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Smart FiWi-HetNets: Lessons Learned for 5G Visionaries

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Director of 5G Innovation Centre (5GIC), University of Surrey, UK:

“We can exceed 1 Tbps wirelessly. This is the same capacity as <u>fibre optics</u> but we are doing it wirelessly.”

5G May Be More Fiber-Like

Mobile Data Explosion

- Need to support explosion of mobile data traffic widely viewed as main driver behind 5G
- Cisco forecast:
  - 13-fold increase between 2012 and 2017

Internet Bubble (2000)

- Expected bandwidth requirements hugely overestimated
- Result:
  - Way too many optical networks built with serious consequences

History of Optical Networks

- Market flooded with unneeded fiber capacity *
  - 80-90% of the world's installed fiber is unlit
  - Only 18% of the world's submarine fiber is lit

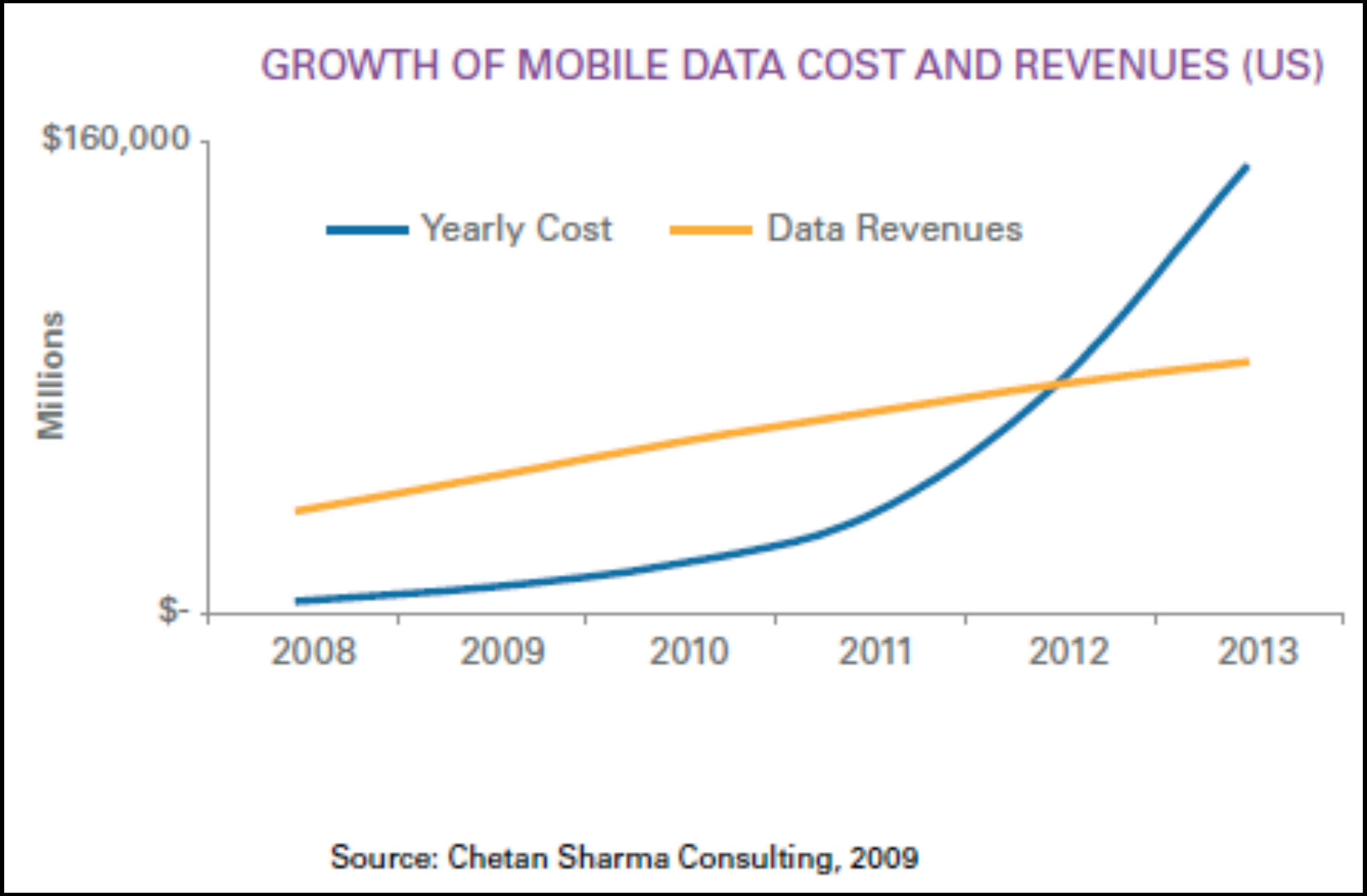
- Prices became so low that customers started to buy up low-cost dark fiber & run their own optical links/ networks

- Monthly leases of optical fiber decreased sharply **
  - 10 Gb/s links Miami-NYC: $75,000 (2005) => $30,000 (2007)
  - 10 Gb/s connections NYC-London: 80% decrease 2002-2007

* D. Sandham, "Into the light," *IET Engineering & Technology*, vol. 4, no. 6, pp. 70-73, 2009.

** D. Sandham, "Into the darkness," *IET Engineering & Technology*, vol. 4, no. 5, pp. 70-73, 2009.

Mobile Networks



Lessons Learned for 5G Visionaries

Lesson 1:

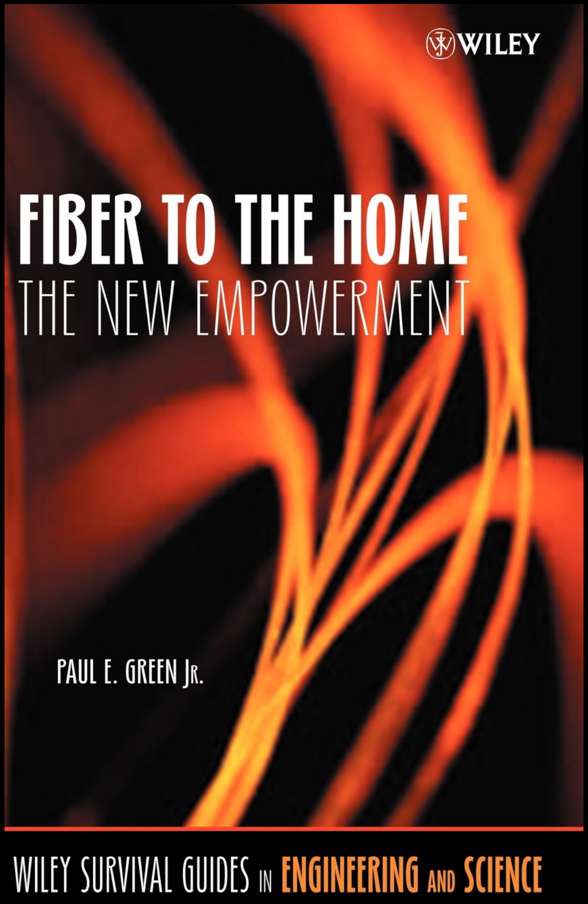
"Avoid revenue crunch due to overestimated bandwidth requirements & unneeded capacity."

The Holy Grail(s)

5G

- 1000x area capacity
- 10 Gb/s peak data rates
- Very low latency (1ms)
- Ultra-high reliability (99.999%)
- 100 billion devices

FTTH (2006)

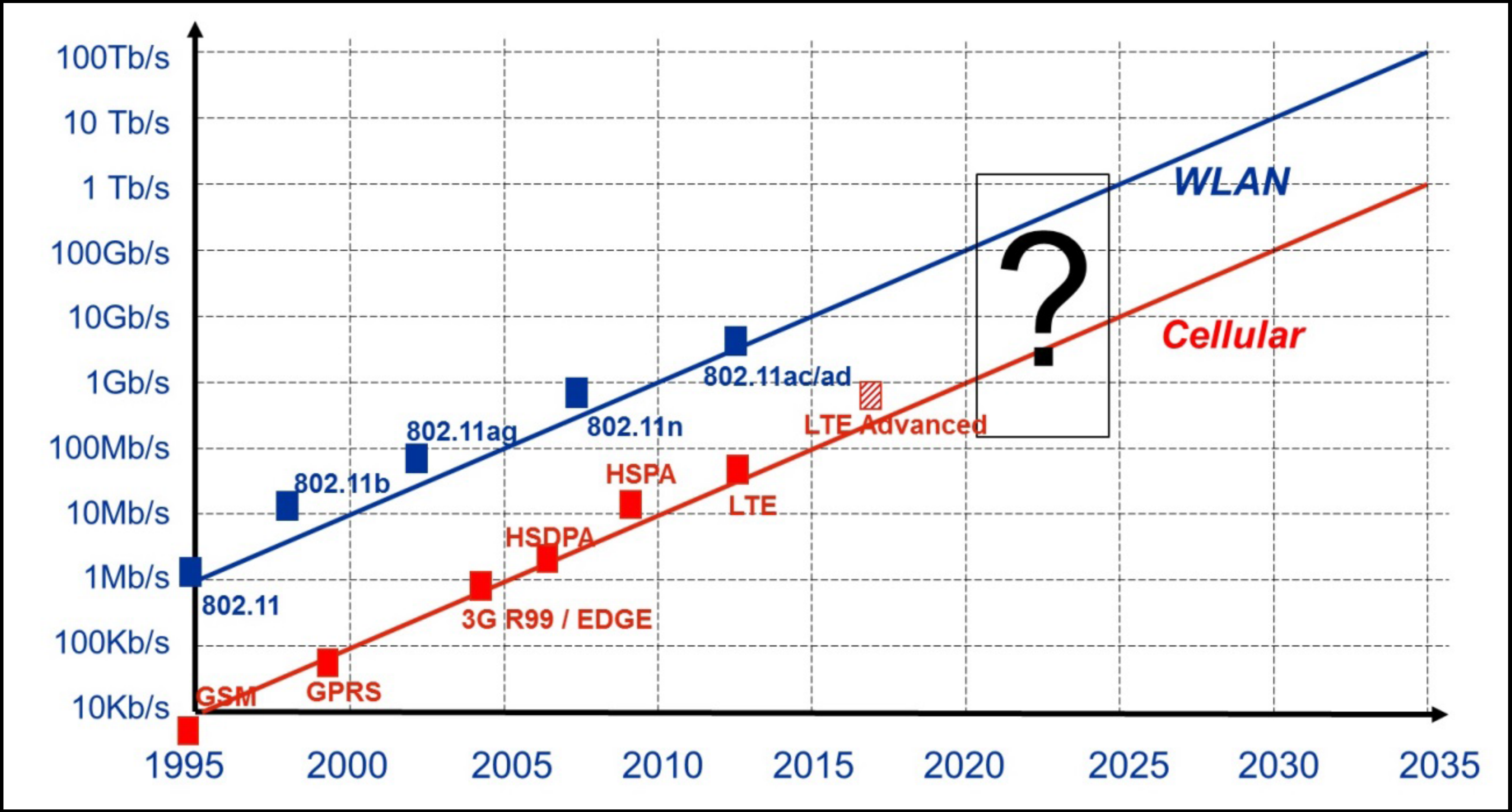


Lessons Learned for 5G Visionaries

Lesson 2:

"Remove major cost barriers to FTTH roll-out by dropping installation cost per home connected by a factor of roughly 0.75 annually."

