg}(C_j) + P_{switch}(N_j^{ant}, C_i)$$



$$P_{j,agg}(C_j) = \begin{cases} P_{low-c}, & \text{if } C_j \le Th_{low-c} \\ P_{high-c}, & \text{otherwise} \end{cases};$$

$$P_{j,switch}(N_j^{ant}, C_j) = \begin{cases} 0, & \text{if } N_j^{ant} = 1 \\ P_S * \left\lceil \dfrac{C_j}{C_{switch}^{MAX}} \right\rceil, & \text{otherwise} \end{cases}$$

$$P_{\text{sink}} = P_{\text{sink},agg}(C_{\text{sink}}) + P_{\text{sink},switch}(N_{\text{sink}}^{ant}, C_{\text{sink}})$$

$$P_{\text{sink},agg}(C_{\text{sink}}) = \begin{cases} P_{low-c}, & \text{if } C_{\text{sink}} \le Th_{low-c} \\ P_{high-c}, & \text{otherwise} \end{cases};$$

$$P_{\text{sink},switch}(N_{\text{sink}}^{ant}, C_{\text{sink}}) = \begin{cases} 0, & \text{if } N_{\text{sink}}^{ant} = 1 \\ P_S * \left\lceil \dfrac{C_{\text{sink}}}{C_{switch}^{MAX}} \right\rceil, & \text{otherwise} \end{cases}$$

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MW backhaul power consumption: impact of topology

P_{bh}^{MW} [W] normalized by the total area covered: Dense Macro case

Area Throughput [Mbps/km2]	Tree				Star				Ring			
	Max # hops				Max # nodes				Max # nodes			
	2	3	4	5	6	8	12	16	4	6	8	10
40	103.3	122.9	126.4	126.4	87.1	80.0	76.4	76.4	145.6	208.5	218.0	222
60	194.9	218.1	221.6	242.6	157.0	146.3	135.7	132.1	270.3	416.0	422.9	423
80	277.0	301.8	312.4	312.4	224.5	210.3	192.5	185.4	389.0	607.6	607.6	611.1

P_{bh}^{MW} [W] normalized by the total area covered: Macro + Pico case

Area Throughput [Mbps/km2]	Tree				Star				Ring			
	Max # hops				Max # nodes				Max # nodes			
	2	3	4	5	6	8	12	16	4	6	8	10
40	264.2	290.9	301.5	308.6	208.2	197.5	183.3	176.2	365.3	559.6	573.5	556.1
60	582.4	641.0	662.1	672.6	457.3	425.3	393.5	375.7	804.7	1226.1	1269.5	1269.5
80	852.5	925.1	956.8	958.5	658.6	616.1	566.4	545.1	1166.9	1843.3	1843.3	1843.3

P. Monti, S. Tombaz, L. Wosinska, J. Zander, "Mobile Backhaul in Heterogeneous Network Deployments: Technology Options and Power Consumption," in Proc. **IEEE ICTON**, 2012

