FiWi Access Networks: Recent Progress & Moonshot Perspectives

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I. Intro

II. Marie Curie IIF research project "Smart-FiWi-HetNets" (following CFPs)

III. Curiosity-driven research (not following CFPs)

I. Intro

Castelldefels 10 Years Ago

Canada 2014

INRS

UQ system similar to UC public university system

INRS is research arm of UQ system

INRS ranks first in Canada in terms of research intensity

What is FiWi?

"It's a typo." (Konstantinos Ntontin, CTTC)

IEEE Sub-TC FiWi – what it does & what it doesn't:

> "The Sub-TC on Fiber-Wireless Integration addresses architectures, techniques, and interfaces for the integration of fiber and wireless network segments in a unified wired-wireless infrastructure … It does not address architectures or techniques specific to individual optical or wireless networks."

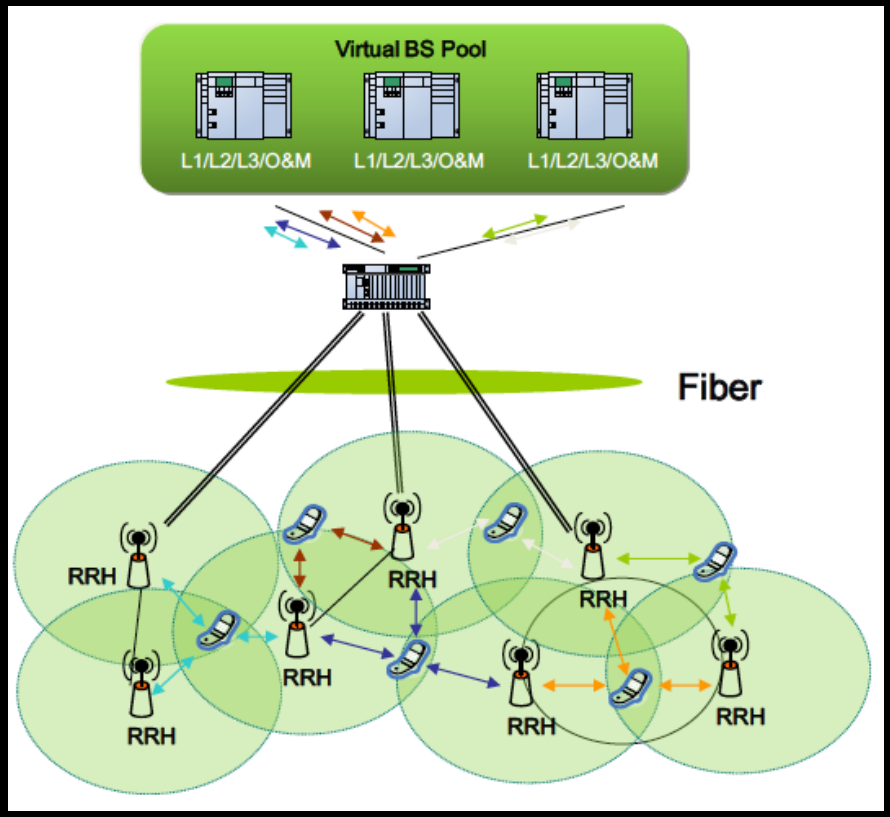
FiWi vs. RoF

RoF: Separation of BBUs & RRHs

Centralized architecture

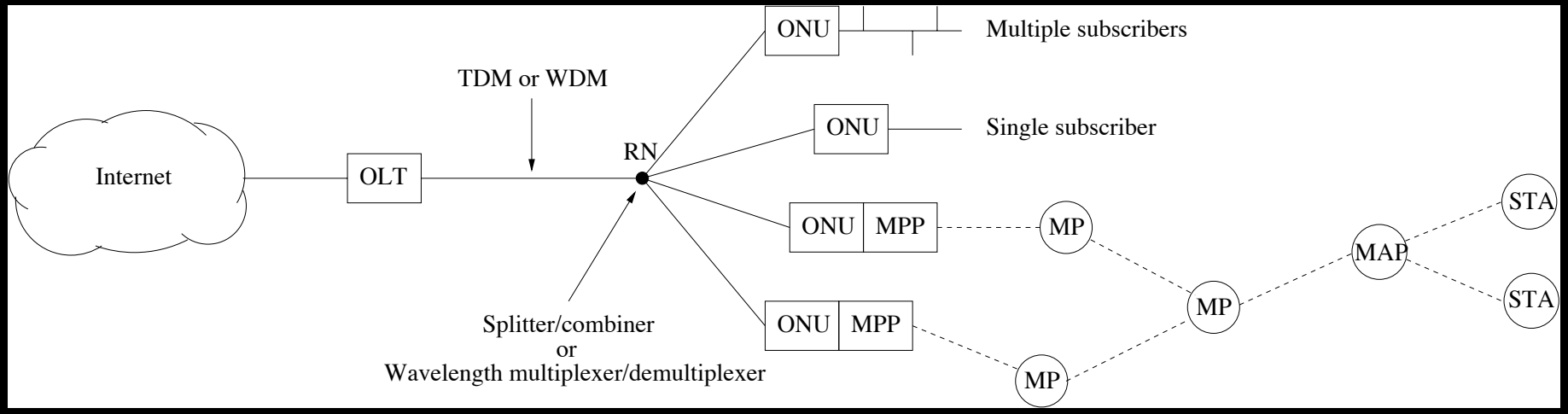
Focus on 4G cellular technologies

C-RAN



China Mobile Research Institute, "C-RAN: The Road Towards Green RAN," *White Paper*, Oct. 2011.

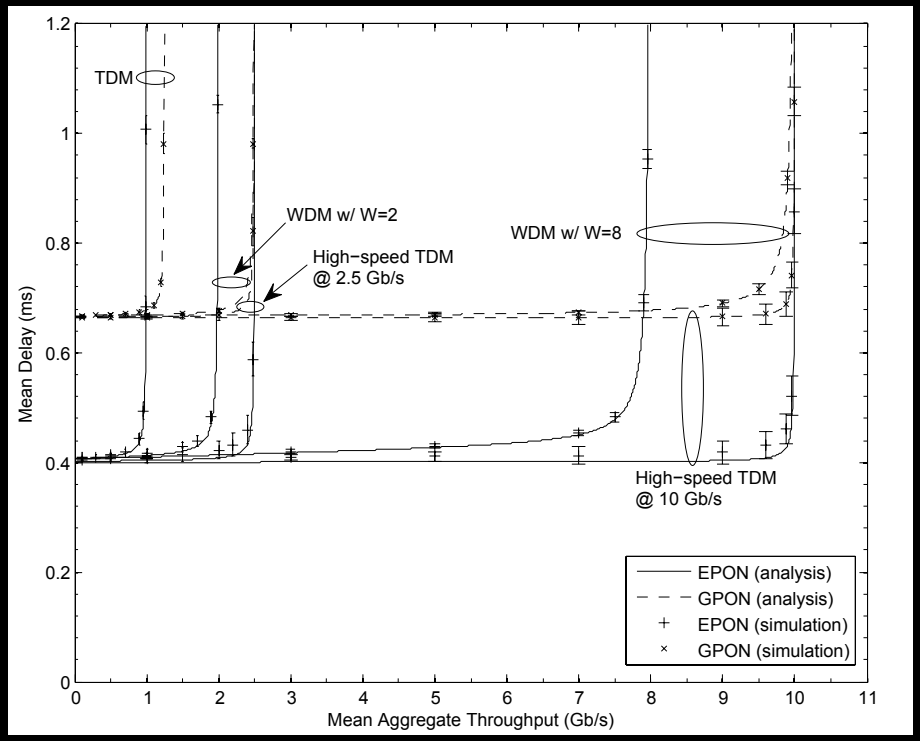
FiWi vs. RoF

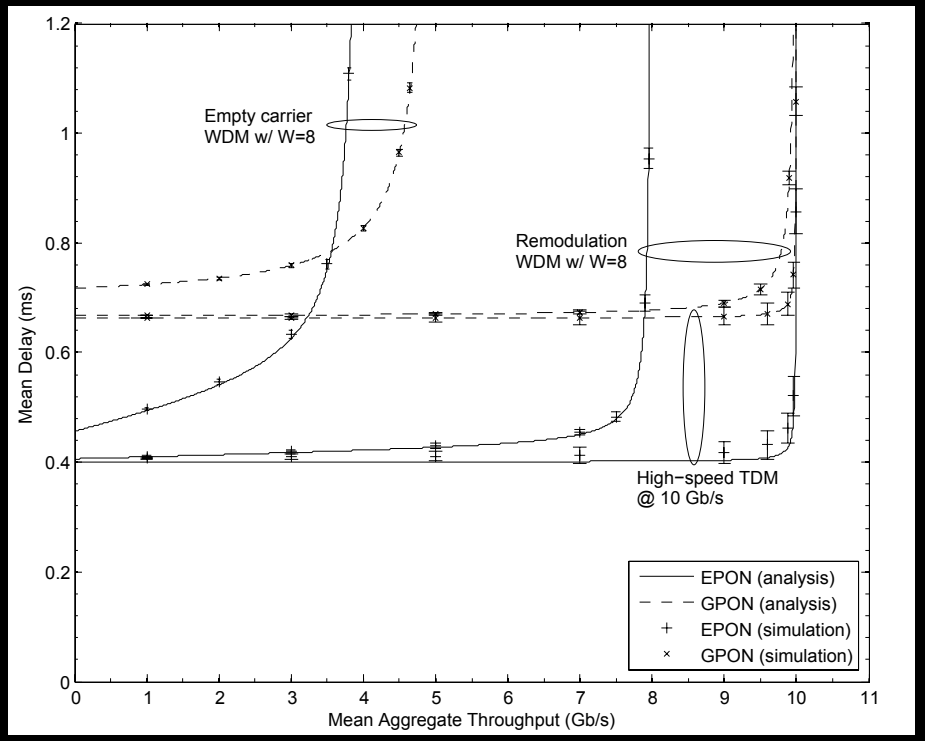


Vast majority of L2/L3 FiWi network studies focused on decentralized Ethernet technologies

- IEEE 802.3ah EPON, IEEE 802.3av 10G-EPON, WDM PON
- IEEE 802.11b/g/n/s WLAN, IEEE 802.11ac VHT WLAN

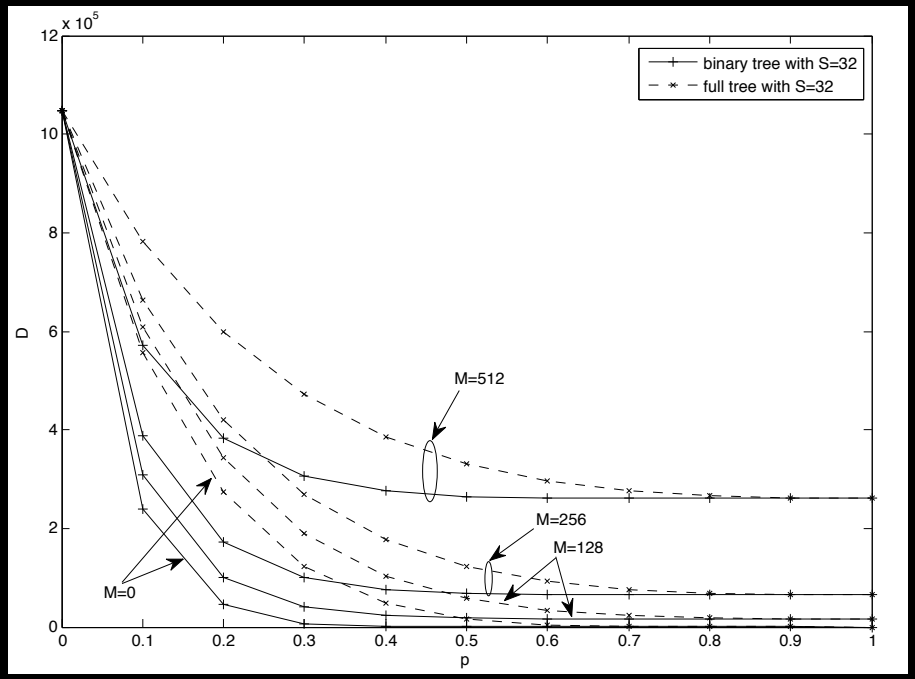
High-Speed TDM or WDM?

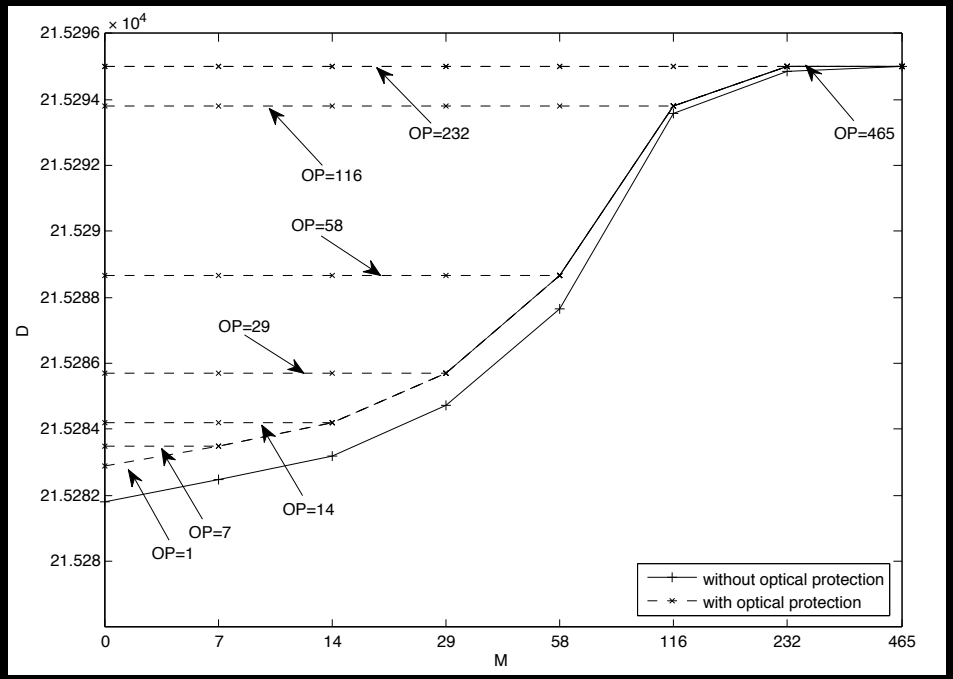




F. Aurzada, M. Scheutzow, M. Reisslein, N. Ghazisaidi, and M. Maier, "Capacity and Delay Analysis of Next-Generation Passive Optical Networks (NG-PONs)," *IEEE Transactions on Communications*, vol. 59, no. 5, pp. 1378-1388, May 2011.