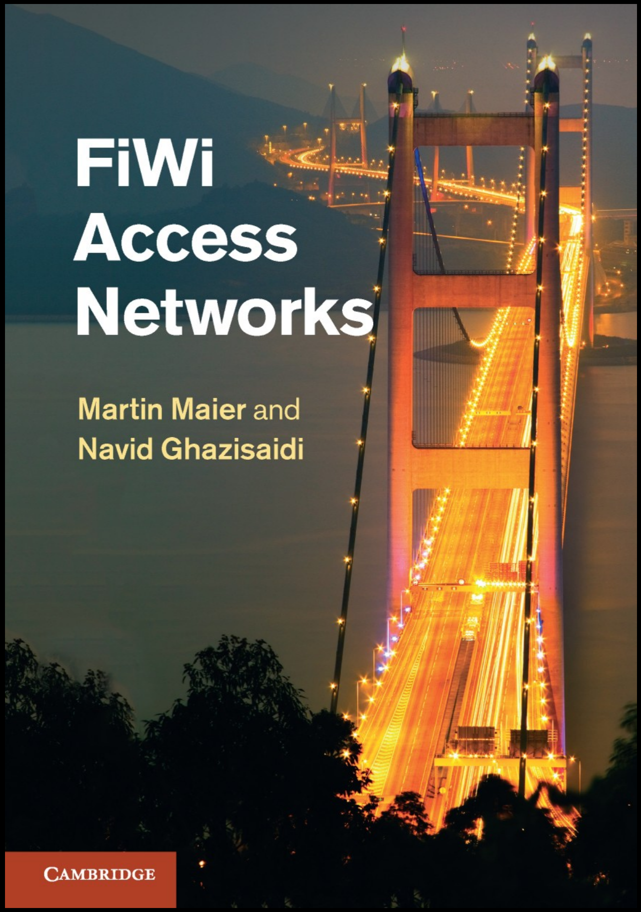
Integrative Vision of 5G



G. Fettweis and S. Alamouti, "5G: Personal Mobile Internet beyond What Cellular Did to Telephony," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 140-145, Feb. 2014.

Fiber-Wireless Integration

<u>FiWi</u> (2012)



<u>Complementary, not competing</u> network technologies

- Optical fiber networks offer reliability, robustness, and capacity
- Wireless networks offer flexibility, ubiquity, and cost savings

