Ultra High Density Wireless Cells

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Ultra High Density Wireless Cells

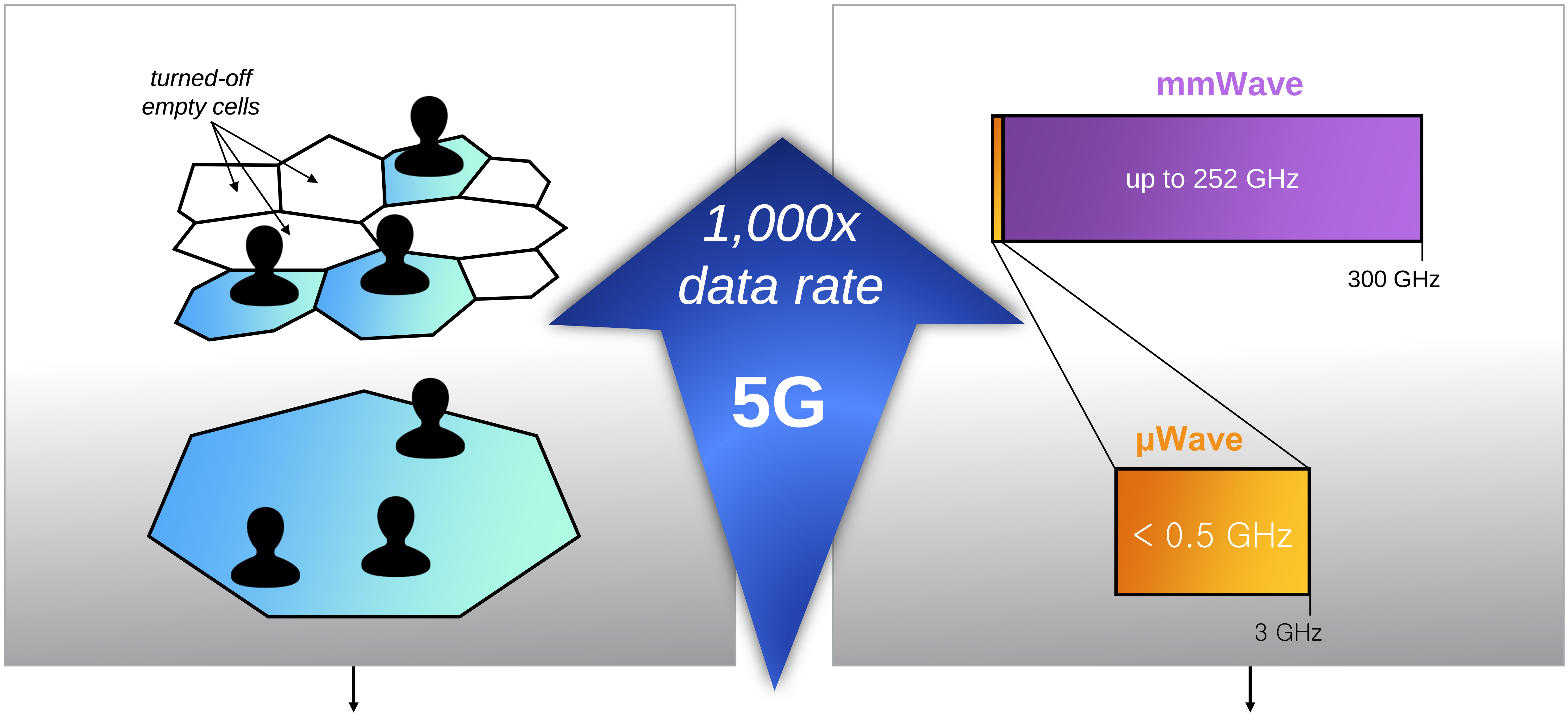
5G Cellular Network Enablers:

1. Base Station (BS) Ultra-Densification

[Qualcomm13, 14]

2. Milimeter-Wave (mmWave) Overlay

[Rappaport13], [Samsung11]



Part I

Part II

[Qualcomm14] Qualcomm, “Hyper-Dense Small Cell Deployment Trial in NASCAR Environment,” April 2014.

[Qualcomm13] I. Hwang, B. Song, and S. S. Soliman, “A Holistic View on Hyper- Dense Heterogeneous and Small Cell Networks,” IEEE Comm. Mag., 2013.

[Rappaport13] T. S. Rappaport, et. al., “Milimeter Wave Mobile Communications for 5G Cellular: It Will Work!,” IEEE Access, 2013.

[Samsung11] Z. Pi and F. Khan, “An Introduction to Milimeter-Wave Mobile Broadband Systems,” IEEE Comm. Mag., 2011.