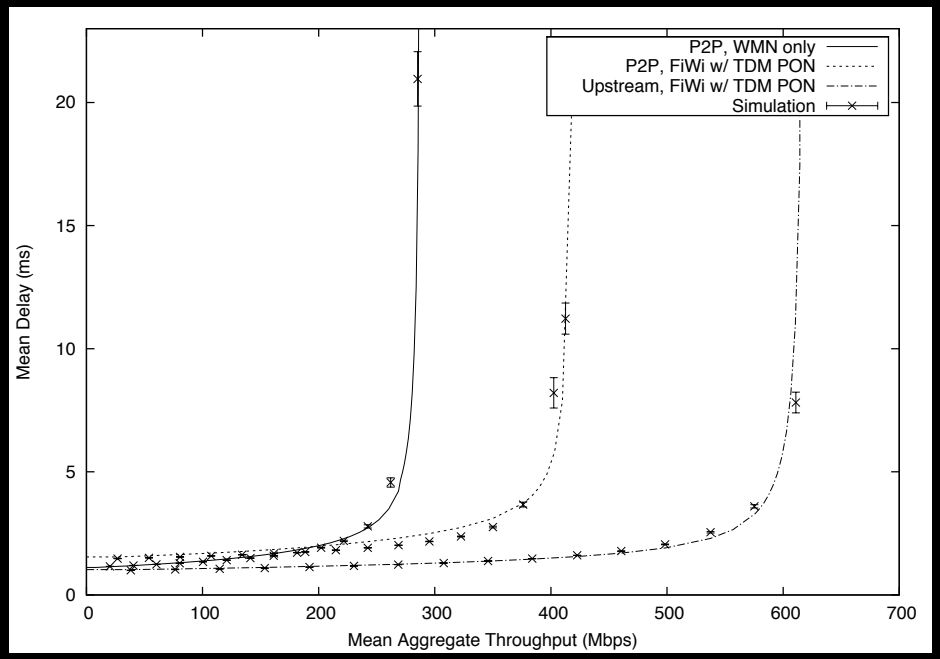
Optical or wireless protection?

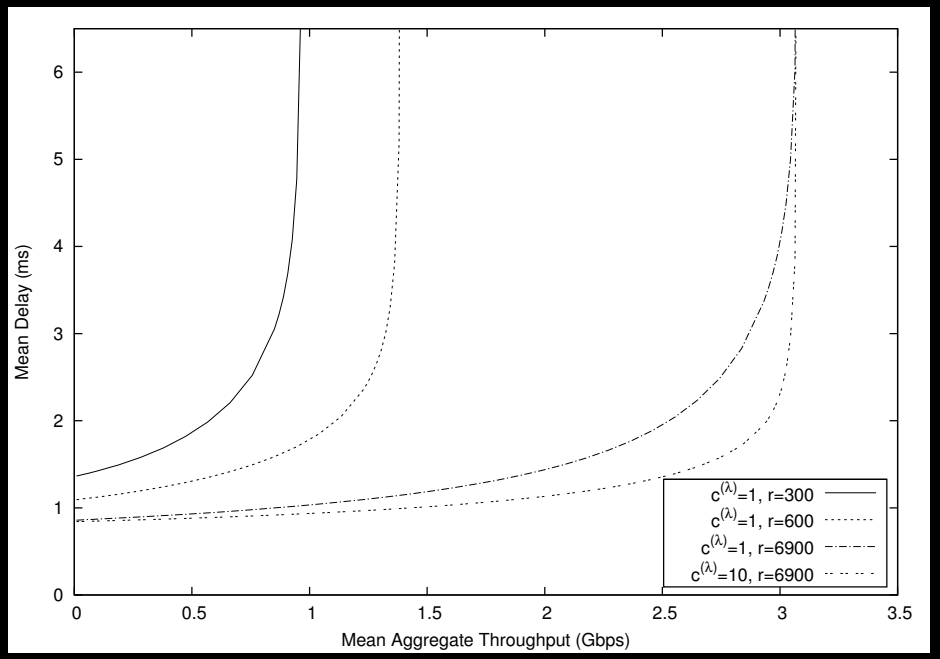




N. Ghazisaidi, M. Scheutzow, and M. Maier, "Survivability Analysis of Next-Generation Passive Optical Networks and Fiber-Wireless Access Networks," *IEEE Transactions on Reliability*, vol. 60, no. 2, pp. 479-492, June 2011.

Will VHT Wireless Do It?





F. Aurzada, M. Lévesque, M. Maier, and M. Reisslein, "FiWi Access Networks Based on Next-Generation PON and Gigabit-Class WLAN Technologies: A Capacity and Delay Analysis," *IEEE/ACM Transactions on Networking*, vol. 22, no. 4, pp. 1176-1189, Aug. 2014.

NSERC 2010

"In coming years, ICT industry will need to change its focus, becoming less an end in itself than a means to an end."

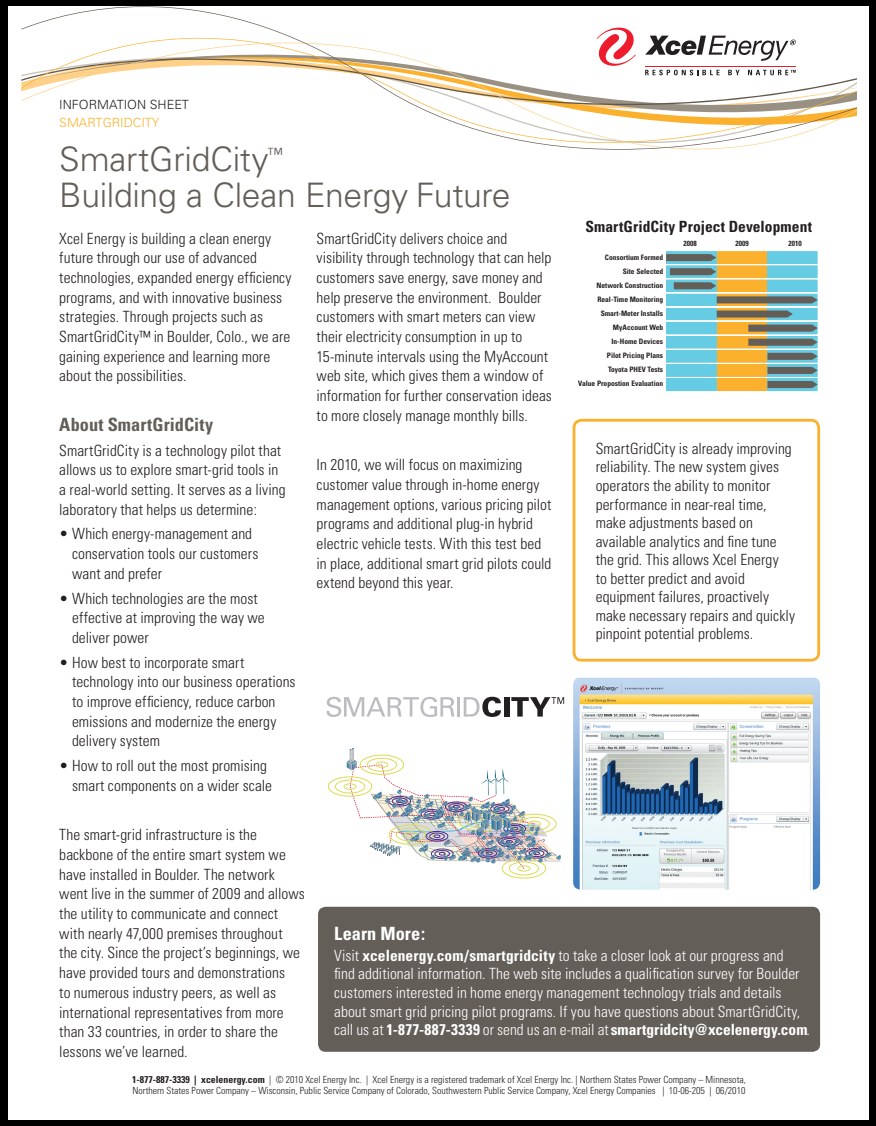
SmartGridCity

Xcel Energy ruled out

- Satellite
- Wireless
- Cable
- DSL

and relied on

- Own fiber
- BPL



Xcel Energy®
RESPONSIBLE BY NATURE™

INFORMATION SHEET
SMARTGRIDCITY

SmartGridCity™
Building a Clean Energy Future

Xcel Energy is building a clean energy future through our use of advanced technologies, expanded energy efficiency programs, and with innovative business strategies. Through projects such as SmartGridCity™ in Boulder, Colo., we are gaining experience and learning more about the possibilities.

About SmartGridCity

SmartGridCity is a technology pilot that allows us to explore smart-grid tools in a real-world setting. It serves as a living laboratory that helps us determine:

- Which energy-management and conservation tools our customers want and prefer
- Which technologies are the most effective at improving the way we deliver power
- How best to incorporate smart technology into our business operations to improve efficiency, reduce carbon emissions and modernize the energy delivery system
- How to roll out the most promising smart components on a wider scale

The smart-grid infrastructure is the backbone of the entire smart system we have installed in Boulder. The network went live in the summer of 2009 and allows the utility to communicate and connect with nearly 47,000 premises throughout the city. Since the project's beginnings, we have provided tours and demonstrations to numerous industry peers, as well as international representatives from more than 33 countries, in order to share the lessons we've learned.

SmartGridCity delivers choice and visibility through technology that can help customers save energy, save money and help preserve the environment. Boulder customers with smart meters can view their electricity consumption in up to 15-minute intervals using the MyAccount web site, which gives them a window of information for further conservation ideas to more closely manage monthly bills.

In 2010, we will focus on maximizing customer value through in-home energy management options, various pricing pilot programs and additional plug-in hybrid electric vehicle tests. With this test bed in place, additional smart grid pilots could extend beyond this year.

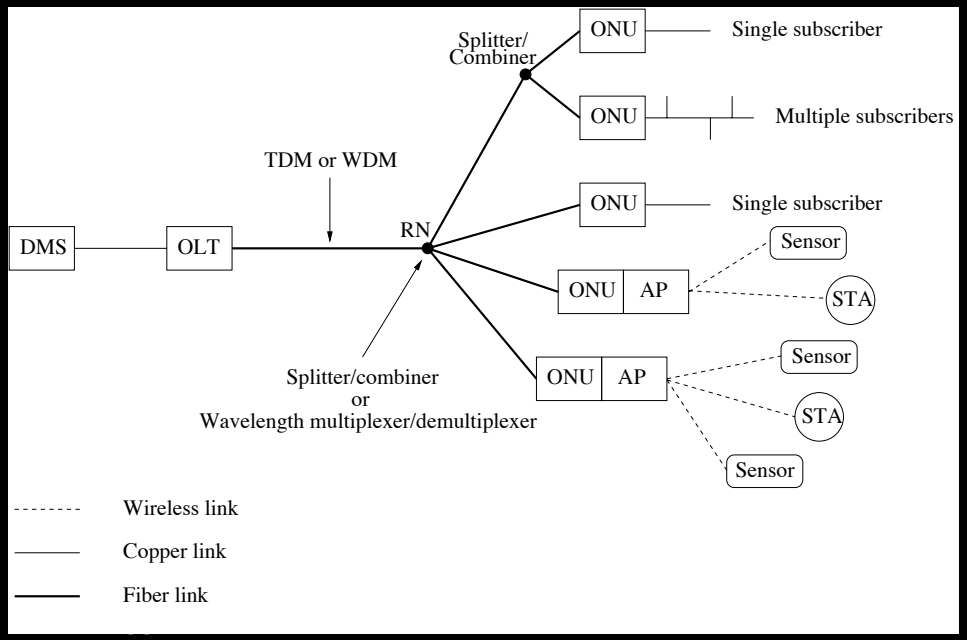
SmartGridCity Project Development

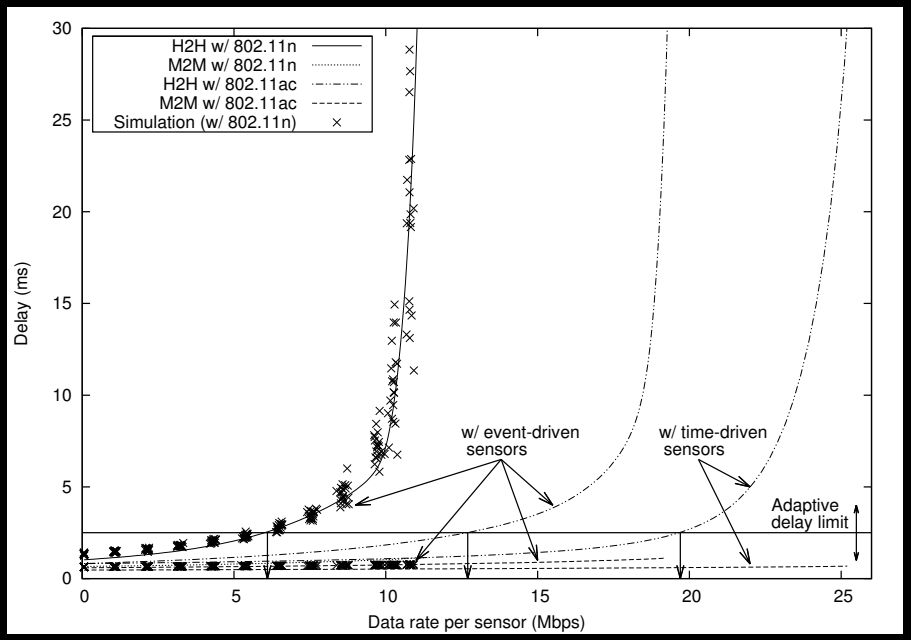
SmartGridCity is already improving reliability. The new system gives operators the ability to monitor performance in near-real time, make adjustments based on available analytics and fine tune the grid. This allows Xcel Energy to better predict and avoid equipment failures, proactively make necessary repairs and quickly pinpoint potential problems.

SMARTGRIDCITY™

Learn More:
Visit **xcelenergy.com/smartgridcity** to take a closer look at our progress and find additional information. The web site includes a qualification survey for Boulder customers interested in home energy management technology trials and details about smart grid pricing pilot programs. If you have questions about SmartGridCity, call us at **1-877-887-3339** or send us an e-mail at **smartgridcity@xcelenergy.com**.