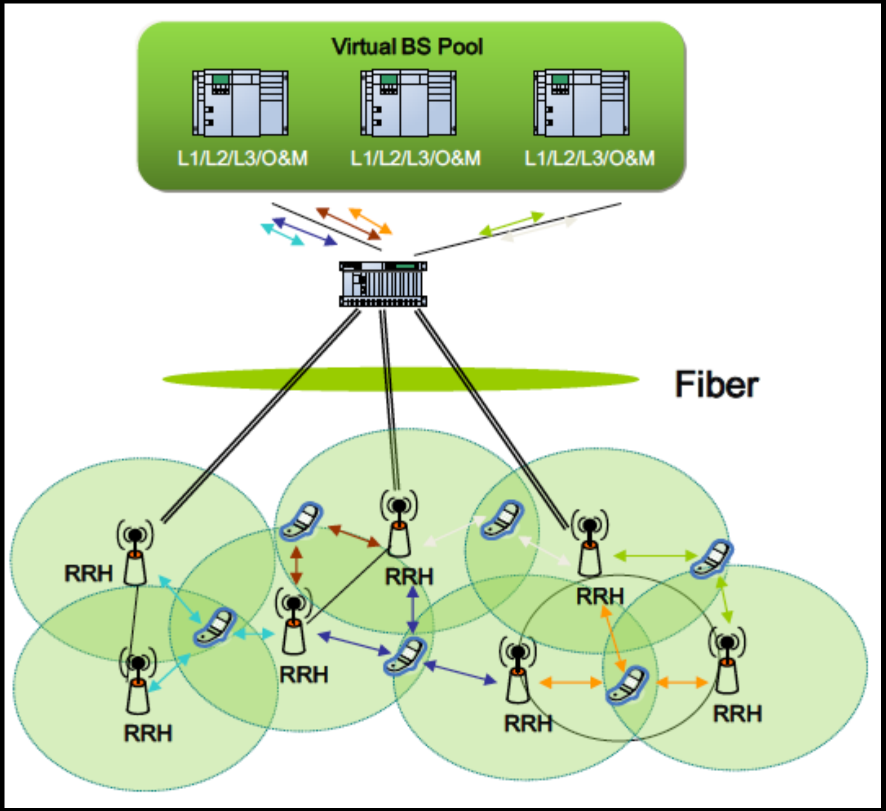
FiWi vs. RoF

RoF: Separation of BBUs & RRHs

Centralized architecture

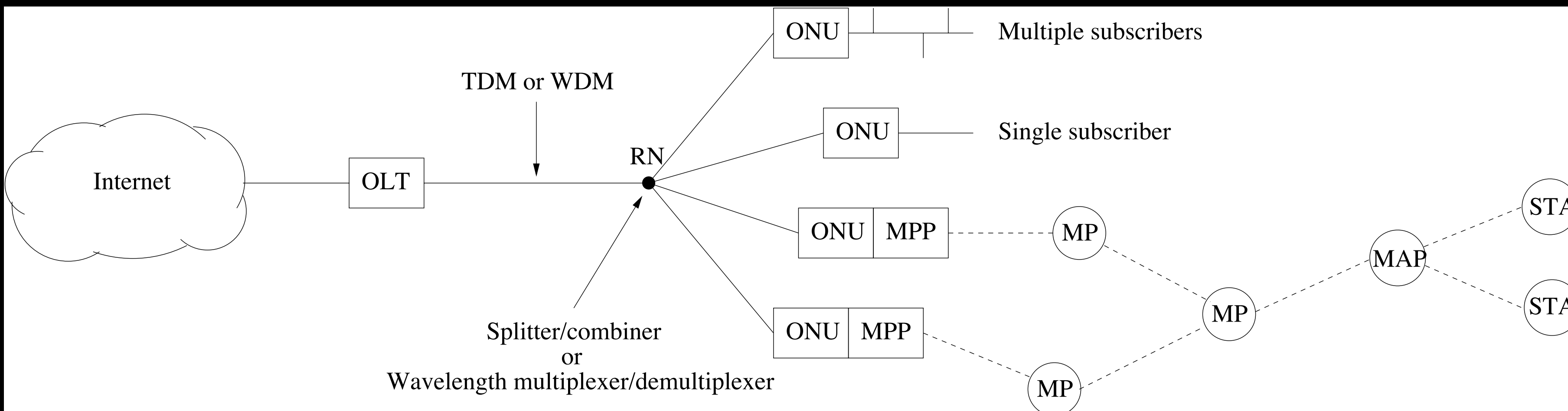
Focus on 4G cellular technologies

C-RAN



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

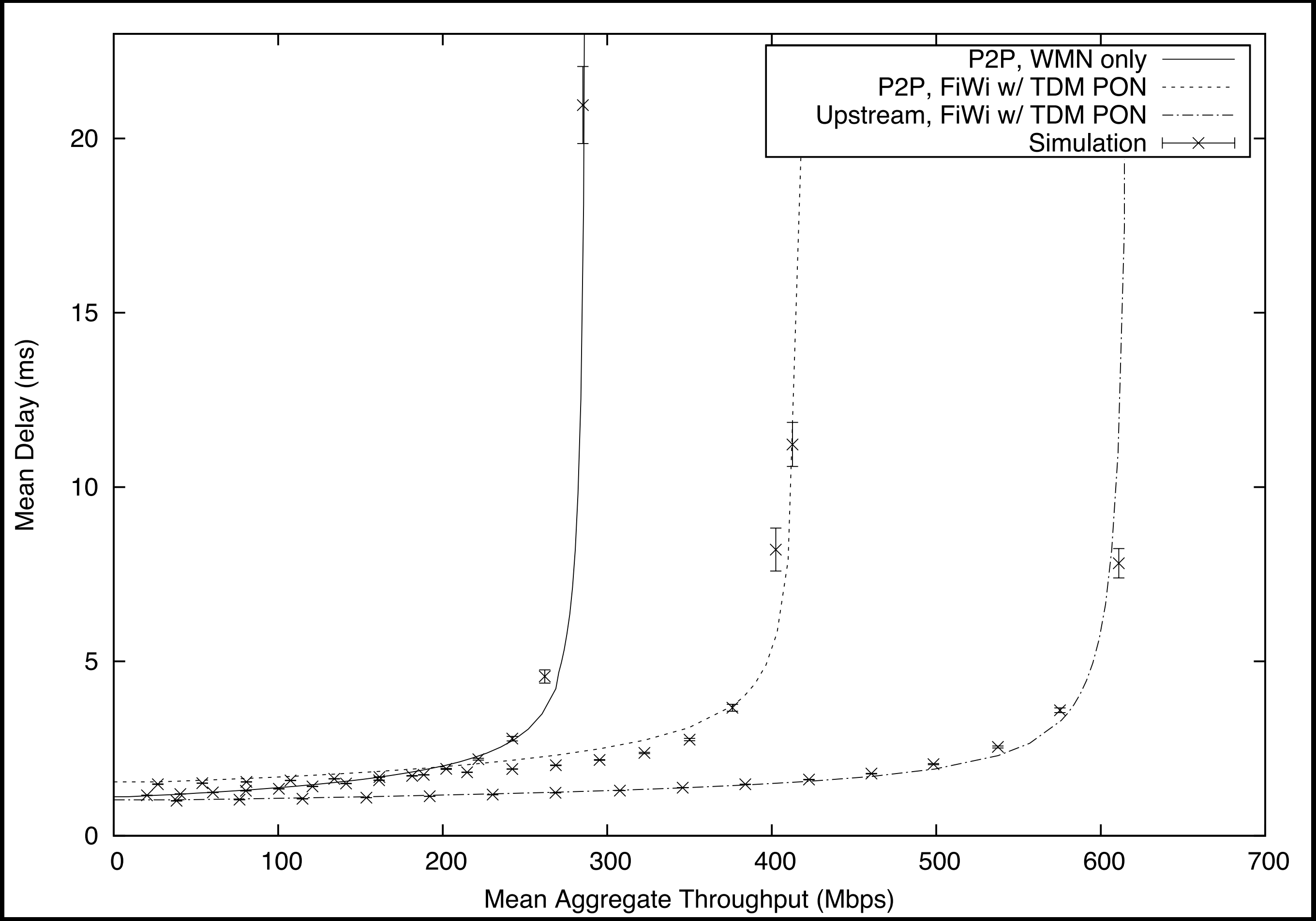
FiWi vs. RoF



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

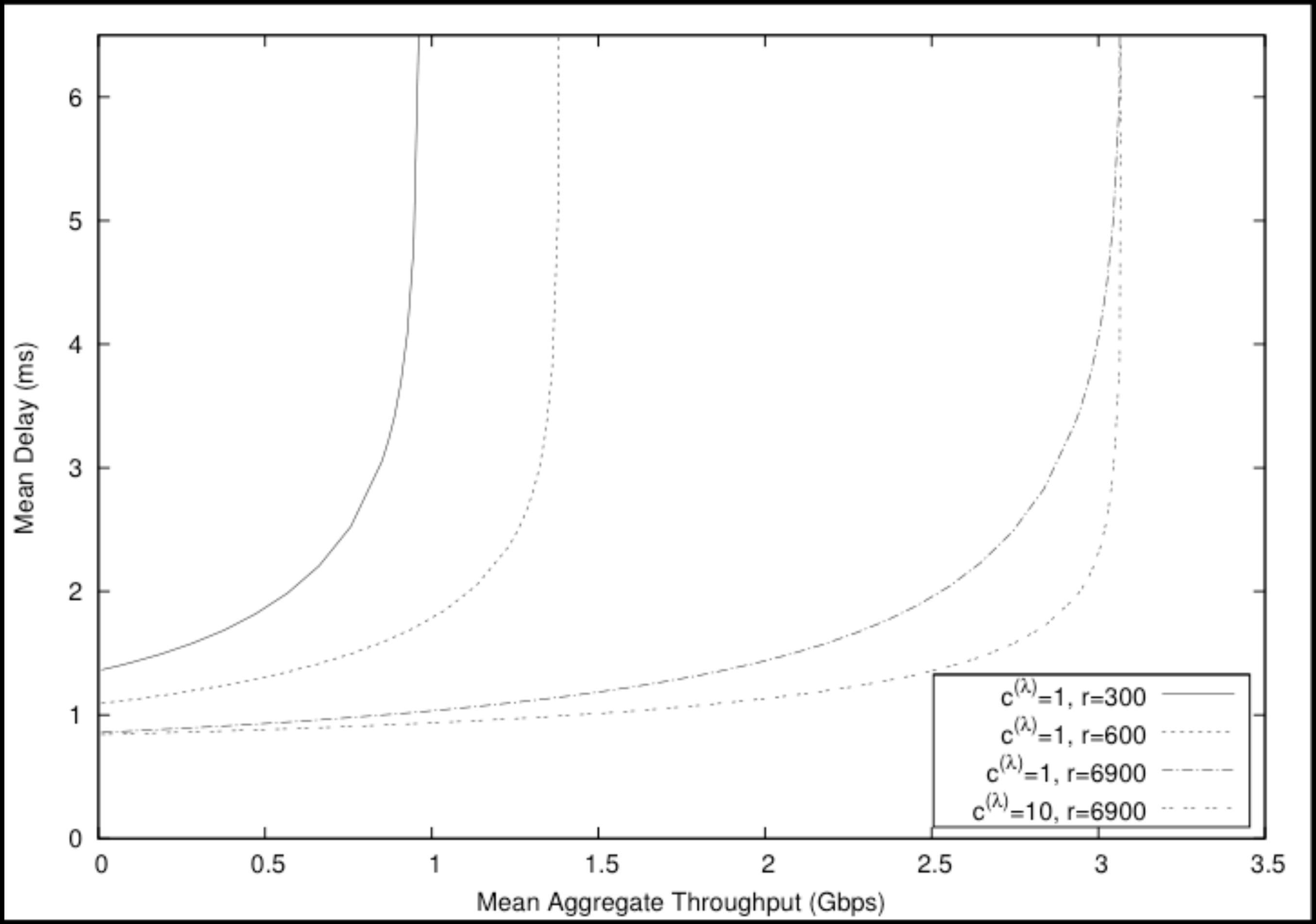
- IEEE 802.3ah EPON, IEEE 802.3av 10G-EPON, WDM PON
- IEEE 802.11b/g/n/s WLAN, IEEE 802.11ac VHT WLAN

Will VHT WLAN Do It?



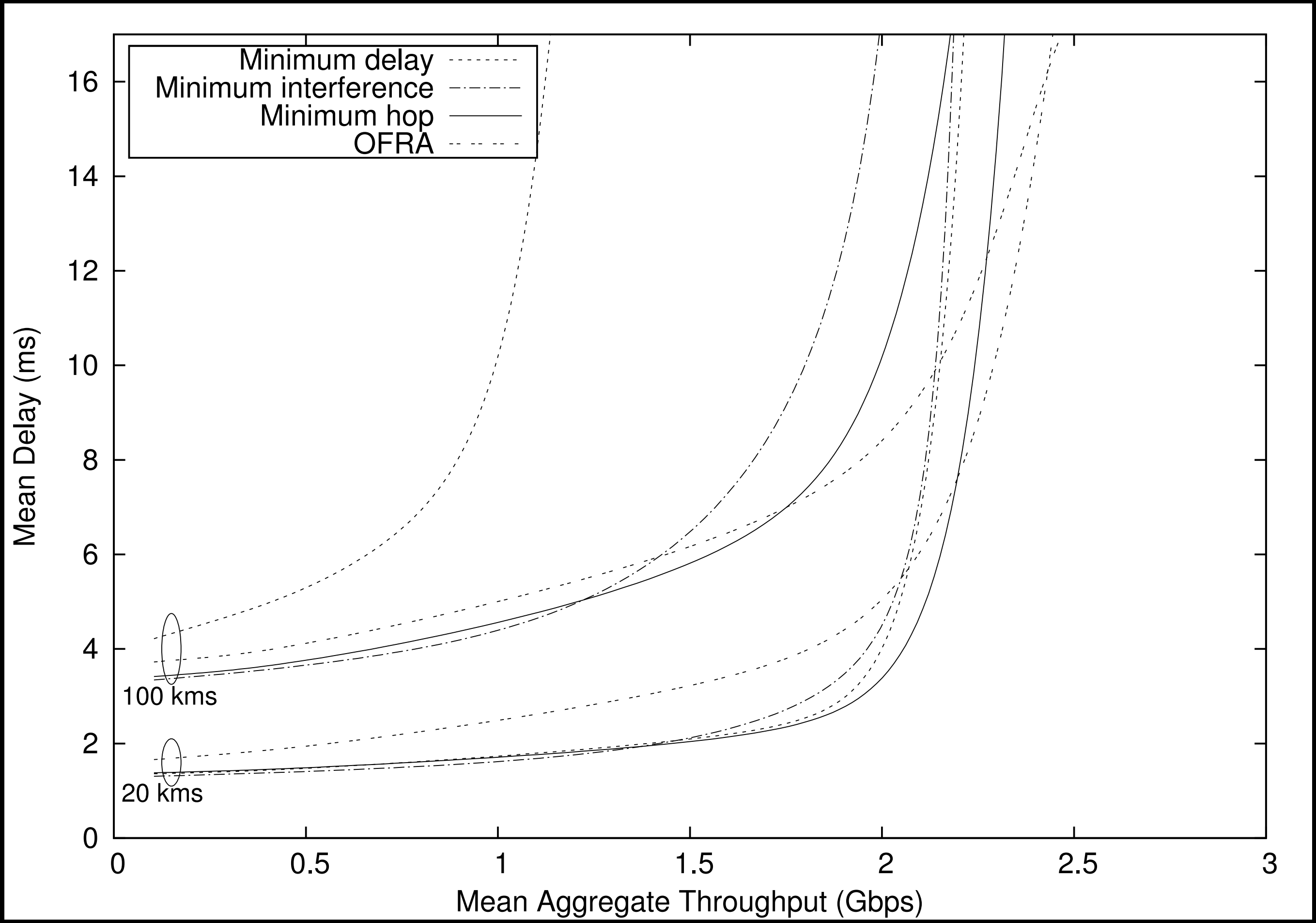
F. Aurzada, M. Lévesque, M. Maier, and M. Reisslein, “FiWi Access Networks Based on Next-Generation PON and Gigabit-Class WLAN Technologies: A Capacity and Delay Analysis,” *IEEE/ACM Transactions on Networking*, vol. 22, no. 4, pp. 1176-1189, Aug. 2014.