Backhaul power consumption: MW vs. Fiber

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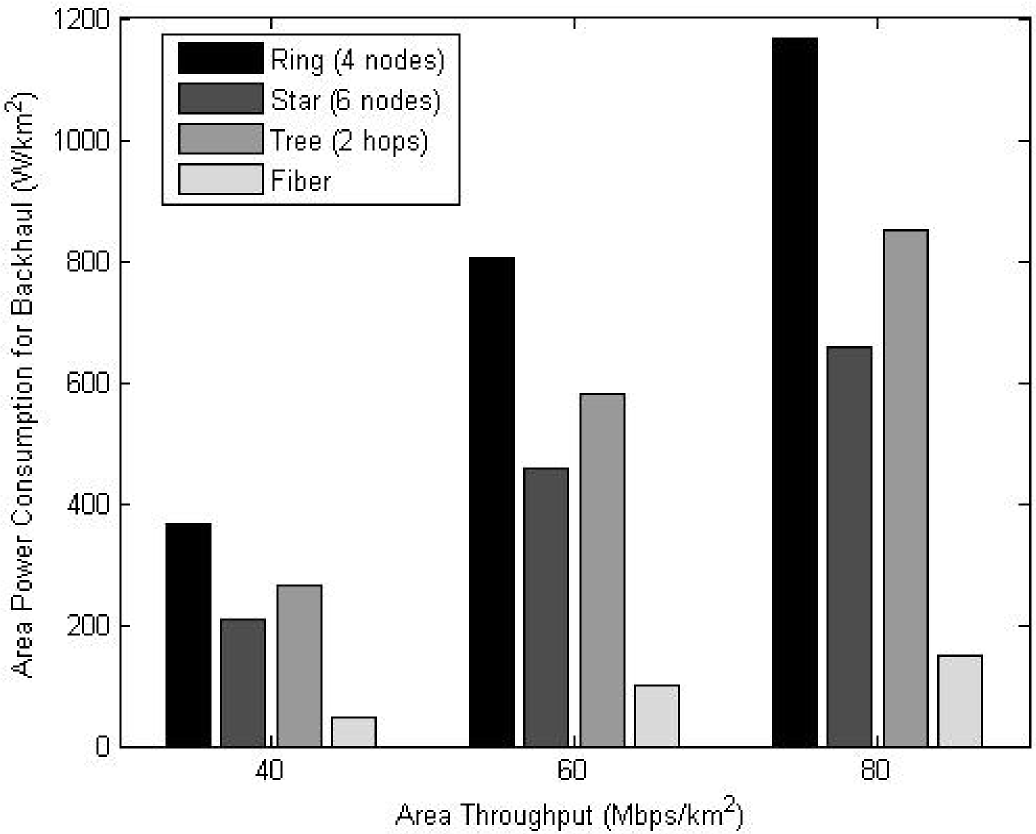
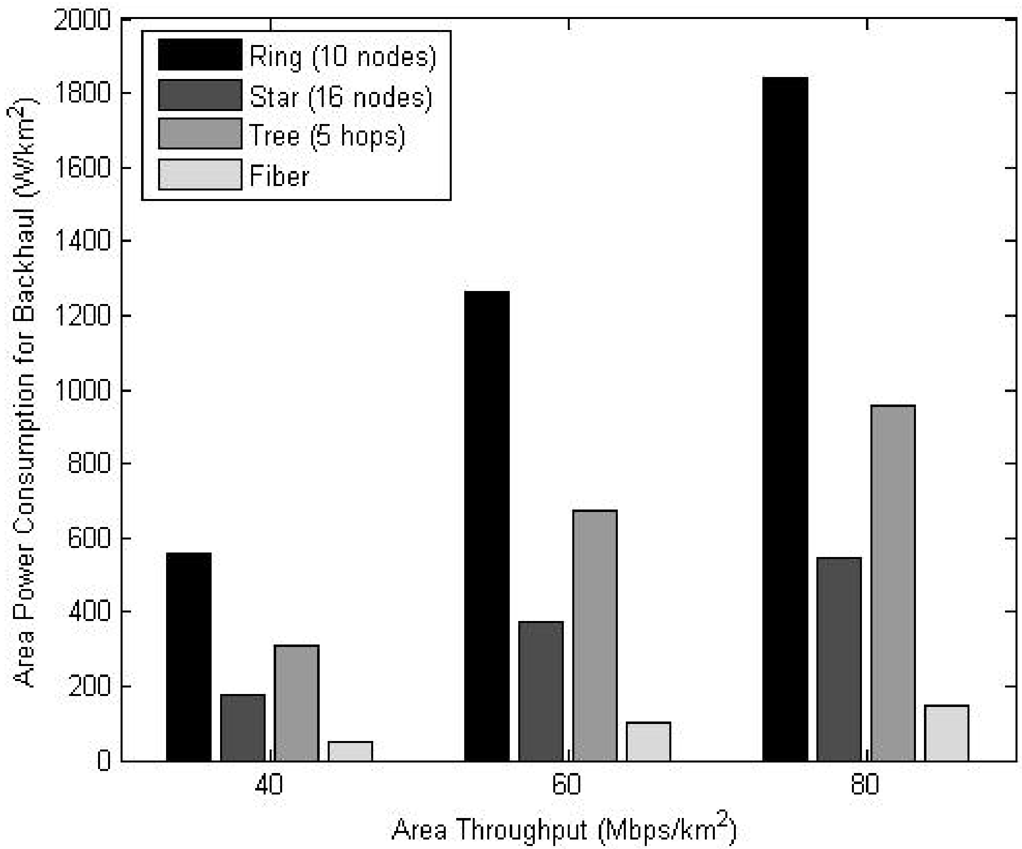
- Macro + Pico case
- Two scenarios: small size (left) and large size microwave topologies (right)





P. Monti, S. Tombaz, L. Wosinska, J. Zander, "Mobile Backhaul in Heterogeneous Network Deployments: Technology Options and Power Consumption," in Proc. **IEEE ICTON**, 2012