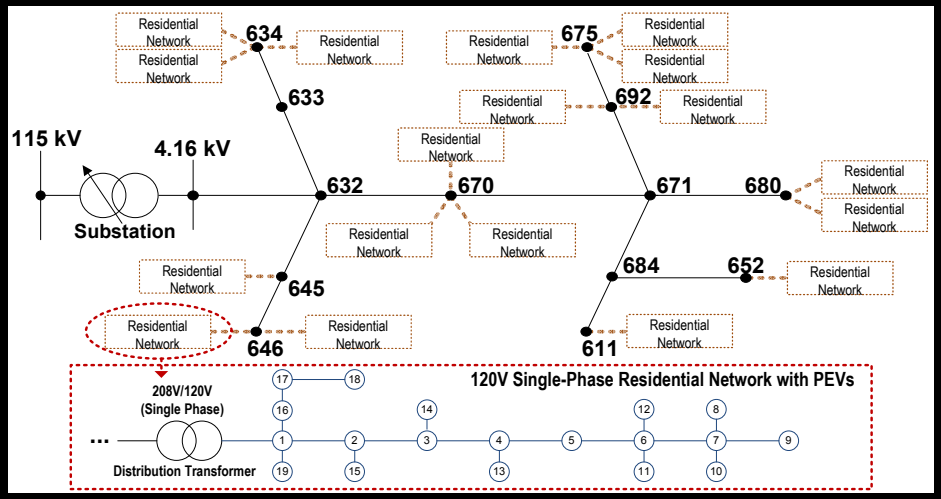
H2H & M2M Coexistence

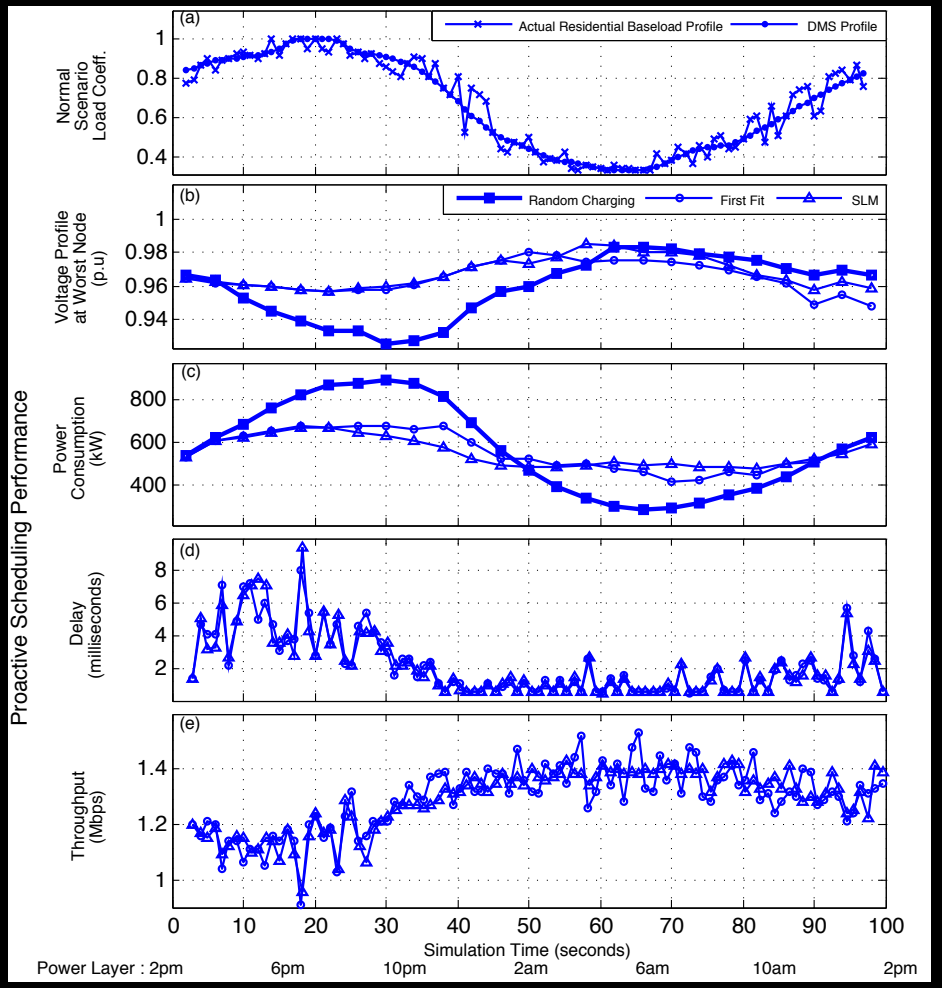




M. Lévesque, F. Aurzada, and M. Maier, "Coexistence Analysis of H2H and M2M Traffic in FiWi Smart Grid Communications Infrastructures Based on Multi-Tier Business Models," *IEEE Transactions on Communications*, vol. 62, no. 11, pp. 3931-3942, Nov. 2014.

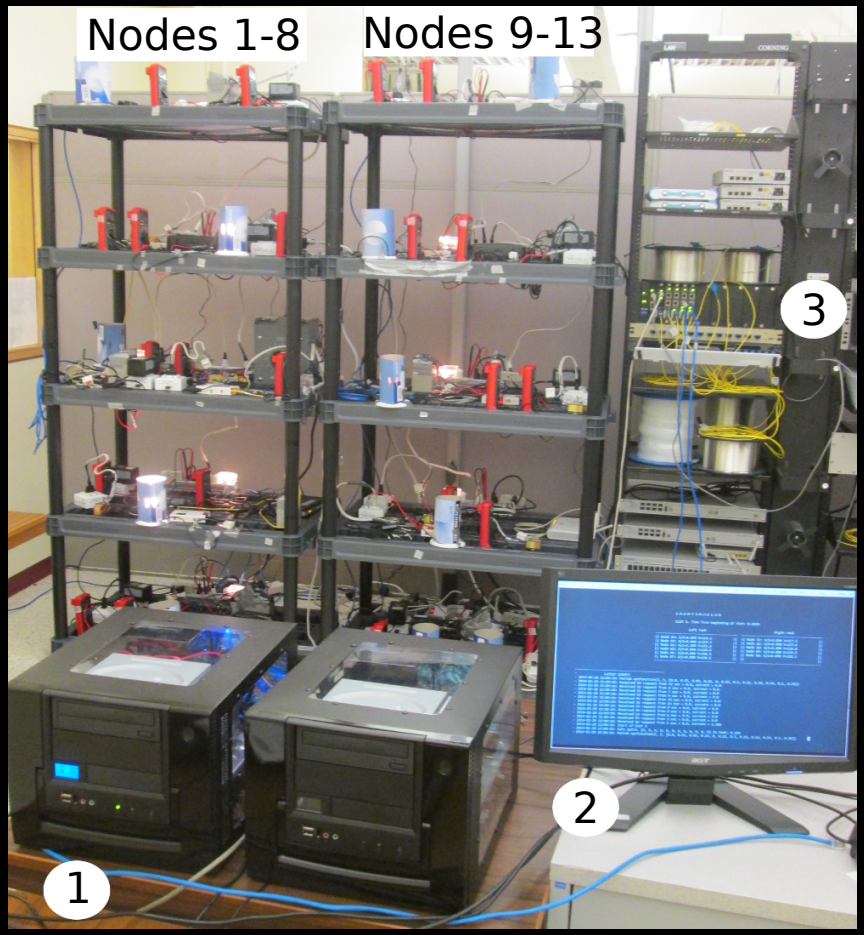
Cosimulation

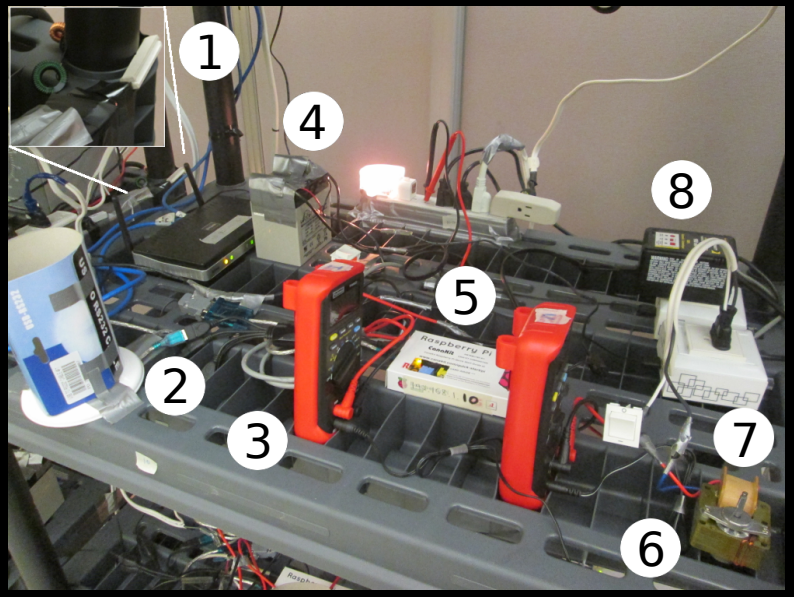




M. Maier and M. Lévesque, "Dependable Fiber-Wireless (FiWi) Access Networks and Their Role in a Sustainable Third Industrial Revolution Economy," *IEEE Transactions on Reliability*, vol. 63, no. 2, pp. 386-400, June 2014.

Smart Grid Testbed





Central EV charging coordination

Local demand response

B. P. Bhattarai, M. Lévesque, M. Maier, B. Bak-Jensen, and J. R. Pillai, "Optimizing Electric Vehicle Coordination over a Heterogeneous Mesh Network in a Scaled-down Smart Grid Testbed," *IEEE Transactions on Smart Grid*, accepted for publication.

II. Marie Curie IIF research project "Smart-FiWi-HetNets"

H. Beyranvand, M. Lévesque, M. Maier, and J. A. Salehi

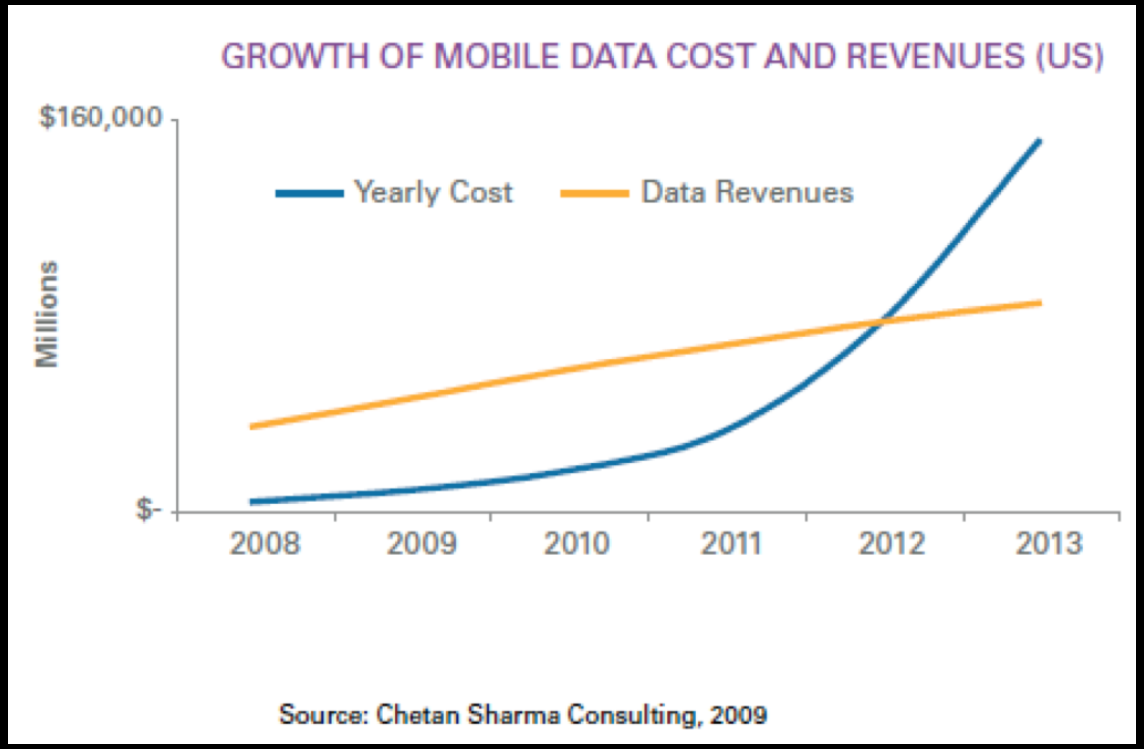
FiWi Enhanced LTE-A HetNets with Unreliable Fiber Backhaul Sharing and WiFi Offloading

Proc., IEEE INFOCOM, Hong Kong, April/May 2015

Mobile Data Traffic

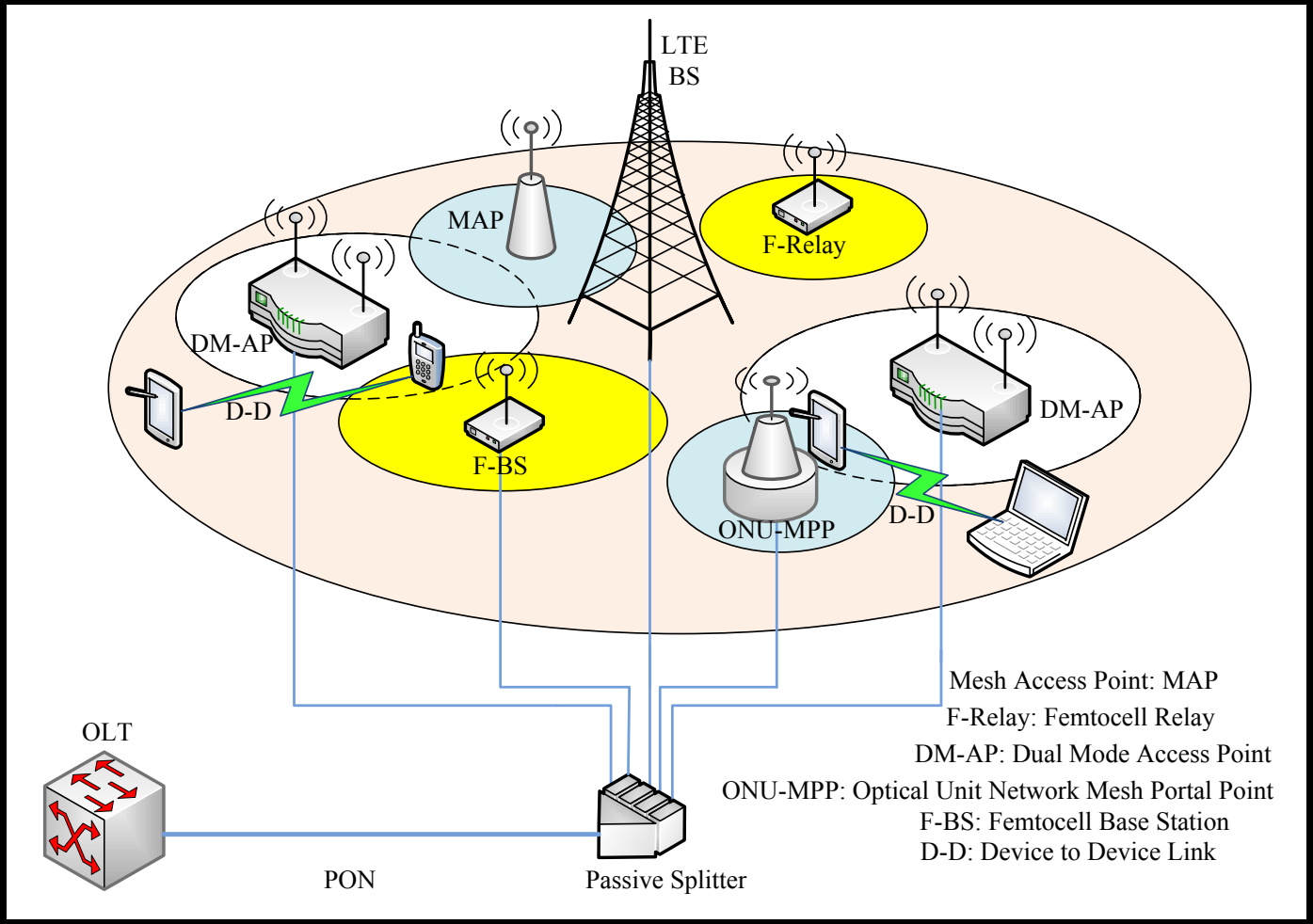
Unprecedented worldwide growth of mobile data traffic

- 13-fold increase between 2012 and 2017 (Cisco)



Bridgewater Systems, "Sharing the Load: The Value of Subscriber, Service, and Policy Control in Mobile Data Traffic Offload," June 2010.