Will VHT WLAN 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.

Integrated Routing



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Lessons Learned for 5G Visionaries

Lesson 3:

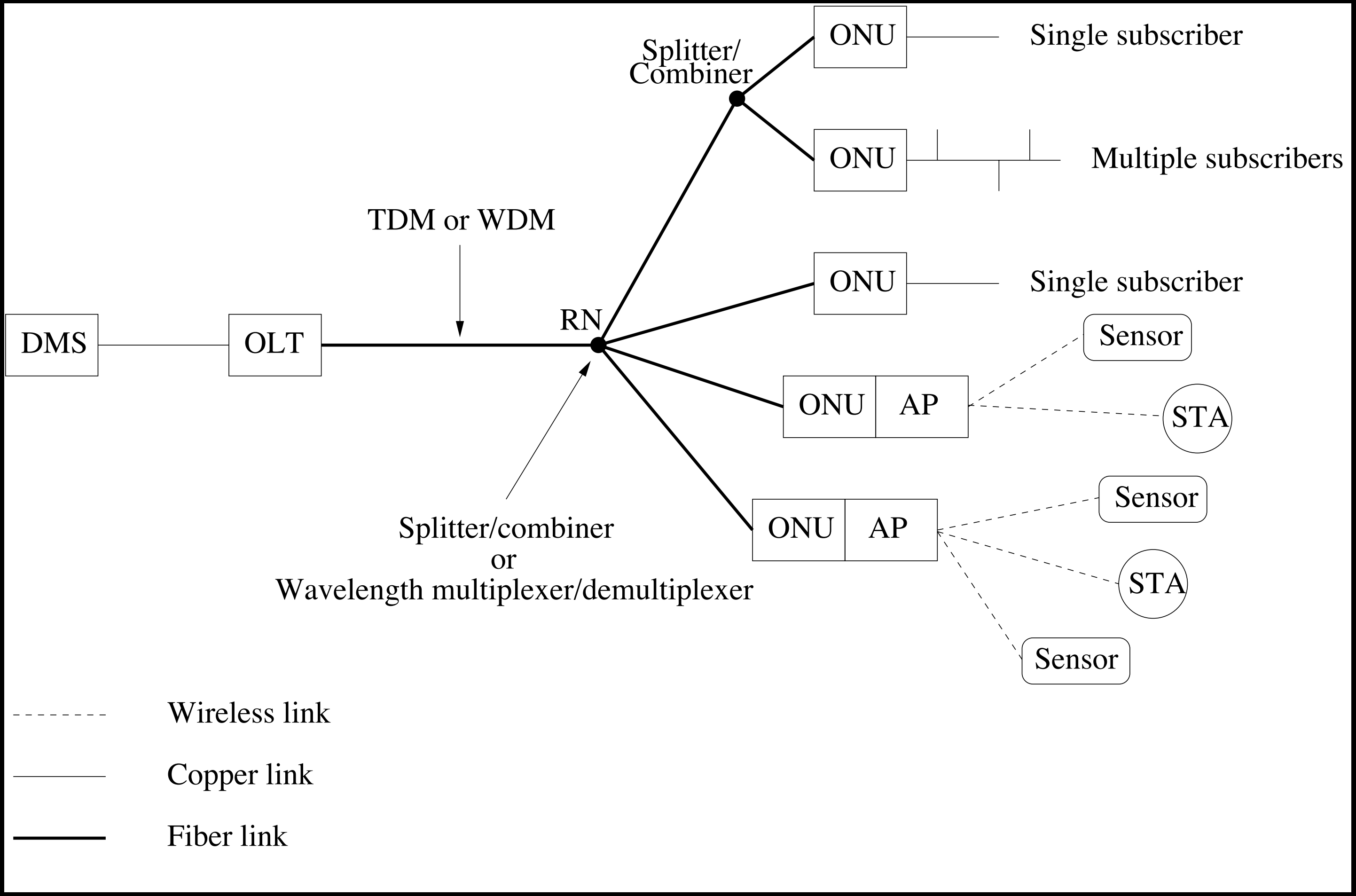
"Leverage on respective strengths of disparate networking technologies & merge them smartly."

Multi-Tier Business Models

FiWi Smart Grid Communications Infrastructures

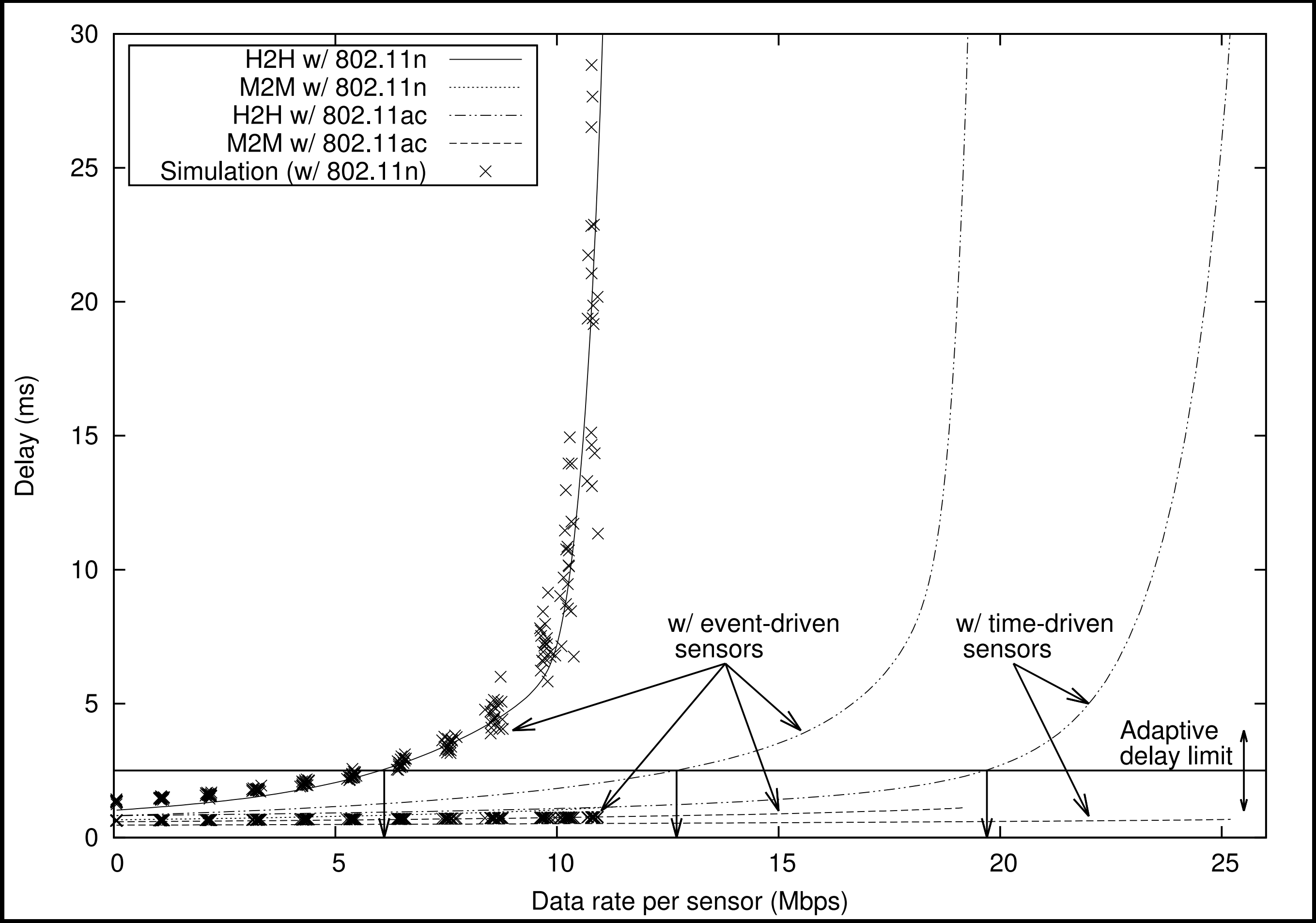
- FTTH networks increasingly installed by utilities & municipalities rather than incumbents (Europe: 22%)
- Example: National Swiss Fibre Net of OPENAXS
  - Association of 22 regional electricity utilities
  - Goal: 80% FTTH connected households by 2020
  - Infrastructure sharing via open access