Backhaul impact on total network power consumption

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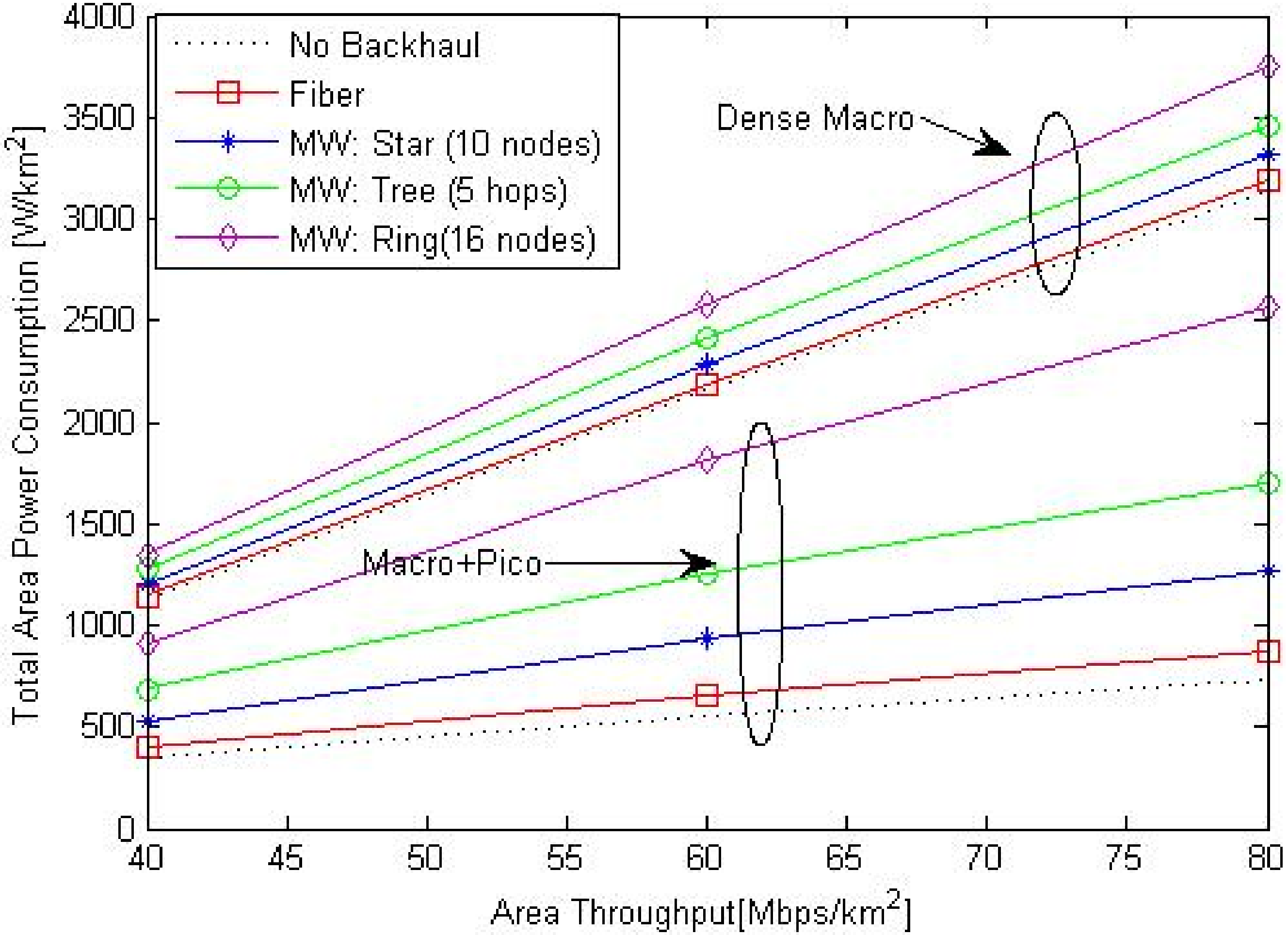
- Three scenarios: no backhaul, MW backhaul and fiber backhaul



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Conclusions

- Presented a number of research challenges triggered by energy optimization both the access and core network segment
- Energy consumption reduction is indeed important to take into account *but*
- Looking at energy only while optimizing the network segment under consideration is not sufficient anymore
- A number of trade offs are at play:
  - QoT
  - Delay
  - Cost
  - Resiliency
  - … not to mention issues derived from convergence
- Future studies can not neglect this important new dimensions

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- A. Muhammad, P. Monti, I. Cerutti, L. Wosinska, P. Castoldi, A. Tzanakaki, “Energy-Efficient WDM Network Planning with Dedicated Protection Resources in Sleep Mode,” in Proc. of IEEE Global Communication Conference (GLOBECOM), December 6-10, Miami, FL, USA, 2010
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Upcoming Workshop at ICC 2013 on Green Broadband Access
(CFP under preparation)