LTE-A HetNets: Small Cells



Backhaul Latency

HetNets raise new research challenges:

- Cell association & biasing
- Mobility management
- Interference coordination
- SON
- Backhaul bottleneck

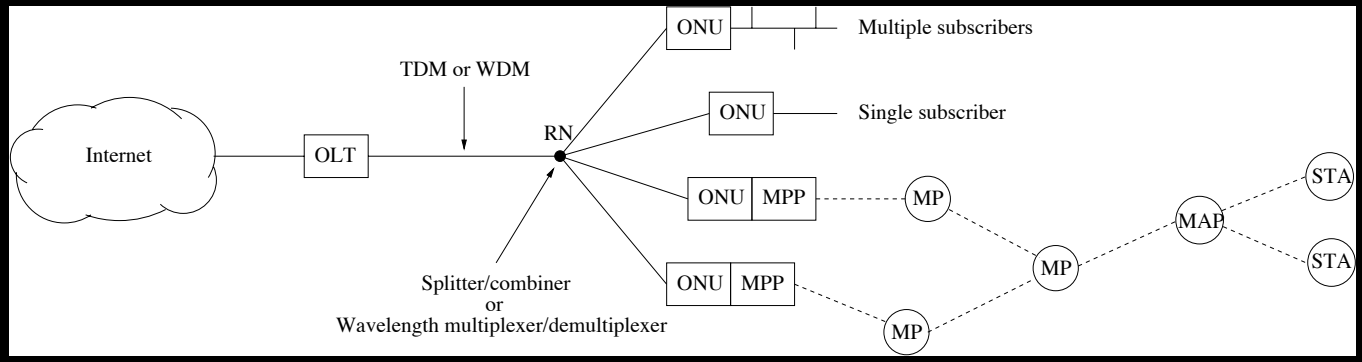
  - ✓ Most 4G LTE research focused on wireless front-end only
  - ✓ Ultimately the major factor limiting CoMP performance is latency rather than capacity of the backhaul *

* T. Biermann *et al.*, "How Backhaul Networks Influence the Feasibility of Coordinated Multipoint in Cellular Networks," *IEEE Communications Magazine*, vol. 51, no. 8, pp. 168-176, Aug. 2013.

Backhaul Reliability

Fiber backhaul sharing

- Key to cost-effective deployment & operation of small networks
  - ✓ E.g., AT&T leverages existing PON based FTTN network, right of way, and powering facilities for small cell backhaul



PONs

- Inherently low operational costs
- Reliability issues due to (typically unprotected) fiber cuts

WiFi Offloading

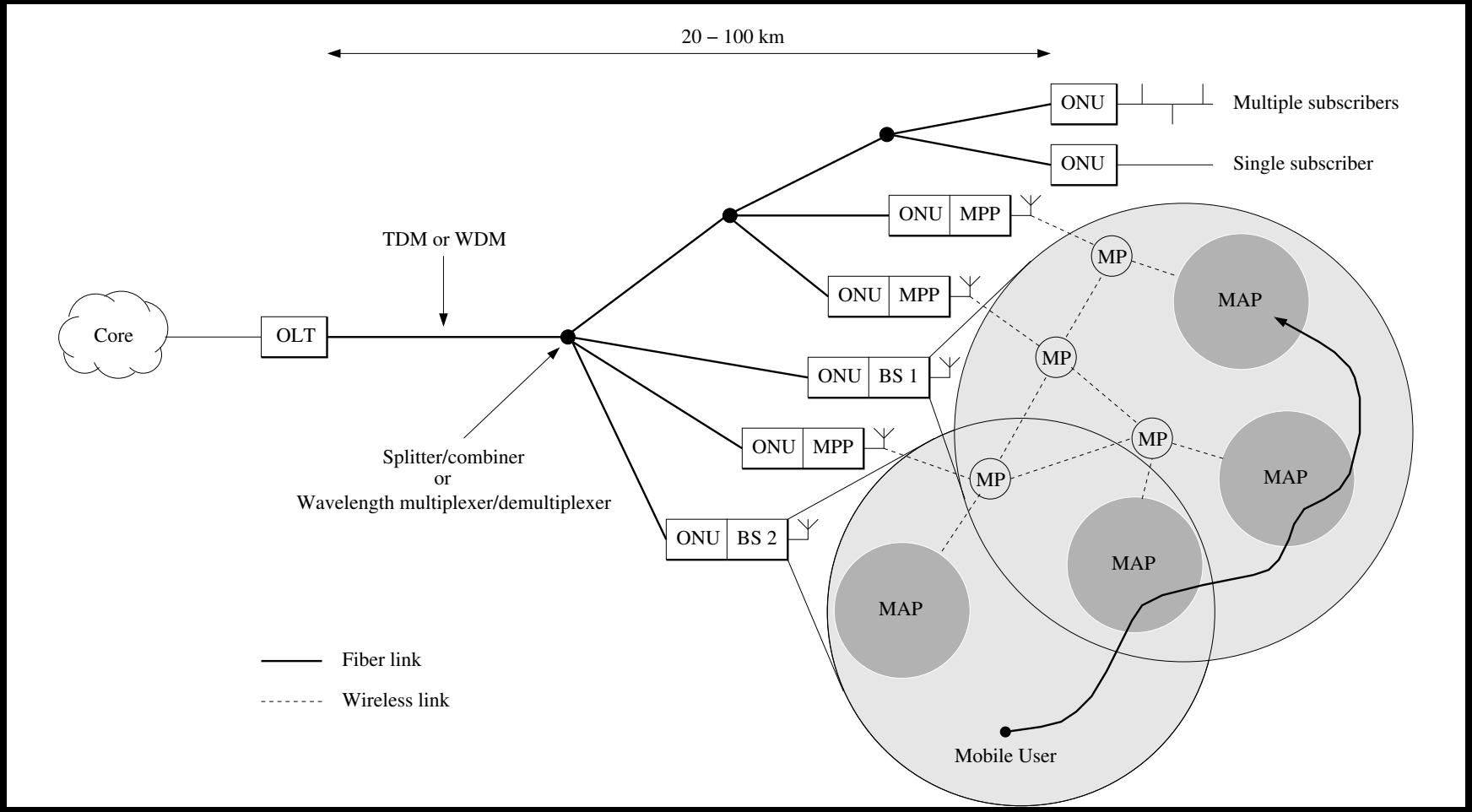
FiWi vs. 4G LTE – the bugging question:

> "Which role will data-centric Ethernet based FiWi access networks play in future mobile networks, if any?"

… and then came along WiFi offloading

- Already built-in WiFi in dual-mode (4G/WiFi) devices
- Free unlicensed WiFi bands
- Significantly less expensive than a network rollout
- Gigabit-class VHT WLAN provides higher data rates than any other wireless technology

FiWi Enhanced LTE-A HetNets



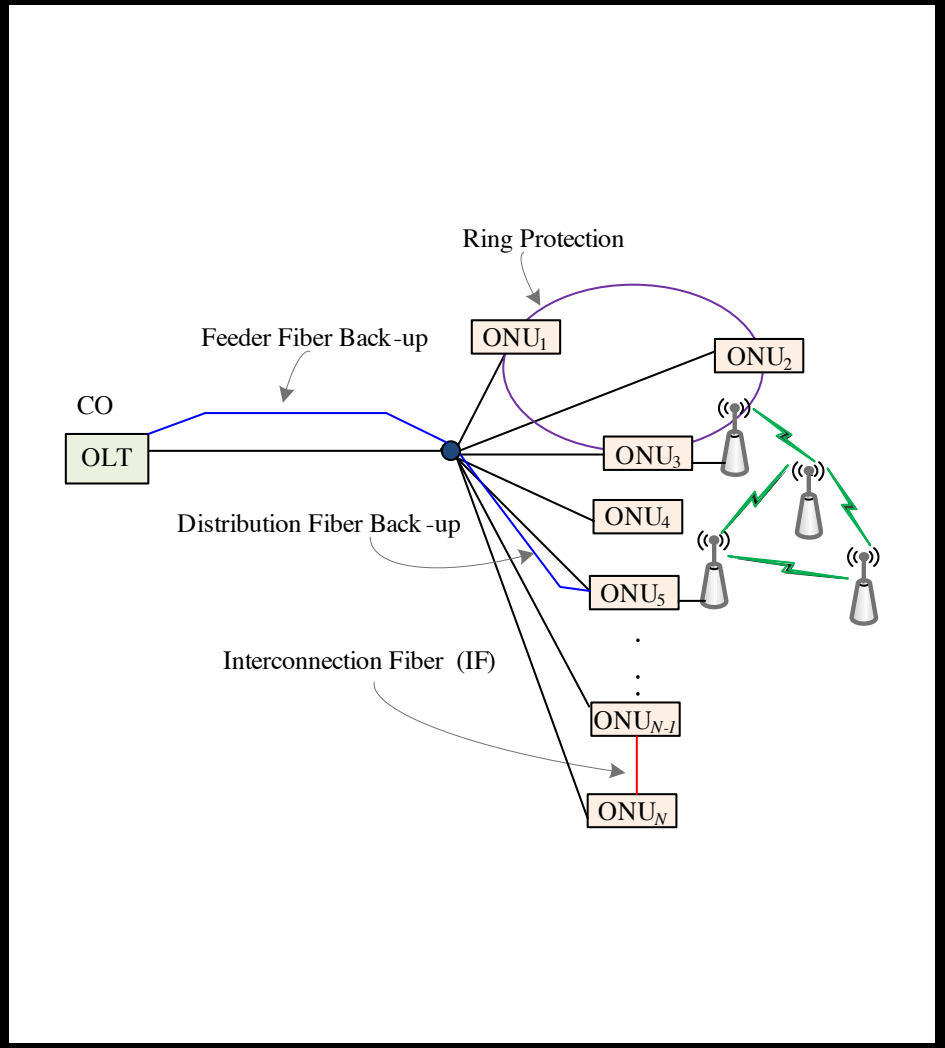
FiWi Enhanced LTE-A HetNets

Localized fiber-lean back-haul redundancy strategies

- Interconnection fiber
- Protection ring
- Inter-ONU communications

Wireless protection

- Wireless bypassing of backhaul fiber faults



Analysis

Performance metrics of interest

- FiWi connectivity
- Delay
- Maximum aggregate throughput
- Offloading efficiency

Analysis

Assumptions

- Fiber link failure probability at PON stage n:

$$p_n$$

- Wireless service outage probability of MPP, MP, and MAP:

$$P_f^{MPP}, P_f^{MP}, \text{ and } P_f^{MAP}$$

- CCDF of WiFi connection and interconnection times fits truncated Pareto distribution:

$$\frac{\alpha\gamma^{\alpha}}{1-\left(\frac{\gamma}{\nu}\right)^{\alpha}} \cdot x^{-(\alpha+1)}, \quad 0 < \gamma \leq x \leq \nu$$

Analysis

Assumptions

- Random spatial model for location of MAPs (and MUs)
  - ✓ Poisson point process with density:

$$\lambda_{MAP} \text{ (and } \lambda_{MU})$$

  - ✓ Circular spatial coverage area with radius:

$$r_{MAP}$$

- Offloading deadline
  - ✓ On-the-spot offloading: $d = 0$
  - ✓ Delayed offloading: $d \sim U(0, D)$

Analysis

Assumptions

- Traffic model and routing
  - ✓ Arbitrary traffic matrix among OLT, MUs, FWUs i and j:
    $$\mathbf{S} = (S_{ij})$$
  - ✓ Arbitrary distribution of packet length L:
    $\overline{L}$ and ς_L^2
  - ✓ Arbitrary fault-aware routing algorithm

FiWi Connectivity

Temporal FiWi connectivity probability of MU_k:

$$P_{C_{temporal}}^{MU_k} = p_{temporal}^{MAP}\left(1 - P_f^{MAP_q}\right)\left(1 - P_f^{MP_1}\right)\cdots \left(1 - P_f^{MP_l}\right)\left(1 - P_f^{MPP_y}\right) \left(1 - \prod_{\forall x | x \leftrightarrow y}\left[1 - \left(1 - \prod_{i=1}^{N_{WP(y,x)}} P_f^{Path_i^{w(y,x)}}\right)\left(1 - P_f^{ONU_x}\right)\right]\right)$$