H2H & M2M Coexistence



M. Lévesque, F. Aurzada, M. Maier, and G. Joós, "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.

Sensor Latency



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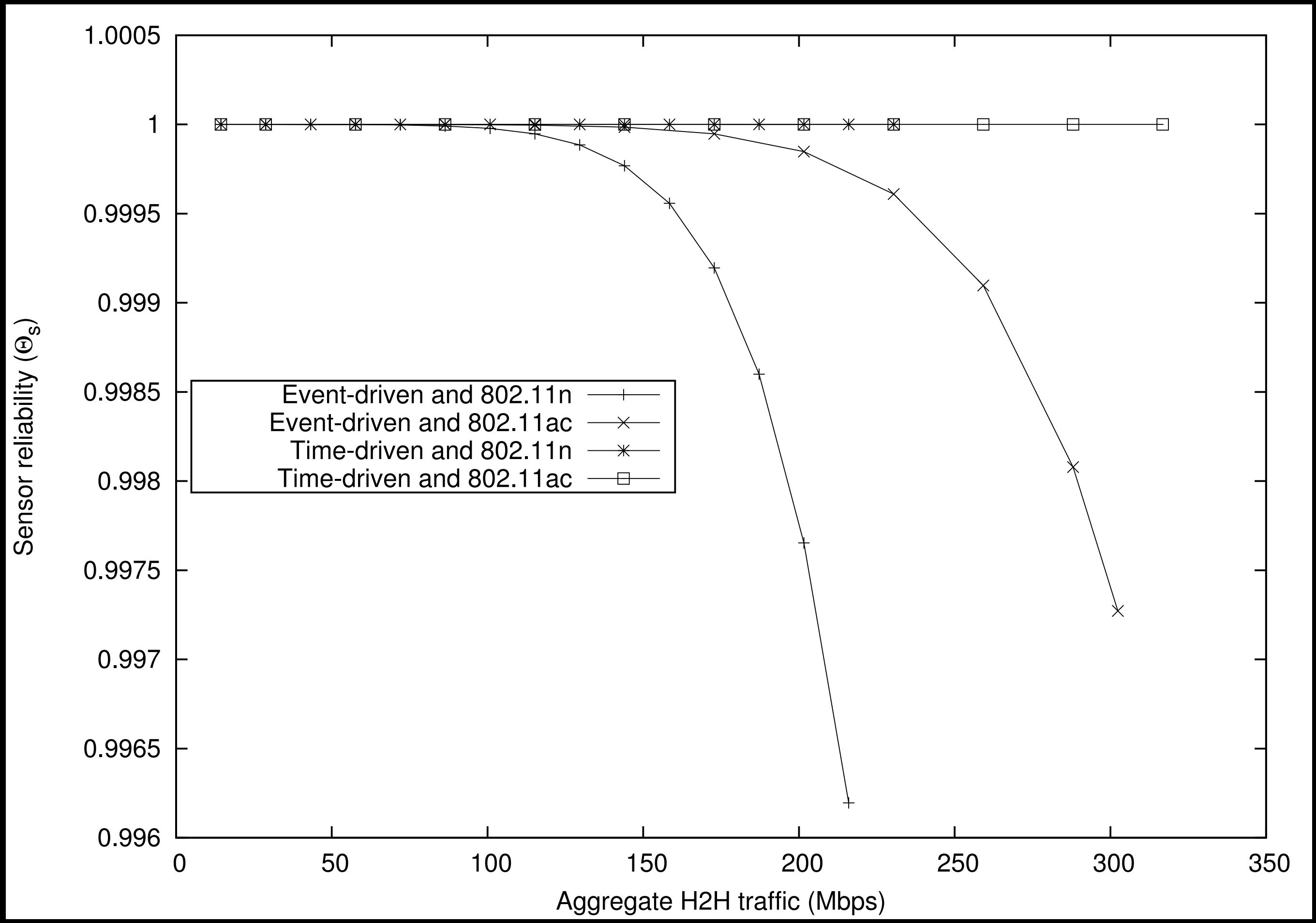
Sensor Reliability



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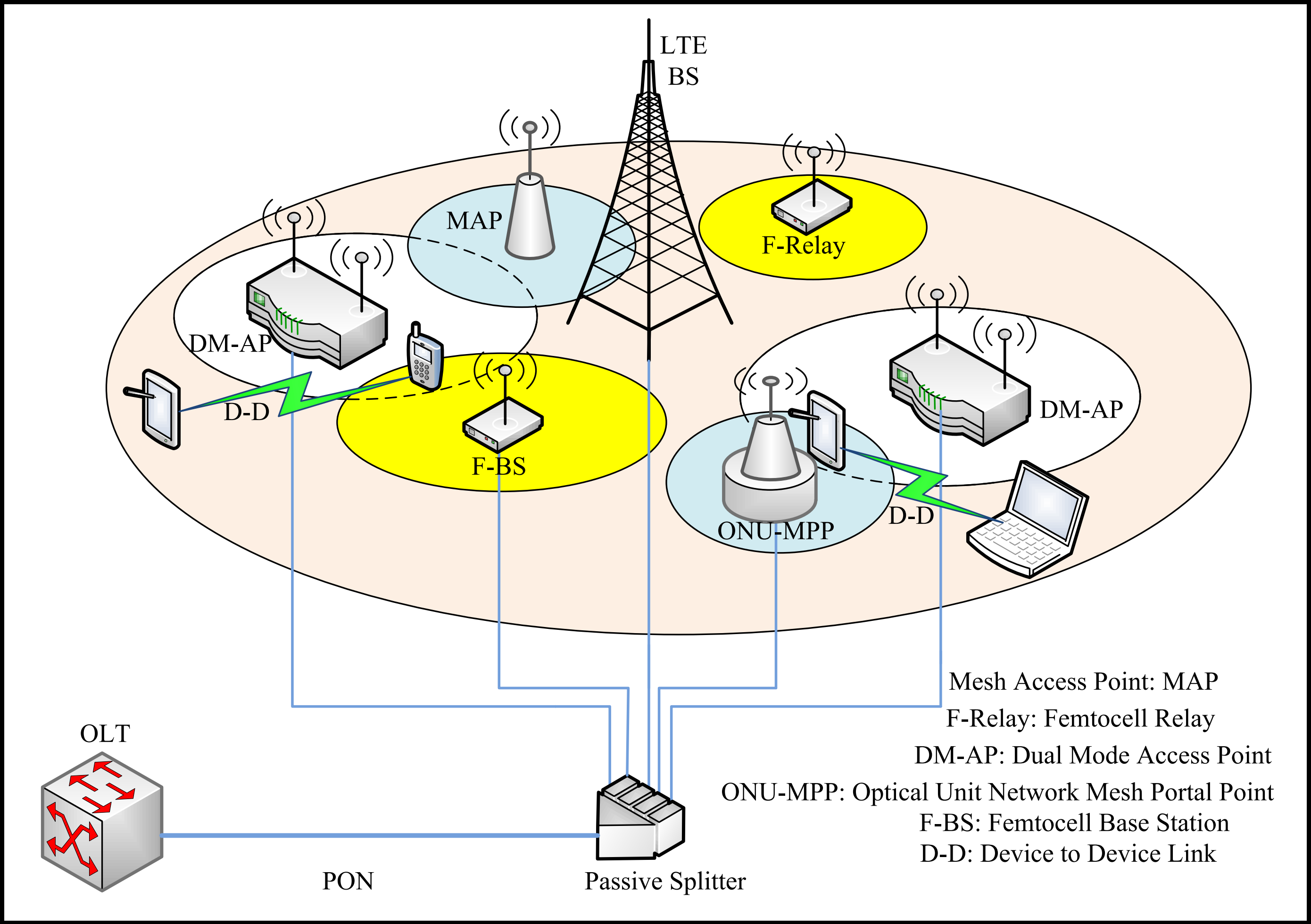
Lessons Learned for 5G Visionaries

Lesson 4:

"Multi-tier business models & innovative partner-ships among diverse players are arguably more important than technological feasibility."

LTE-A HetNets: Small Cells



Backhaul Latency

HetNets raise new research challenges:

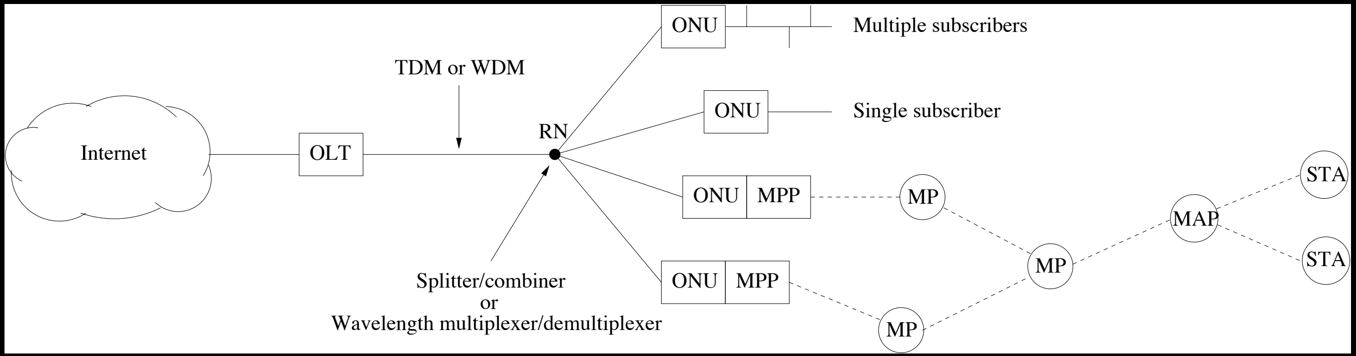
- Cell association & biasing
- Mobility management
- Interference coordination
- SON
- Backhaul bottleneck
  - Most 4G LTE research focused on wireless front-end only
  - Ultimately the major factor limiting CoMP performance is latency rather than capacity of the backhaul *