FiWi Connectivity

Spatial FiWi connectivity probability of MU_k:

$$P_{C_{spatial}}^{MU_k} = \left(1 - \left(\frac{A_{cell} - \pi r_{MAP}^2}{A_{cell}}\right)^{\lambda_{MAP} \cdot A_{cell}}\right)$$
$$\left(1 - P_f^{MAP_q}\right)\left(1 - P_f^{MP_1}\right)\cdots\left(1 - P_f^{MP_l}\right)\left(1 - P_f^{MPP_y}\right)$$
$$\left(1 - \prod_{\forall x | x \leftrightarrow y}\left[1 - \left(1 - \prod_{i=1}^{N_{WP(y,x)}} P_f^{Path_i^{w(y,x)}}\right)\left(1 - P_f^{ONU_x}\right)\right]\right)$$

End-to-End Delay

Routing path between FWU_i and MU_j using WiFi mesh and inter-ONU communications w/o traversing OLT:

$$D^{e-e}_{FiWi-IF(FM)} = \sum_{i=1}^{N_{FP}} \left(\Phi\left(\frac{\bar{L}}{c_{PON}} \Gamma_i^{IF}, \bar{L}, \varsigma_L^2, c_{PON} \right) + \frac{\bar{L}}{c_{PON}} + \tau_i \right) + D^d_{MPP_\omega} + D^d_{MAP_\omega} + \sum_{i=1}^{N_{WP}-1} D^d_{MP_i}$$

End-to-end delay is obtained as weighted sum of the above & 9 other routing paths

Maximum Aggregate Throughput

Maximum permissible amount of traffic provided end-to-end delay remains below certain threshold D_{th}:

$$MAT = min\Big\{MAT_{LTE-A}(M) \cdot \Big(1 - WAR + \frac{WAR}{1 - WOR}\Big), MAT_{LTE-A}(M) \cdot (1 - WAR) + \frac{MAT_{WiFi}(WAR \cdot M)}{WOR}\Big\} + S_{PON}$$

WiFi availability ratio (WAR): $0 \leq WAR \leq 1$

WiFi offloading ratio (WOR): $0 \leq WOR \leq 1$

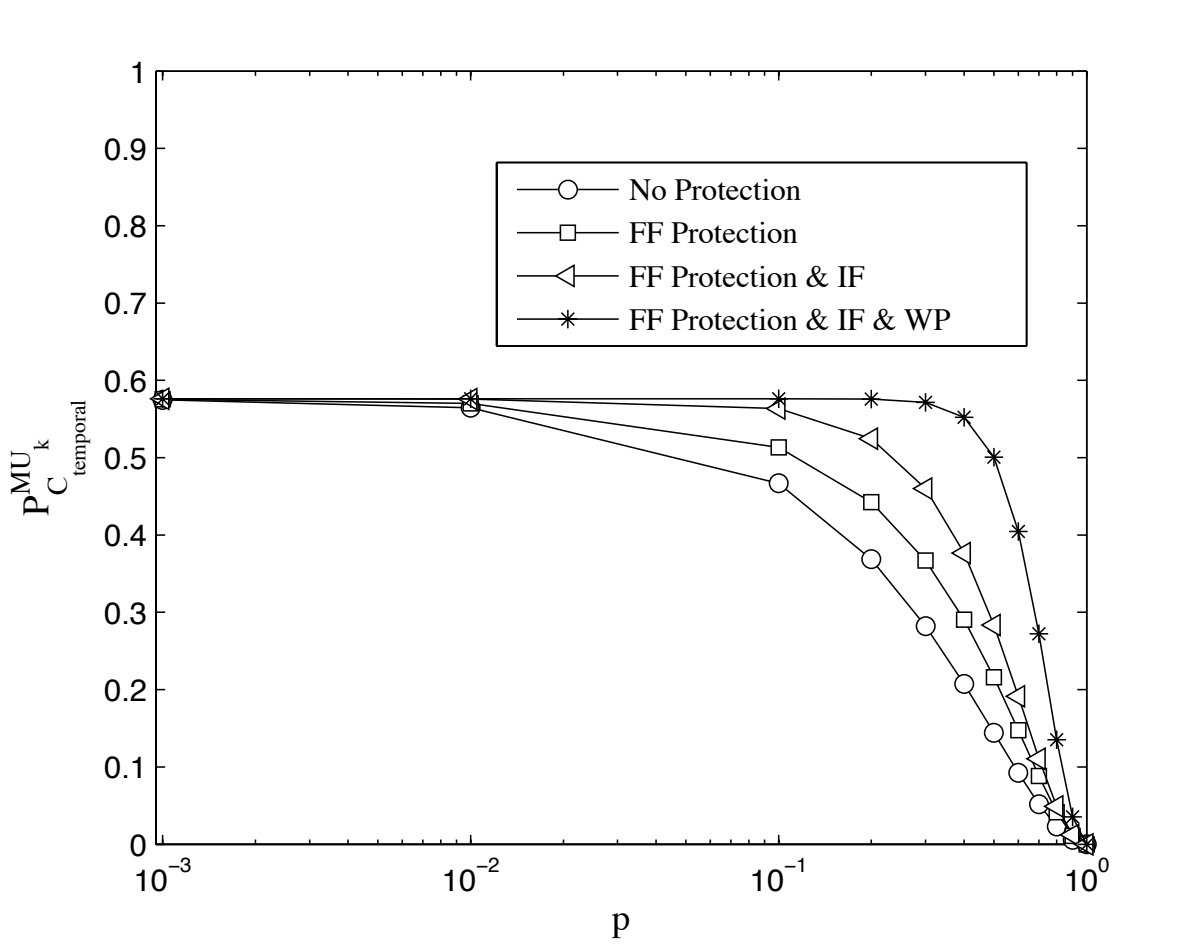
Offloading Efficiency

Ratio of bytes transferred through WiFi & total number of bytes generated by MUs:

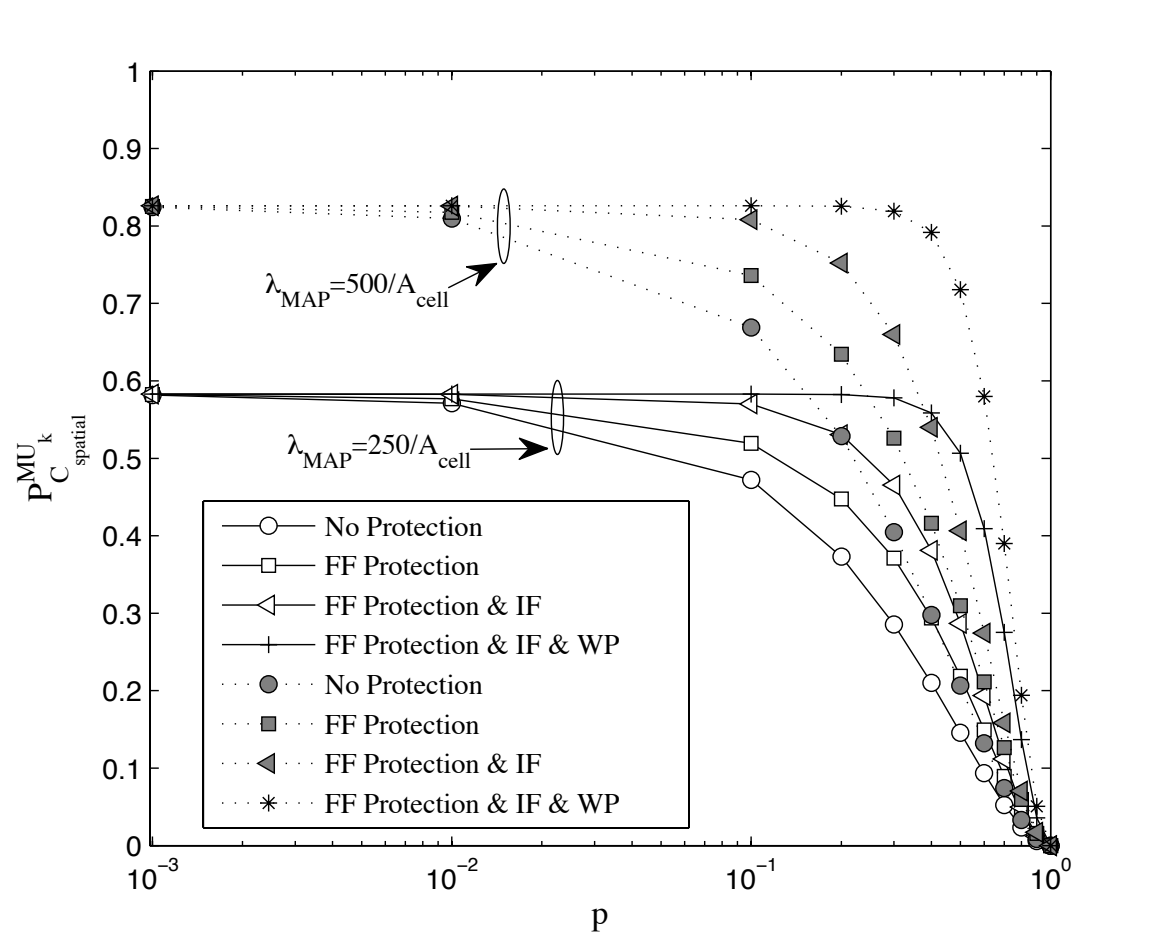
$$\eta_{off} = 1 - \frac{\sum_{k=2}^{K} \beta_k \pi_{(k,1)} + \sum_{k=1}^{K} \frac{k}{d} \pi_{(k,0)}}{\lambda}$$

WiFi interconnection & connection times exponentially distributed with rate θ_i and θ_c, respectively.

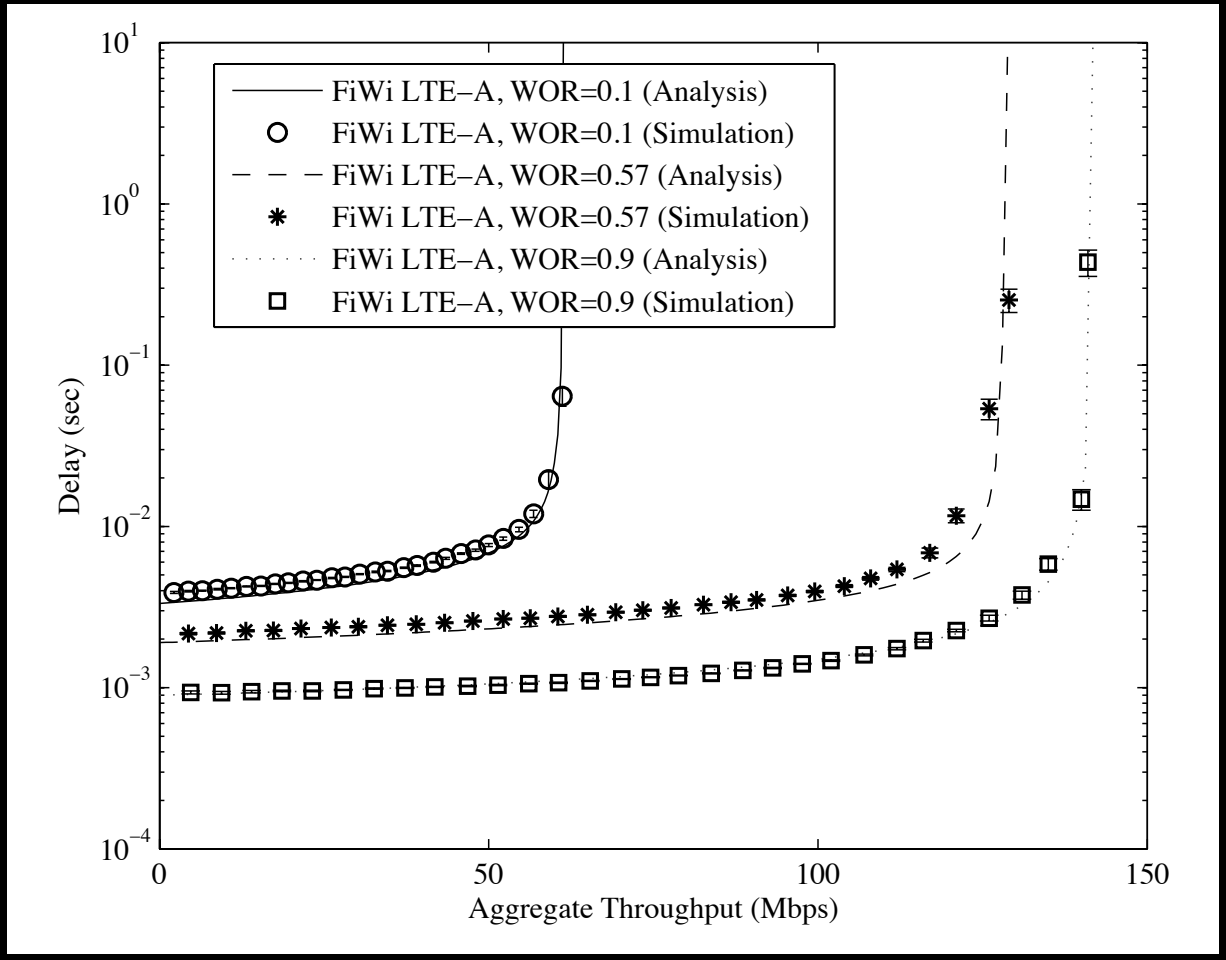
Results


No Protection
FF Protection
FF Protection & IF
FF Protection & IF & WP
$P^{MU_k}_{C_{temporal}}$
p
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-3}
10^{-2}
10^{-1}
10^{0}

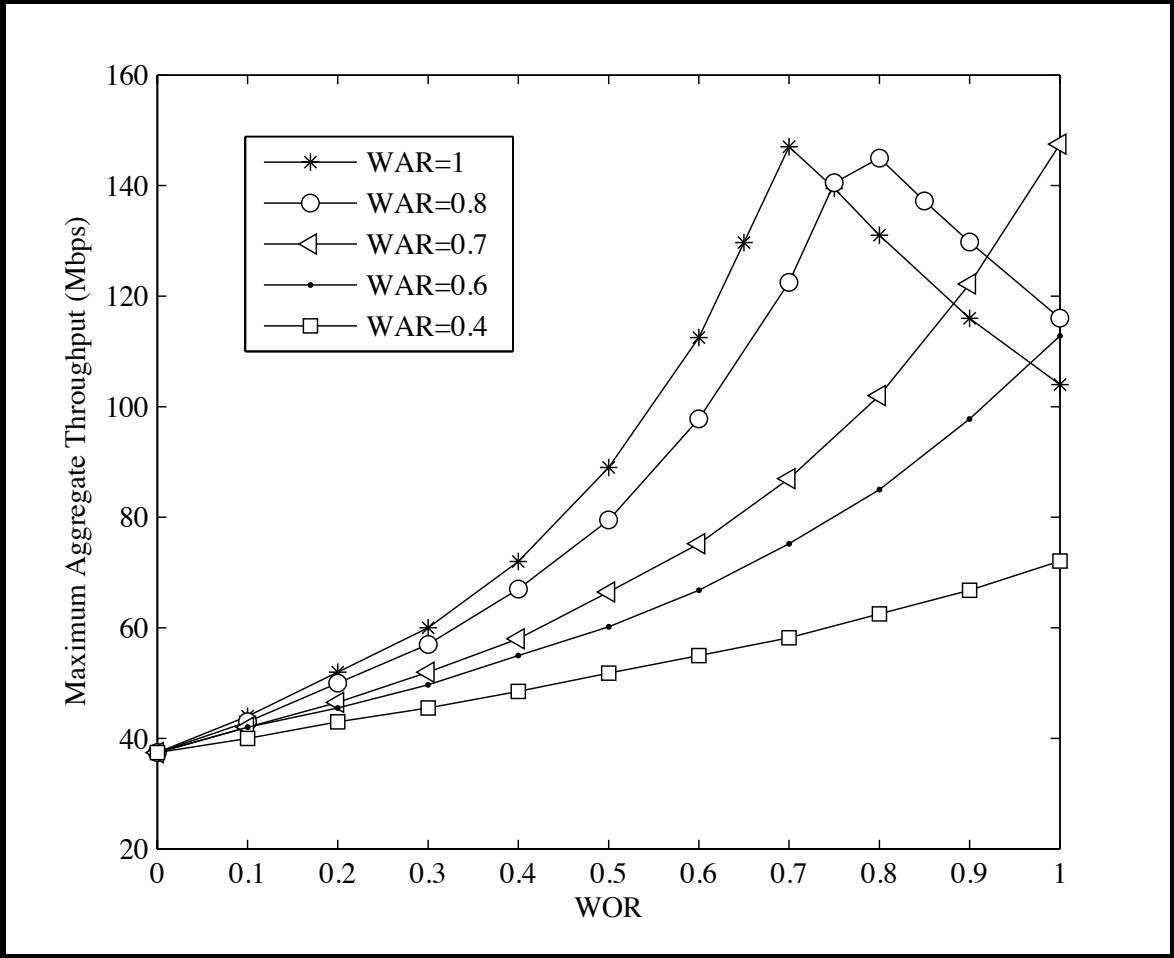
Results


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
p
$P^{MU_k}_{C_{spatial}}$
$\lambda_{MAP}=500/A_{cell}$
$\lambda_{MAP}=250/A_{cell}$
No Protection
FF Protection
FF Protection & IF
FF Protection & IF & WP
No Protection
FF Protection
FF Protection & IF
FF Protection & IF & WP

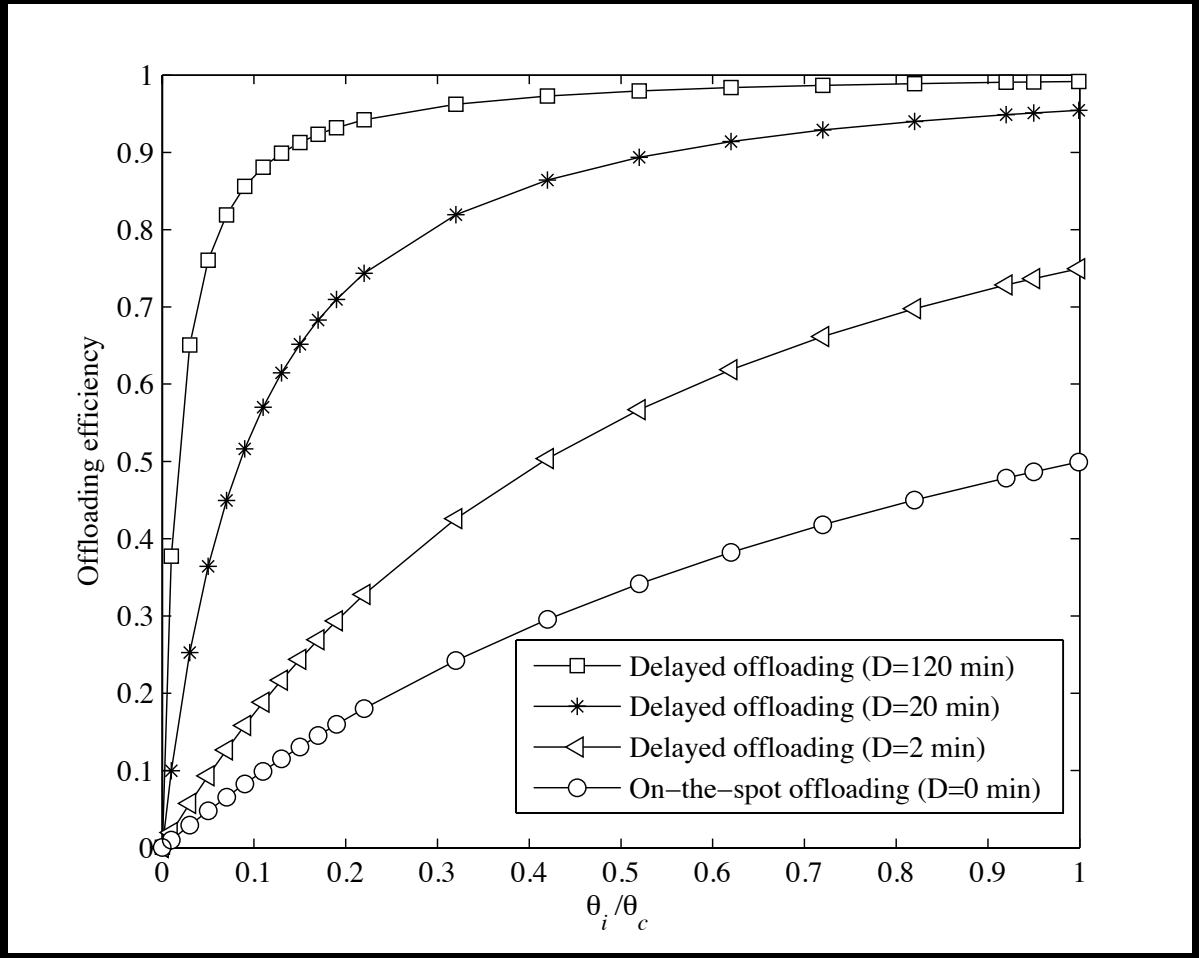
Results


FiWi LTE–A, WOR=0.1 (Analysis)
FiWi LTE–A, WOR=0.1 (Simulation)
FiWi LTE–A, WOR=0.57 (Analysis)
FiWi LTE–A, WOR=0.57 (Simulation)
FiWi LTE–A, WOR=0.9 (Analysis)
FiWi LTE–A, WOR=0.9 (Simulation)
Delay (sec)
Aggregate Throughput (Mbps)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150

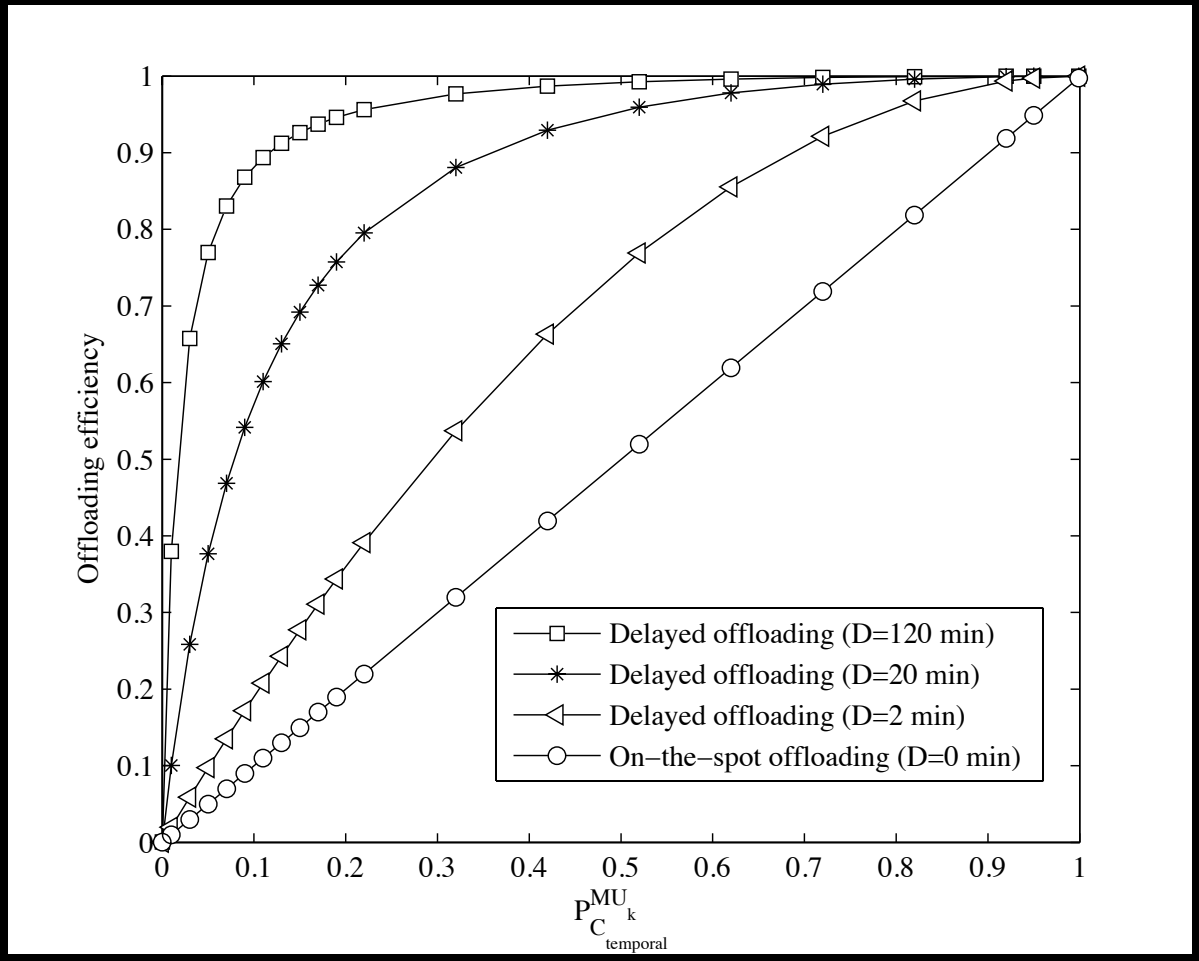
Results


Maximum Aggregate Throughput (Mbps)
WOR
WAR=1
WAR=0.8
WAR=0.7
WAR=0.6
WAR=0.4
160
140
120
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Results


Offloading efficiency
θ_i /θ_c
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Delayed offloading (D=120 min)
Delayed offloading (D=20 min)
Delayed offloading (D=2 min)
On−the−spot offloading (D=0 min)

Results


Offloading efficiency
$P_{C_{temporal}}^{MU_k}$
Delayed offloading (D=120 min)
Delayed offloading (D=20 min)
Delayed offloading (D=2 min)
On−the−spot offloading (D=0 min)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

III. Curiosity-driven research

M. Maier

FiWi Access Networks: Future Research Challenges and Moonshot Perspectives (Invited Paper)

Proc., IEEE ICC Workshops, Sydney, Australia, June 2014

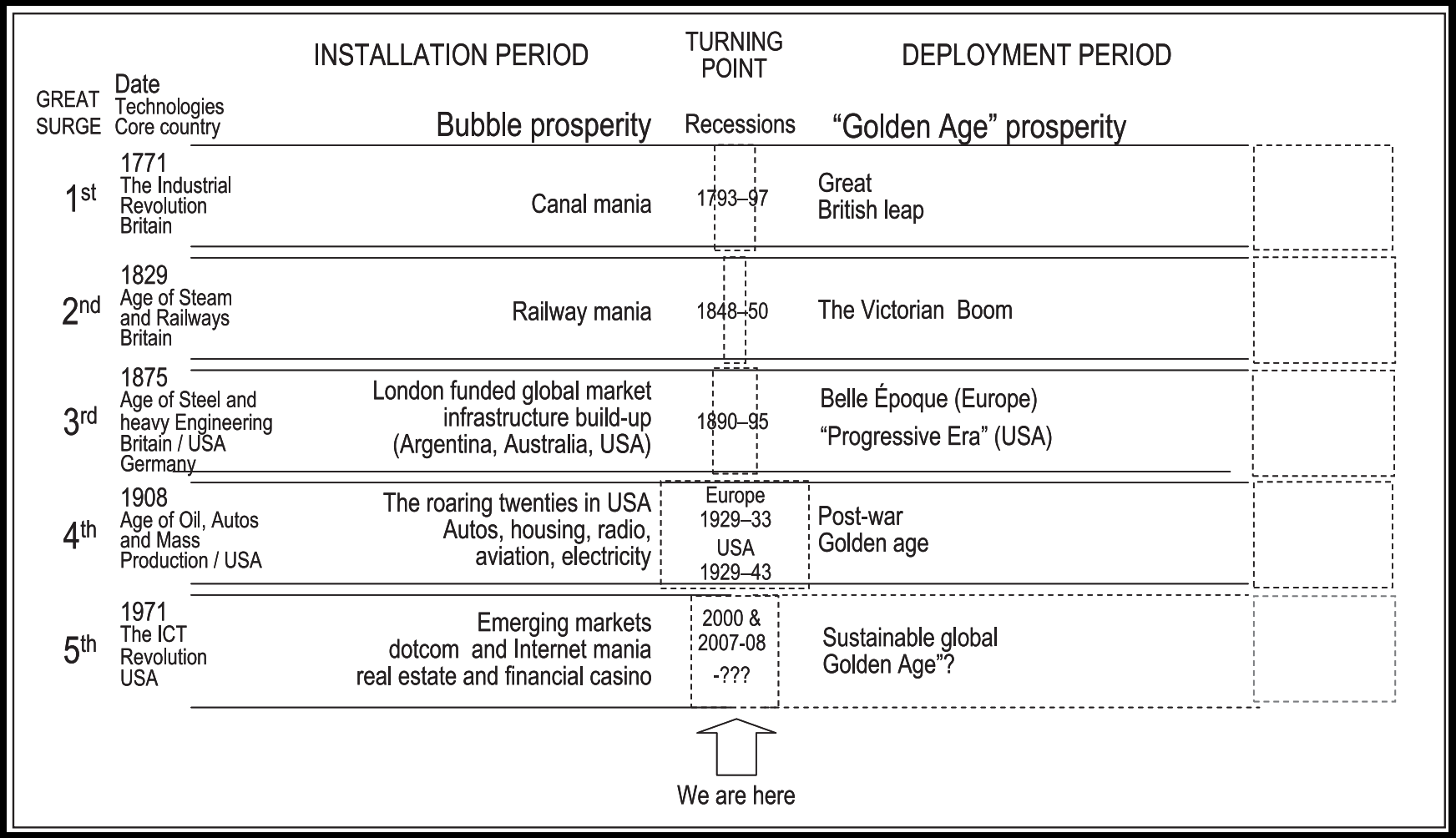
Prof. Mirzakhani Wins Fields Medal

Stanford News, Aug. 12, 2014:

"… outstanding example of curiosity-driven research"

"… the thing that really separates her, is the originality in how she puts together these disparate pieces"

Drawing Lessons From History



C. Perez, "Unleashing a golden age after the financial collapse: Drawing lessons from history," Environmental Innovation and Societal Transitions, vol. 6, pp. 9-23, March 2013.