* 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

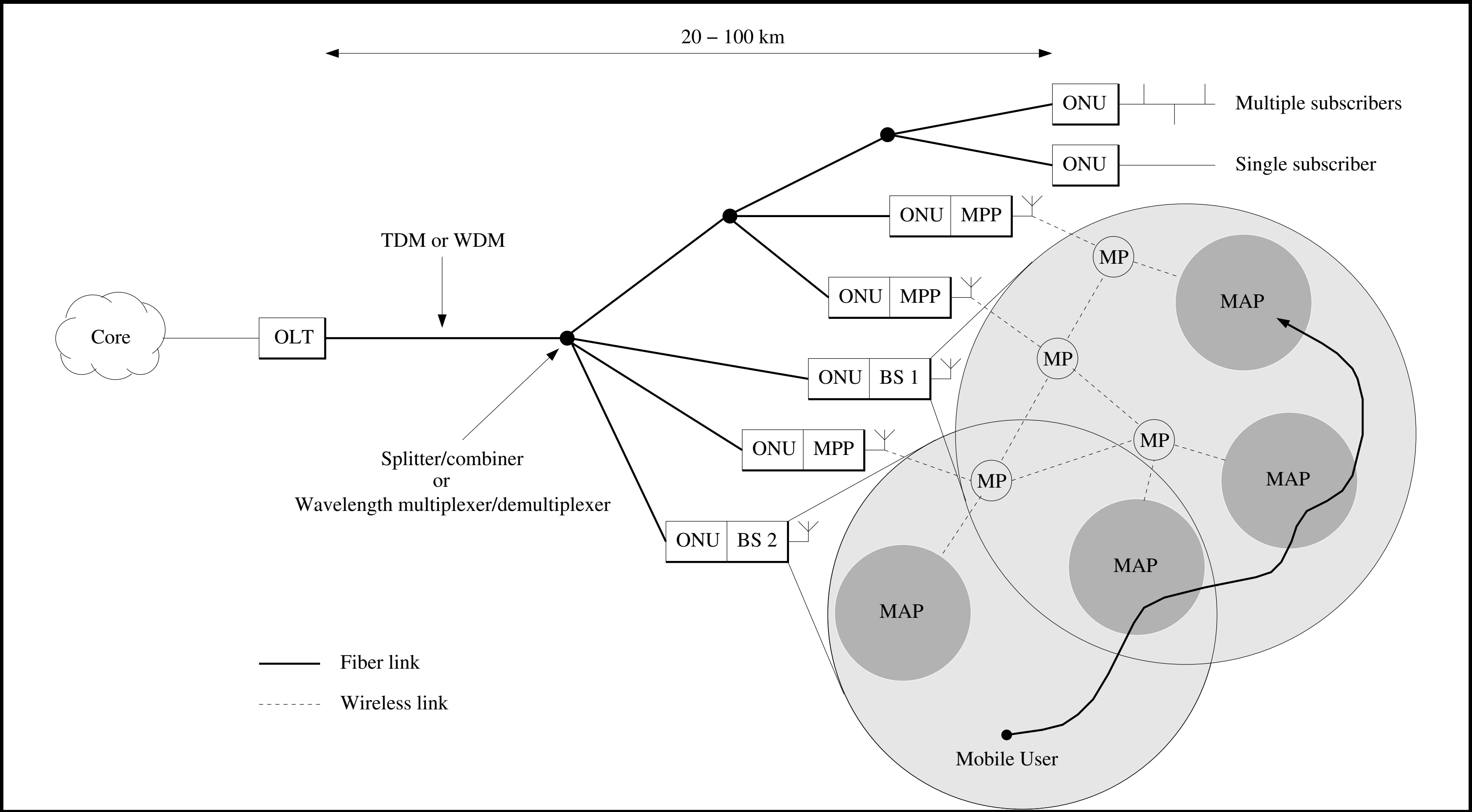
FiWi vs. 4G LTE – the bugging question:

“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



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.

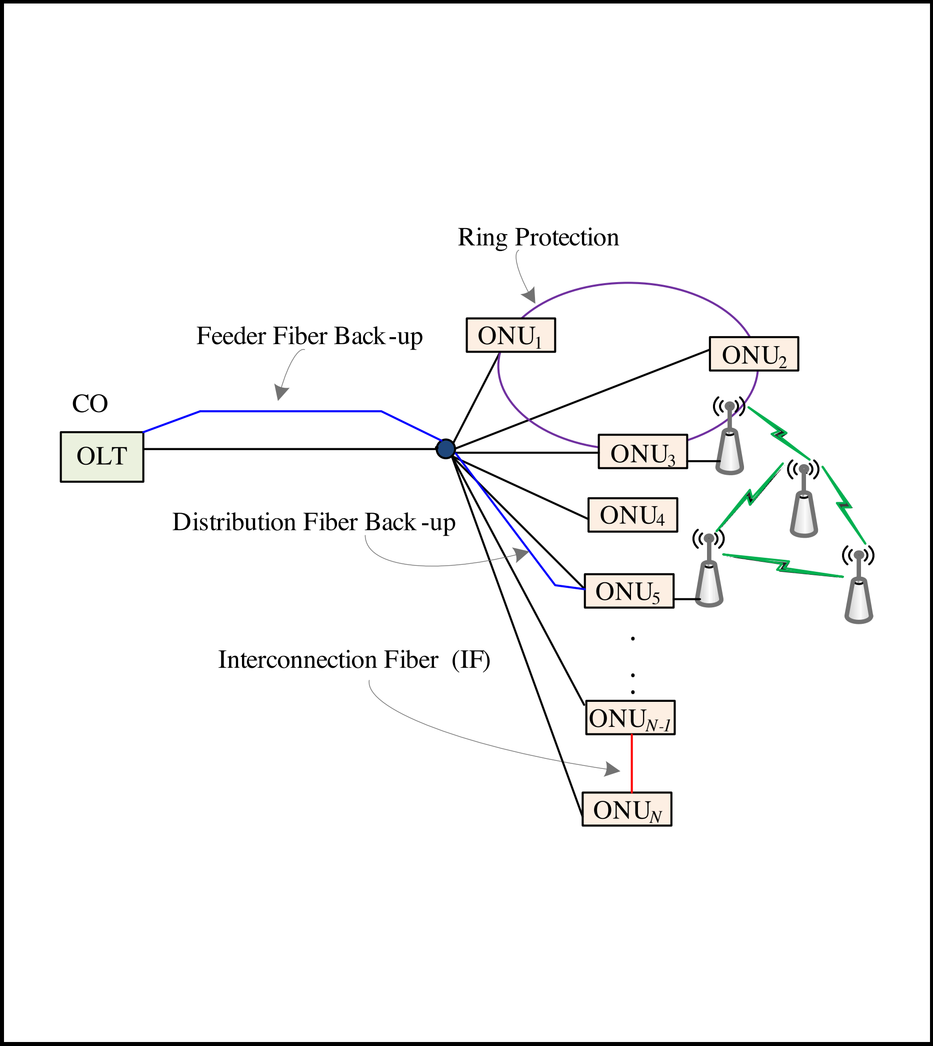
FiWi Enhanced LTE-A HetNets

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:

    λ_{MAP} (and λ_{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:
    $$\mathbf{S} = \left(S_{ij}\right)$$
  - Arbitrary distribution of packet length L:
    $$\bar{L} \text{ and } \varsigma_L^2$$
  - 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:

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

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}:

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

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

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

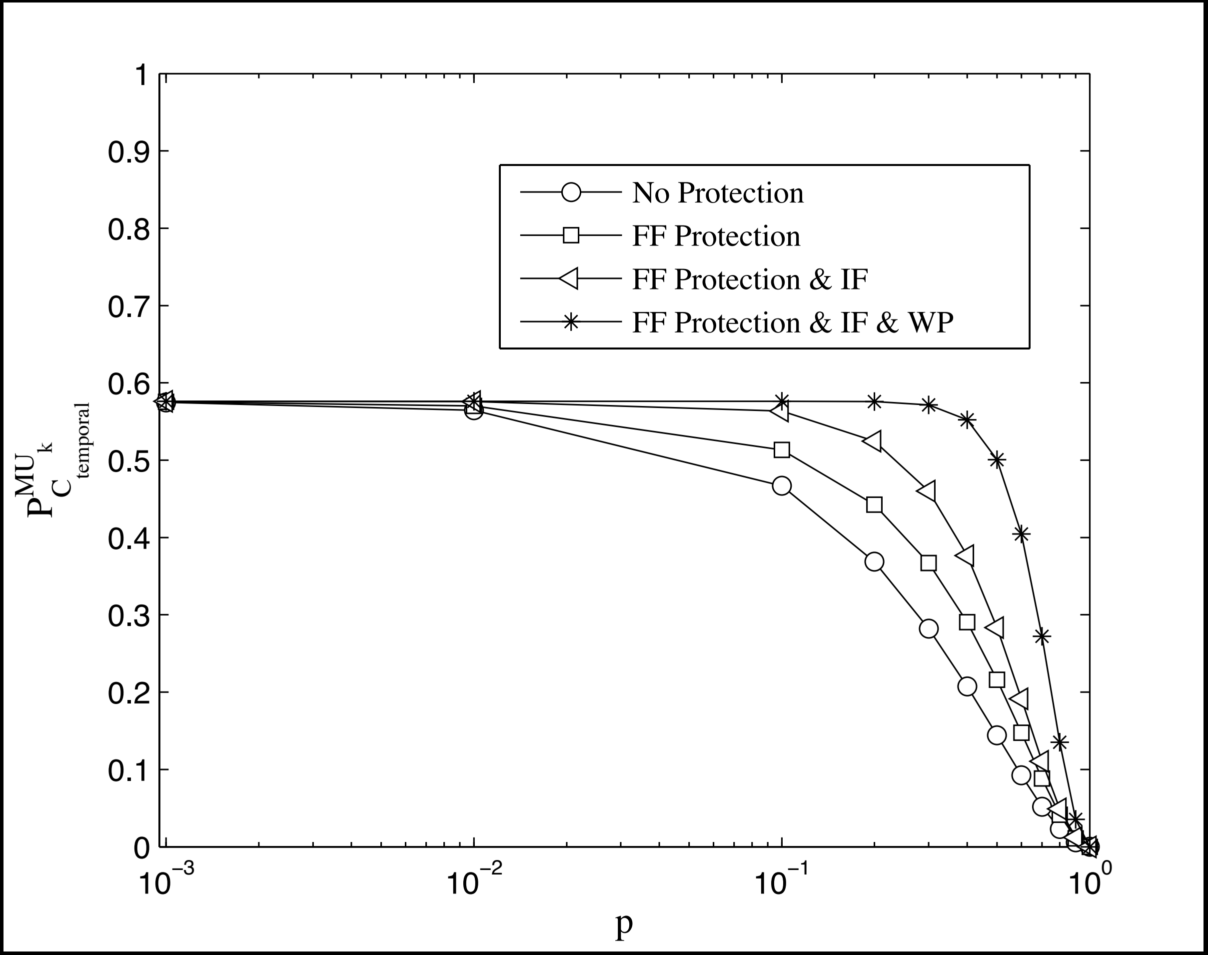
Offloading Efficiency

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

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

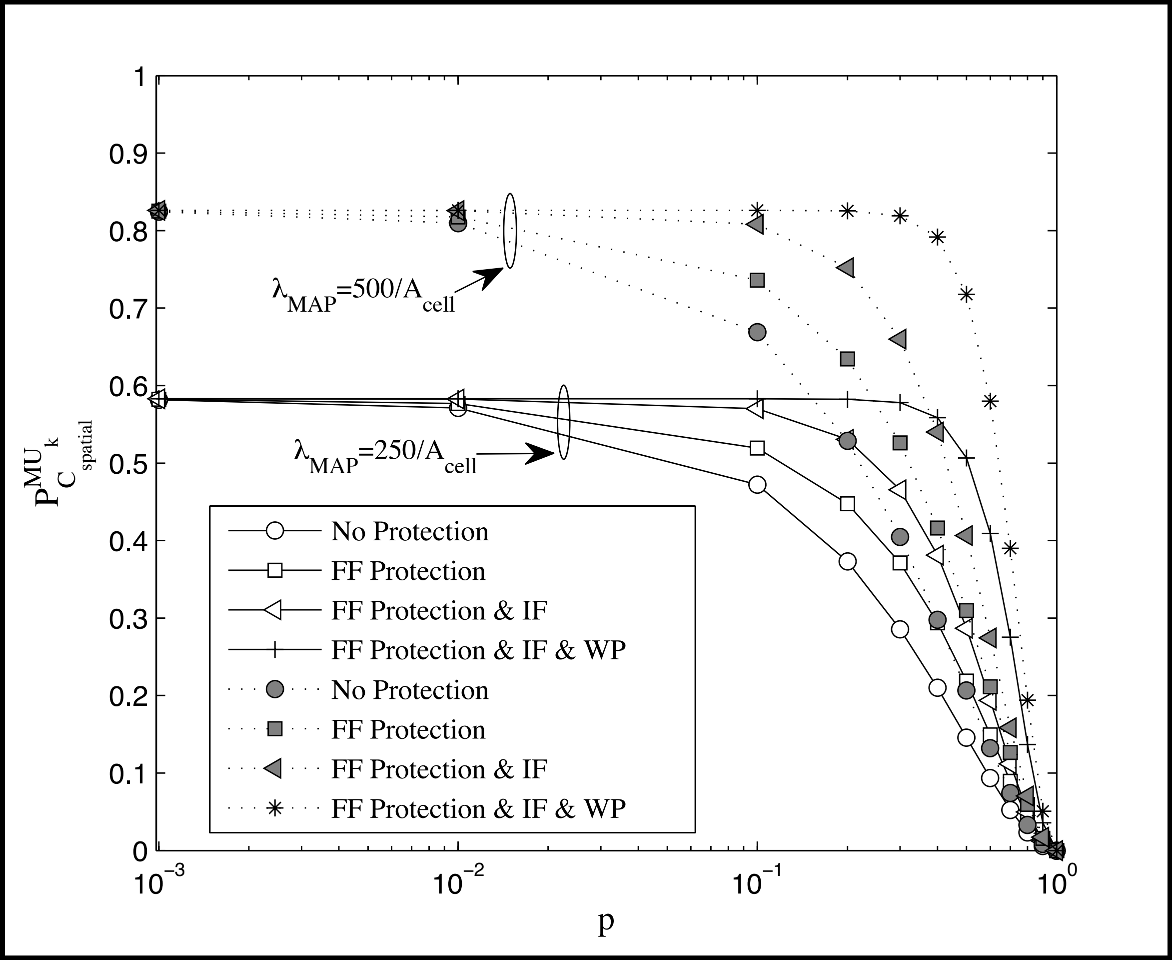
WiFi interconnection & connection times exponentially distributed with rate θ_i and θ_c, respectively.

Results



No Protection
FF Protection
FF Protection & IF
FF Protection & IF & WP
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
$P^{MU_k}_{C_{temporal}}$

Results



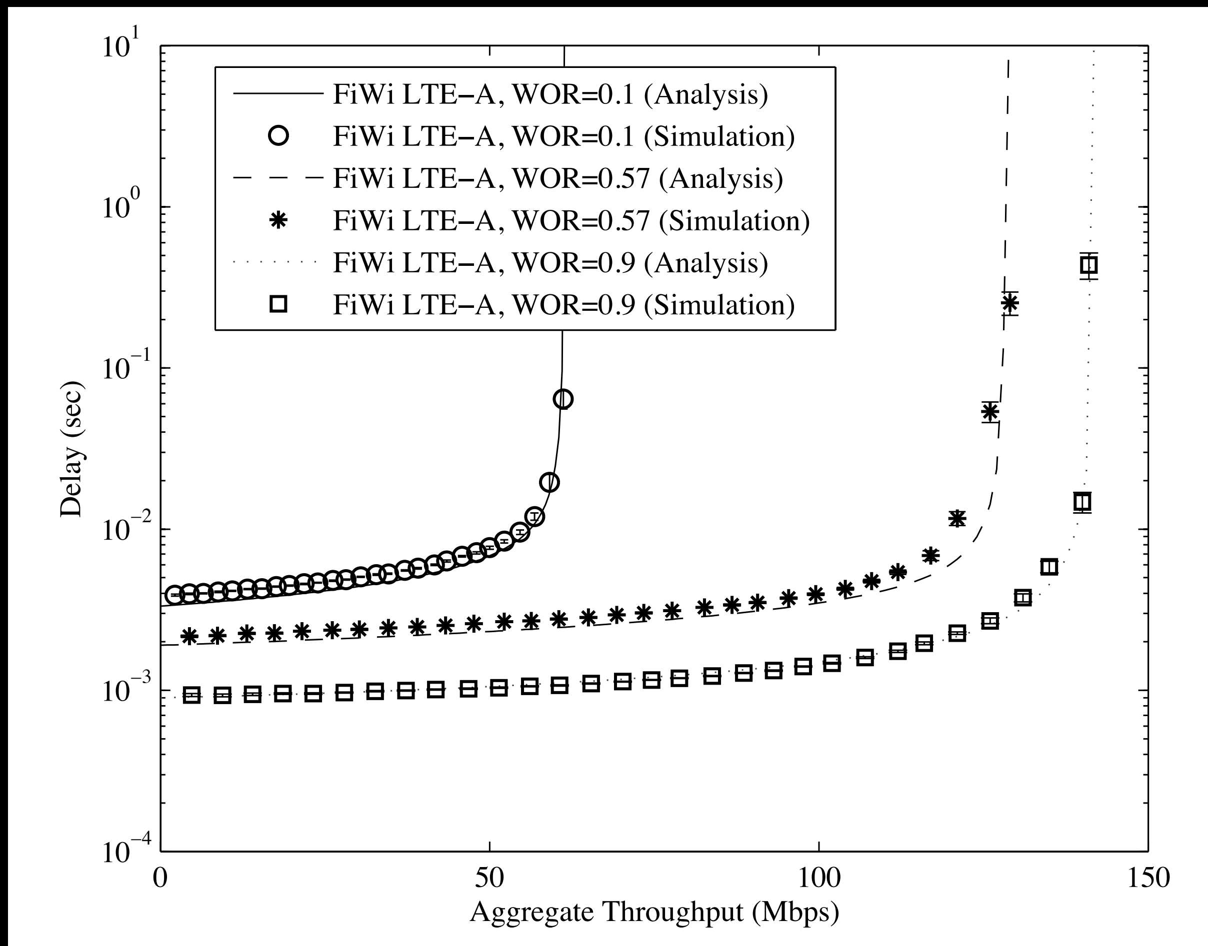
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-3}
10^{-2}
10^{-1}
10^{0}
p
$P^{MU_k}_{C_{spatial}}$
λ_{MAP}=500/A_{cell}
λ_{MAP}=250/A_{cell}
No Protection
FF Protection
FF Protection & IF
FF Protection & IF & WP
No Protection
FF Protection
FF Protection & IF
FF Protection & IF & WP

Lessons Learned for 5G Visionaries

Lesson 5:

"Integrative vision of 4G & FiWi enables ultra-high reliability of mobile user FiWi connectivity for PON failure probability as high as 0.1 and beyond."

Results



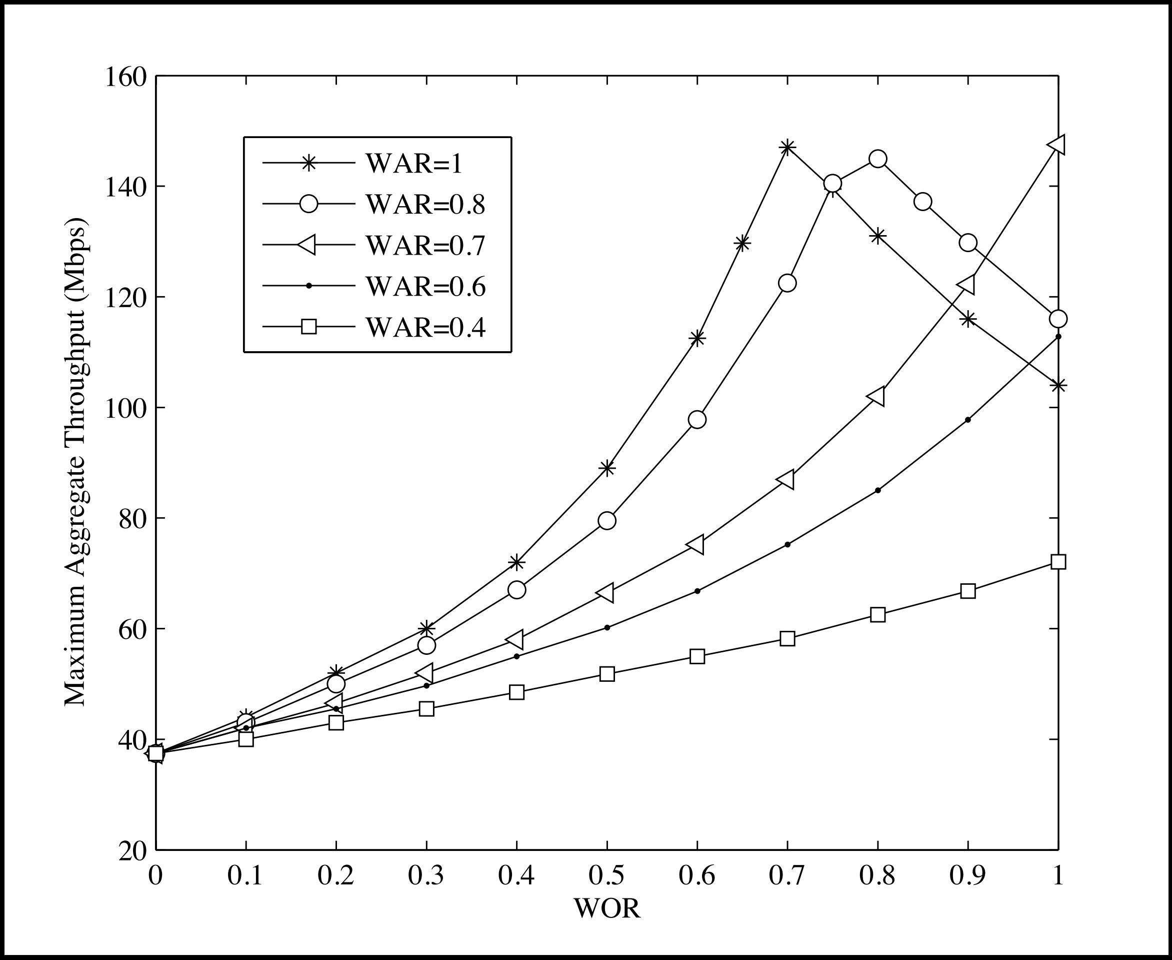
FiWi LTE−A, WOR=0.1 (Analysis)
FiWi LTE−A, WOR=0.1 (Simulation)
FiWi LTE−A, WOR=0.57 (Analysis)
FiWi LTE−A, WOR=0.57 (Simulation)
FiWi LTE−A, WOR=0.9 (Analysis)
FiWi LTE−A, WOR=0.9 (Simulation)
Delay (sec)
Aggregate Throughput (Mbps)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150