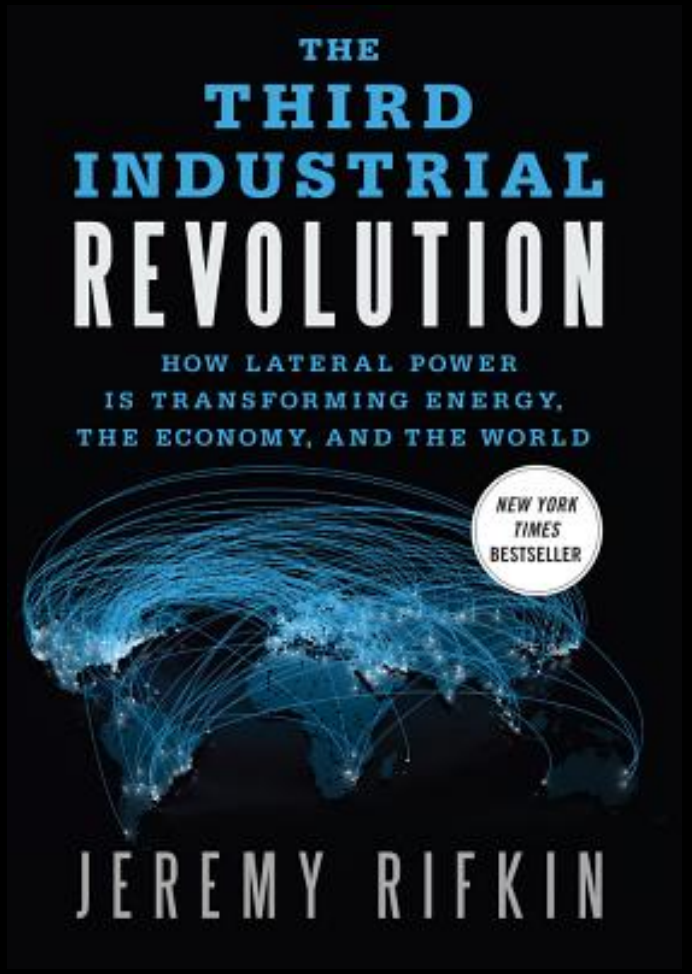
Internet of Things

The term “Internet of Things” was coined by Kevin Ashton, MIT, back in 1995.

Third Industrial Revolution

- "The Five Pillars"
  - Renewable energies
  - Positive-energy buildings
  - Energy storage technologies
  - Electric vehicles
  - Energy Internet

- Officially endorsed by EC as <u>economic growth roadmap</u> toward a competitive low carbon society by 2050



Europe 2020: EU's Growth Strategy

7 flagship initiatives to boost growth & jobs

Smart growth

- Digital agenda for Europe
- Innovation Union
- Youth on the move

Sustainable growth

- Resource efficient Europe
- An industrial policy for the globalisation era

Inclusive growth

- An agenda for new skills and jobs
- European platform against poverty

Innovation Union

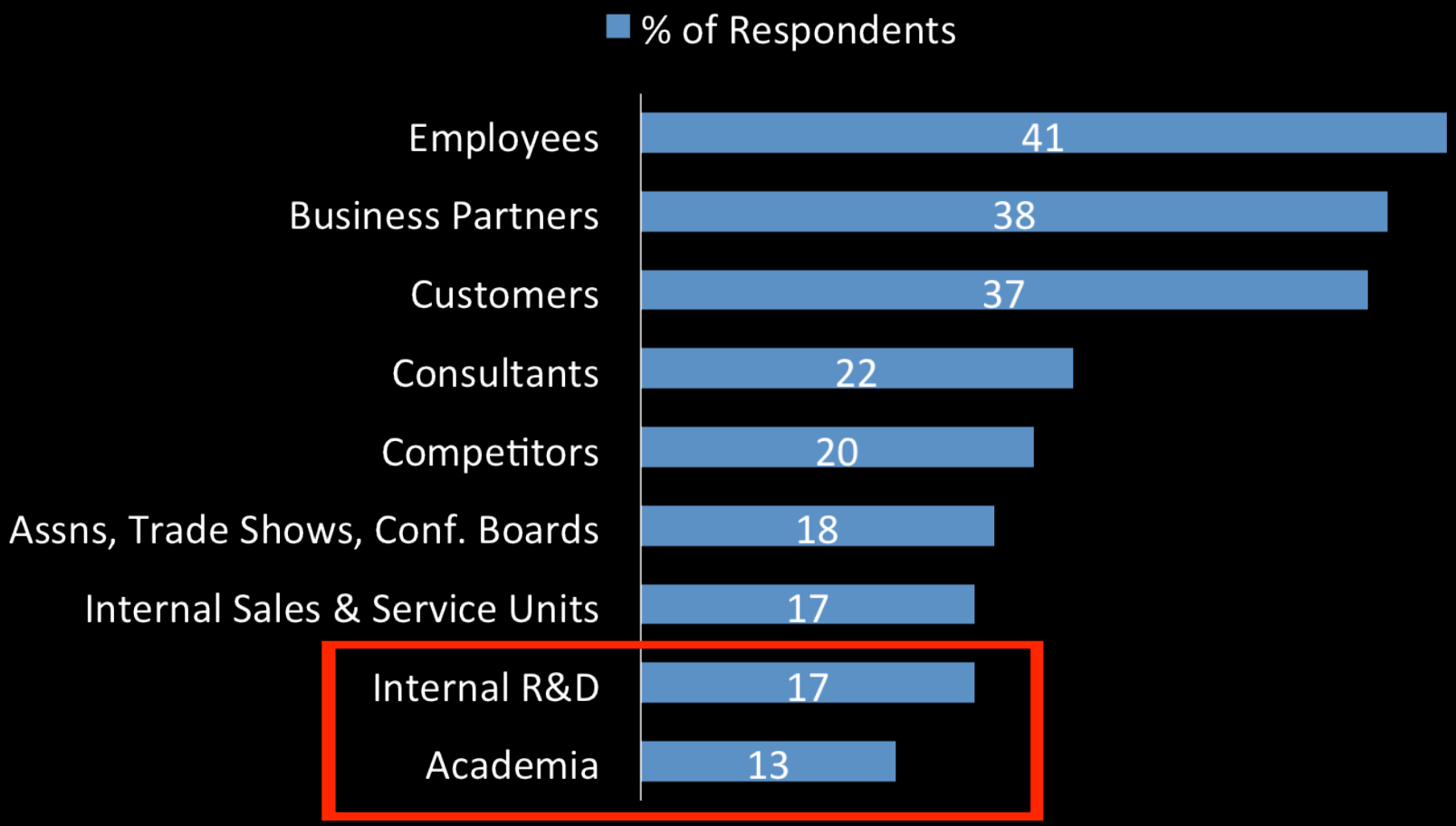
<u>European Union is turning into an Innovation Union</u>

- Innovation is the main driver of economic growth in the EU

What is Horizon 2020 ?

- Financial instrument implementing the Innovation Union
- <u>Coupling research & innovation</u>

Sources of New Ideas & Innovation



Andreas von Bechtolsheim, "The Process of Innovation," Stanford Engineering Hero Lecture, May 2012.

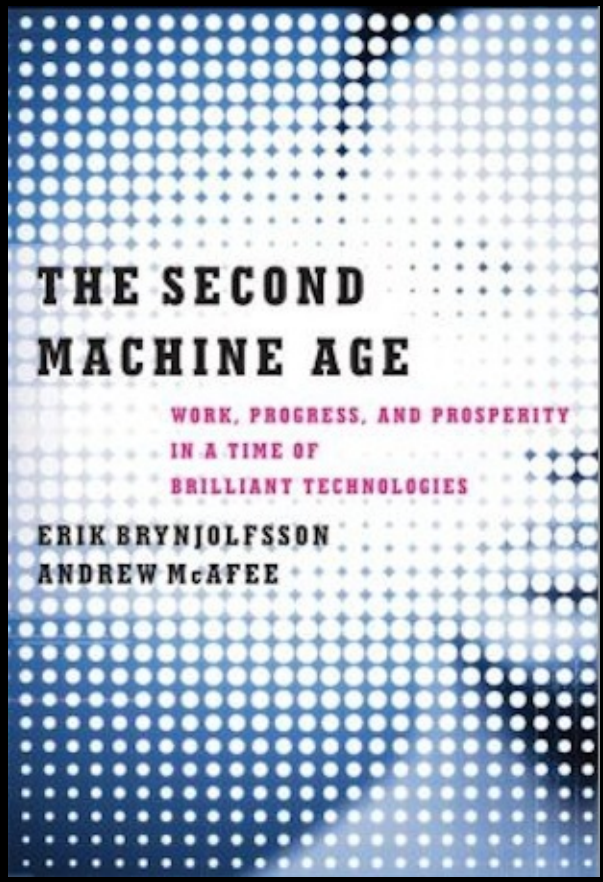
What is Innovation?

"Innovation is the market introduction of a technical or organizational novelty, not just its invention."

Joseph Alois Schumpeter (1883-1950)

How is Innovation Changing?

1) Traditional invention model
   - Incremental steps, patents, etc.
2) "From R&D to C&D"
   - Procter & Gamble, 2000:
     - Explosion of new technologies put pressure on innovation budget
     - Internal R&D productivity leveled off
     - Connect and Develop (C&D)
   - Technology briefs
3) "Recombinant innovation"
   - Rooted in New Growth Theory

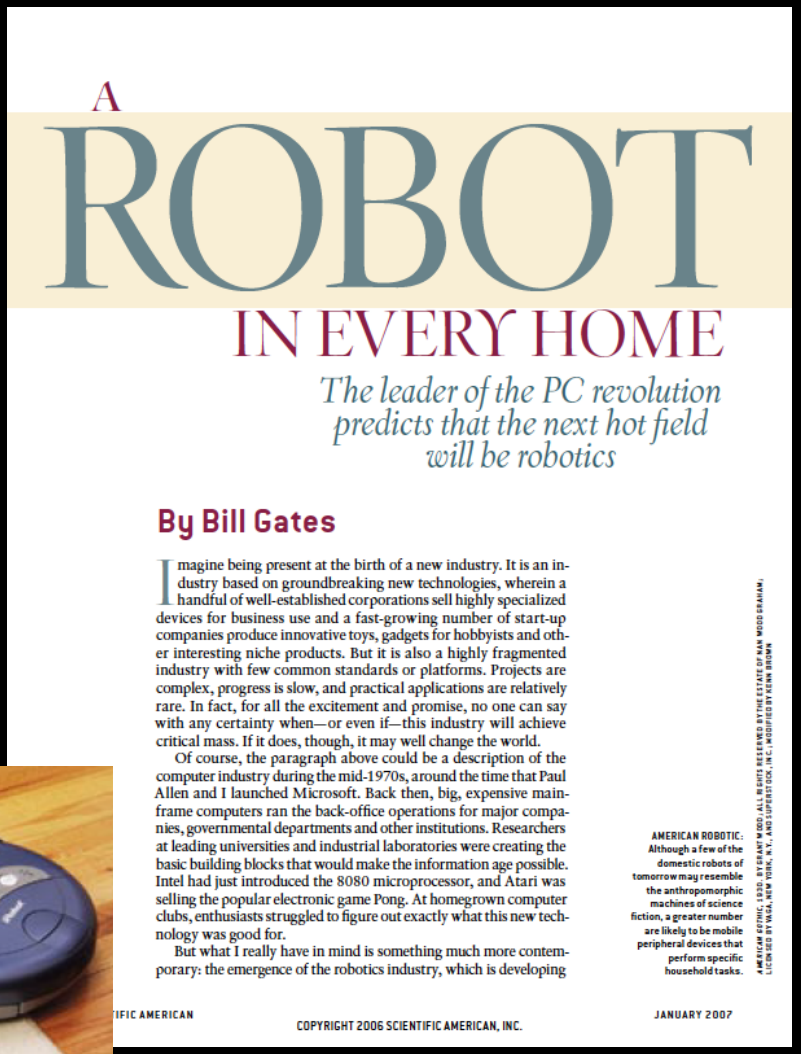


Vision: “A Robot in Every Home”

Bill Gates, Jan. 2007:

- Robotics industry is developing in much the same way as PC business did 30 years ago
- Vision: PC will get up off the desktop & allow us to see, hear, touch, and manipulate objects remotely
- FiWi connected personal/in-home computing facilities & low-cost domestic robots

iRobot Roomba



A
ROBOT
IN EVERY HOME

The leader of the PC revolution predicts that the next hot field will be robotics

By Bill Gates

Imagine being present at the birth of a new industry. It is an industry based on groundbreaking new technologies, wherein a handful of well-established corporations sell highly specialized devices for business use and a fast-growing number of start-up companies produce innovative toys, gadgets for hobbyists and other interesting niche products. But it is also a highly fragmented industry with few common standards or platforms. Projects are complex, progress is slow, and practical applications are relatively rare. In fact, for all the excitement and promise, no one can say with any certainty when—or even if—this industry will achieve critical mass. If it does, though, it may well change the world.

Of course, the paragraph above could be a description of the computer industry during the mid-1970s, around the time that Paul Allen and I launched Microsoft. Back then, big, expensive mainframe computers ran the back-office operations for major companies, governmental departments and other institutions. Researchers at leading universities and industrial laboratories were creating the basic building blocks that would make the information age possible. Intel had just introduced the 8080 microprocessor, and Atari was selling the popular electronic game Pong. At homegrown computer clubs, enthusiasts struggled to figure out exactly what this new technology was good for.

But what I really have in mind is something much more contemporary: the emergence of the robotics industry, which is developing

AMERICAN ROBOTIC: Although a few of the domestic robots of tomorrow may resemble the anthropomorphic machines of science fiction, a greater number are likely to be mobile peripheral devices that perform specific household tasks.

Reality: SoftBank Mobile's "Pepper"

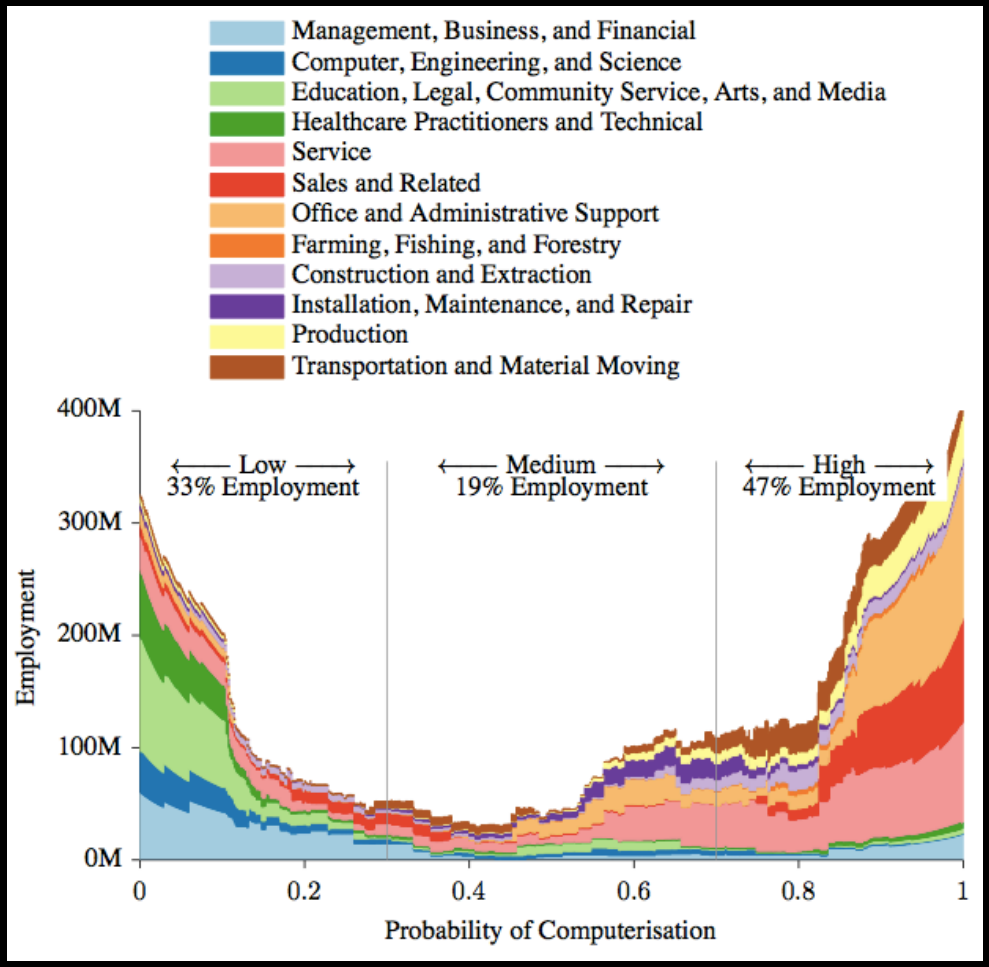
February 2015:

SoftBank Mobile starts selling humanoid robot "Pepper" (Japan & USA)

- WiFi & Cloud AI
- Open OS similar to Android
- Customization for use in health care, entertainment, and construction industries
- Long-term goal: Create a society that coexists with intelligent robots

The Future of Employment

About 47% of total US employment at high risk of being automated (over a decade or two)



C. B. Frey and M. A. Osborne, "The Future of Employment: How Susceptible Are Jobs To Computerisation?", Oxford Martin School, University of Oxford, UK, Sept. 2013.

Where Do Jobs Come From?

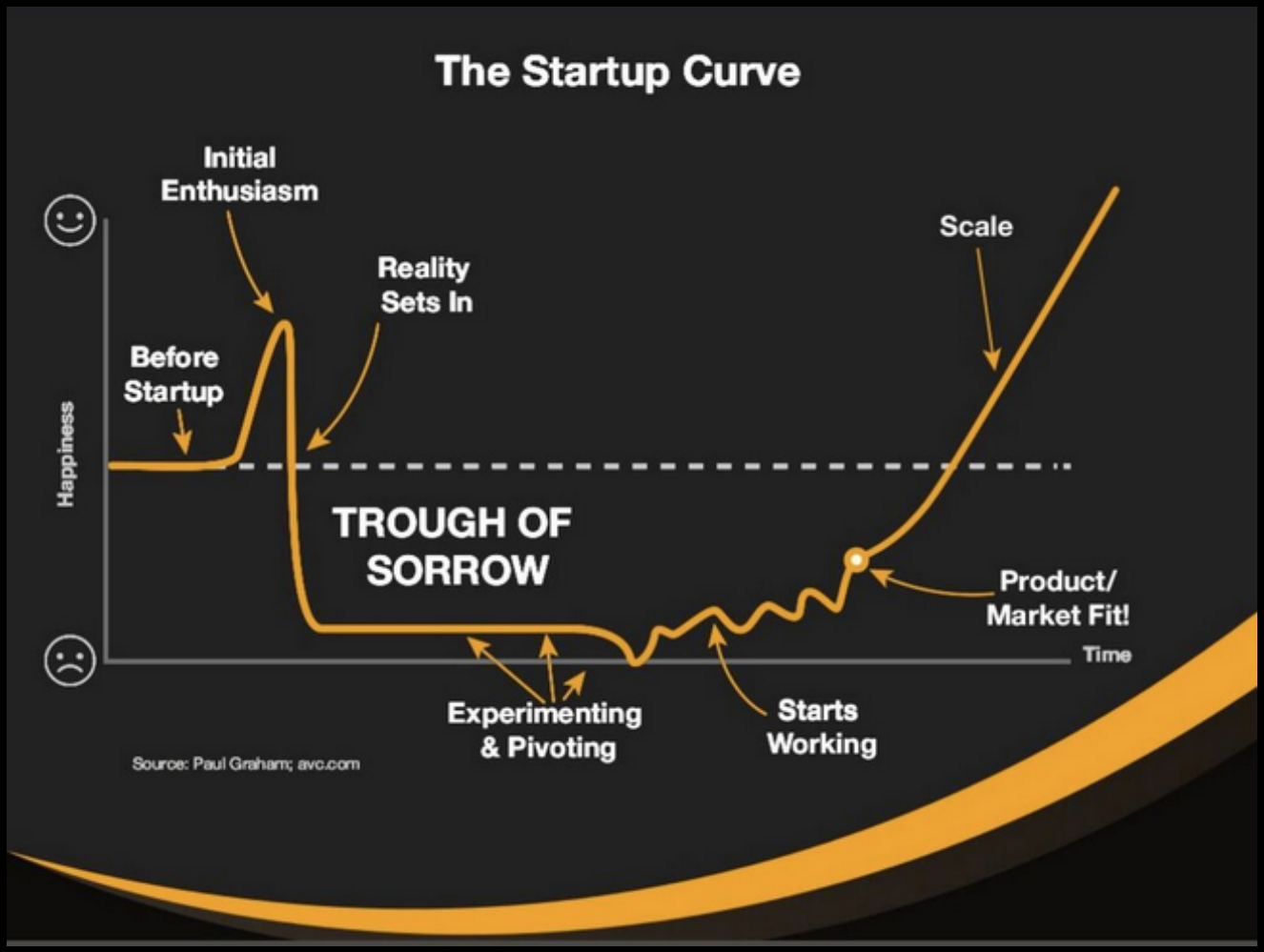
US labor statistics:

- 70% of jobs come from small businesses ≤ 500
- 50% of jobs come from small businesses ≤ 100

Gallup:

- Approximately one million small business startups per year needed in the US

Avoid the “Trough of Sorrow”



Minimum Viable Product (MVP)

Avoid risk of developing product nobody wants

Design MVP to test fundamental business hypotheses

Example: Dropbox

- Simple three-minute video narrating technology as it is meant to work & beta waiting list
- Today a $10 billion company

How Can Science Have Impact on Society?

Increased focus on public return on research investment:

R&D

- Create startups!

Academia

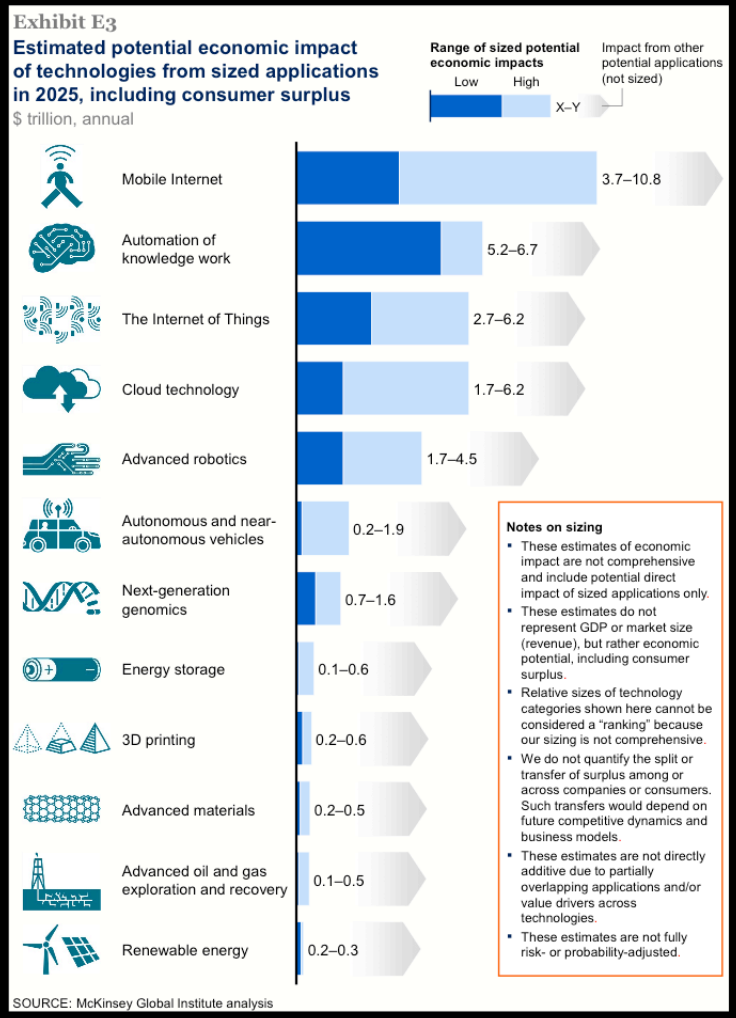
- Create wild ideas & PhD-Entrepreneurs!

Technologies with Economic Impact

The 5 technologies with highest economic impact in 2025:

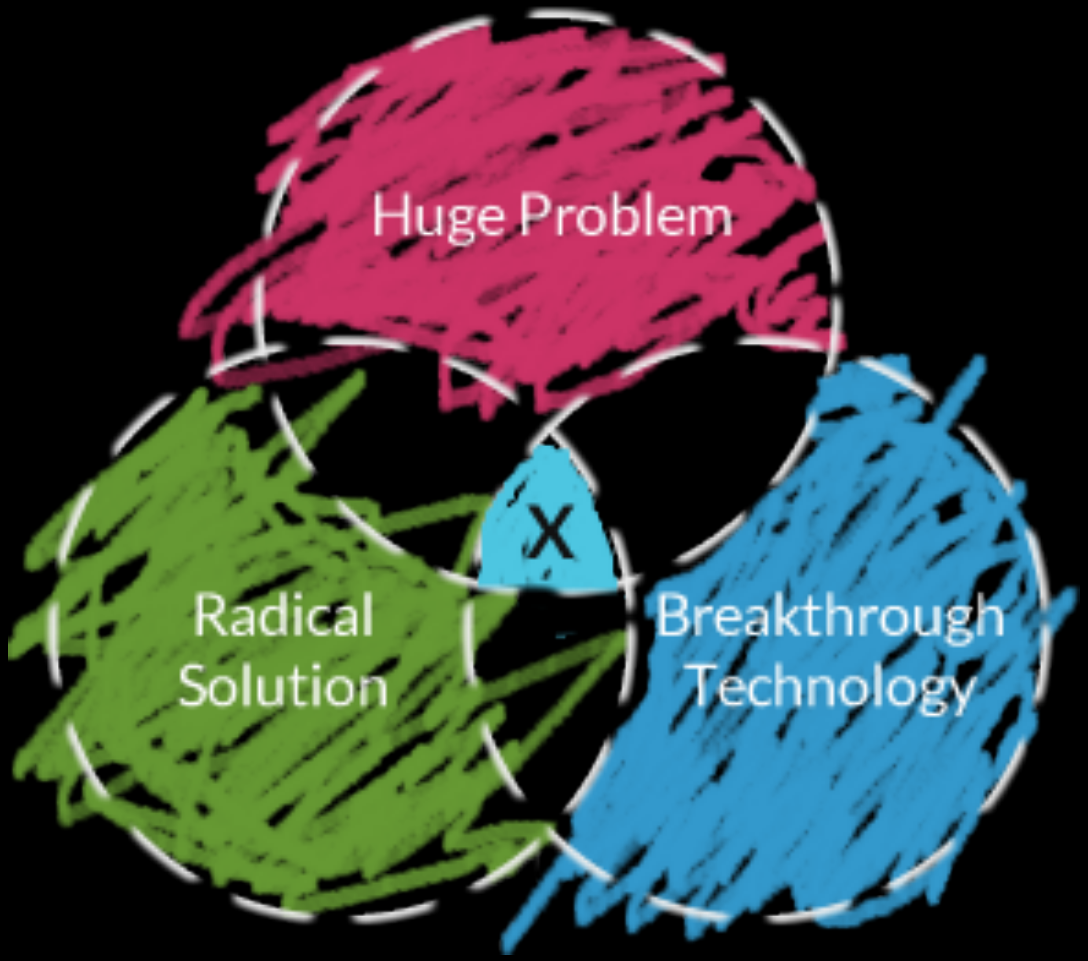
- Mobile Internet
- Automation of knowledge work
- Internet of Things
- Cloud technology
- Advanced robotics

Use FiWi to recombine these 5 GPTs and multiply their impact!?



McKinsey Global Institute, "Disruptive technologies: Advances that will transform life, business, and the global economy," May 2013.

Google [x]: Moonshots




It is better to be roughly right
than precisely wrong
John Maynard Keynes, British economist (1883 - 1946)

Thank you