Lessons Learned for 5G Visionaries

Lesson 6:

"Achieve very low latency of 1 ms over wide range of traffic loads by setting WOR = 0.9."

Results



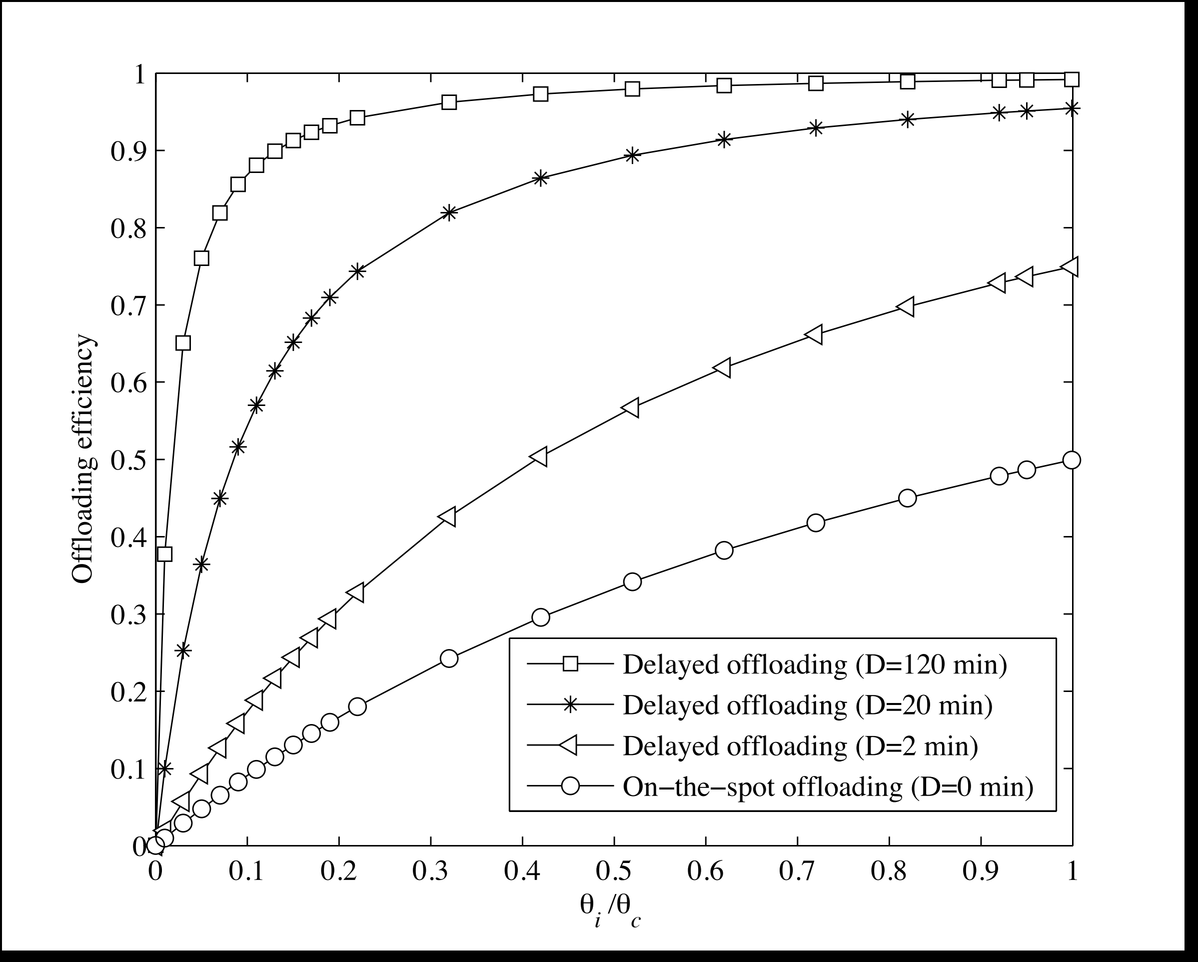
WAR=1
WAR=0.8
WAR=0.7
WAR=0.6
WAR=0.4
Maximum Aggregate Throughput (Mbps)
160
140
120
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
WOR

Lessons Learned for 5G Visionaries

Lesson 7:

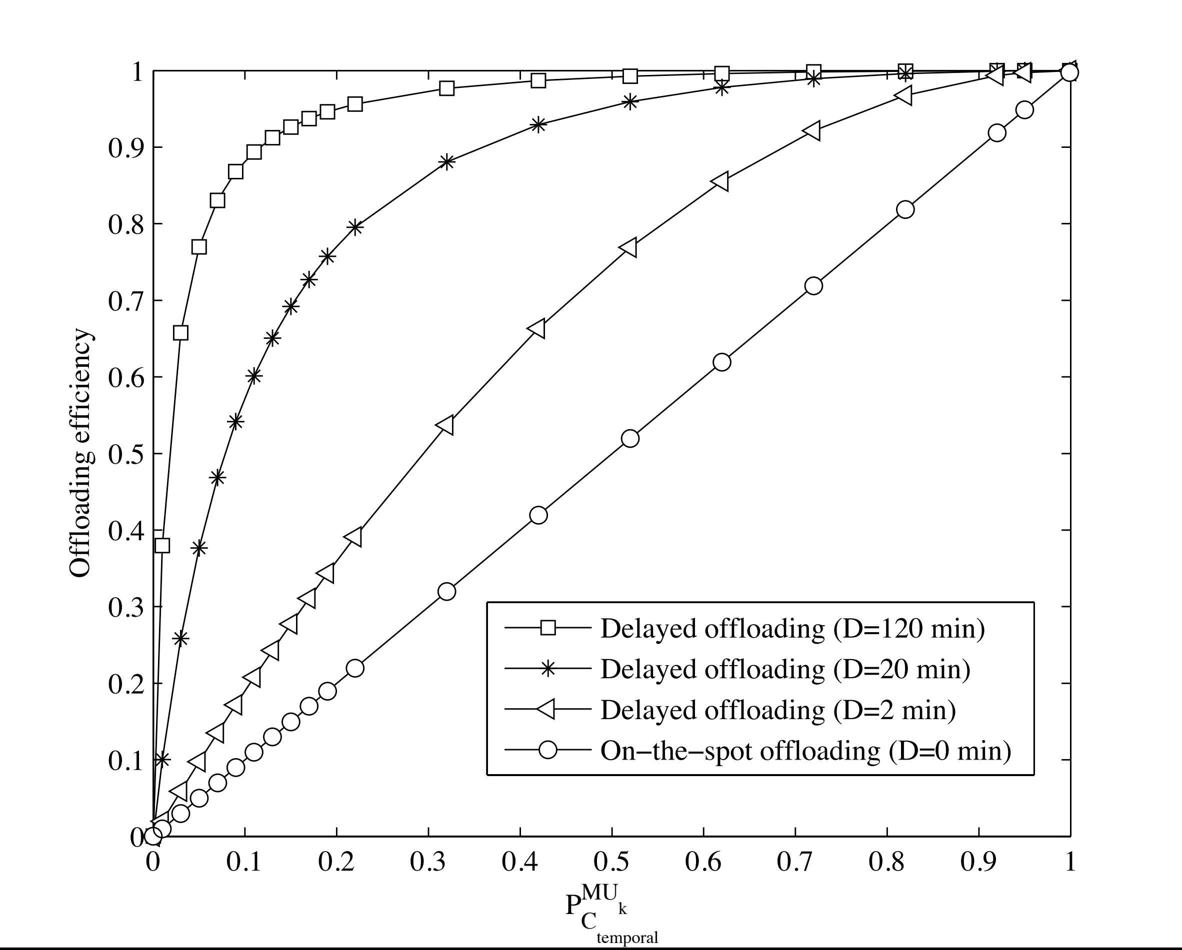
"Maximize aggregate throughput by offloading all data traffic onto WiFi for WAR ≤ 0.7."

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

Lessons Learned for 5G Visionaries

Lesson 8:

"Achieve 100% WiFi offloading efficiency of delay-tolerant mobile data traffic for temporal FiWi connectivity probability of 0.5 or higher."

22 April 2015

Google Official Blog

Insights from Googlers into our products, technology and the Google culture

Google launches Project Fi:

Project Fi

- Stringing together T-Mobile/Sprint’s 4G LTE networks & free open WiFi hotspots into one wireless service
- Simple service plan (no annual contract)
  - 20$ per month for Fi Basics
  - 10$ per GByte for cellular data in US & abroad
  - Reimbursement of unused data

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