Part I.

Asymptotic Behavior of Ultra-Dense Cellular Networks and Its Economic Impact [GC14]

- Spectral Efficiency (SE) in downlink ultra-dense cellular networks
- Profit maximizing BS & spectrum OPEX

[GC14] J. Park, S.-L. Kim, and J. Zander, “Asymptotic Behavior of Ultra-Dense Cellular Networks and Its Economic Impact,” *to appear in Proc. IEEE GLOBECOM 2014*.

Motivation

Downlink Cellular Network Average Spectral Efficiency (SE)

Average Rate = Spectrum Amount x **SE**

1. Sparse network ($\lambda_u >> \lambda_b$): **independent of** BS density [Andrews11]
2. Dense network: **increasing function** of BS density with diminishing returns [SMYu13], [SLee12]
3. Ultra-Dense network ($\lambda_u << \lambda_b$): ***?***

[Andrews11] J. G. Andrews, F. Baccelli, and R. K. Ganti, “A Tractable Approach to Coverage and Rate in Cellular Networks,” IEEE Trans. on Comm., 2011.

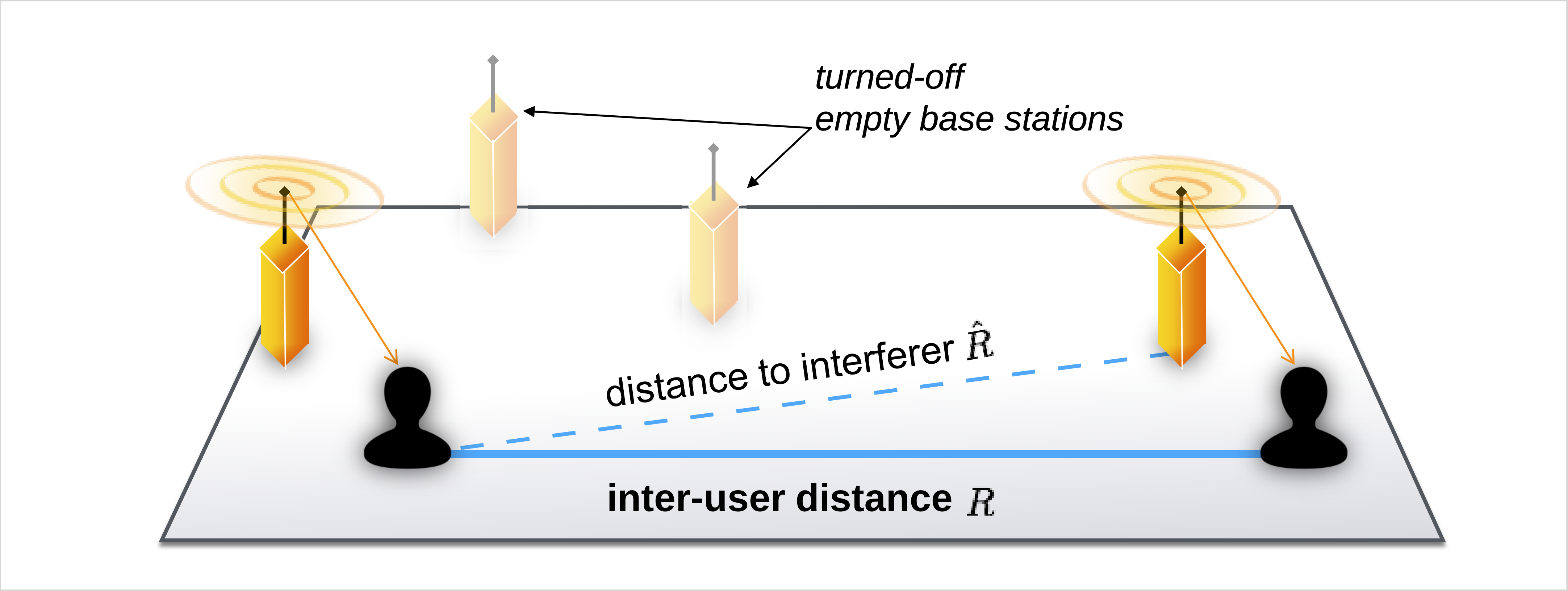
[SMYu13] S. M. Yu and S.-L. Kim, “Downlink Capacity and Base Station Density in Cellular Networks,” Proc. IEEE WiOpt Workshop on SpaSWiN 2013, May 2013.

[SLee12] S. Lee and K. Huang, “Coverage and Economy of Cellular Networks with Many Base Stations,” IEEE Comm. Letters, 2012.

Motivation

User Location Dependent Interfererers in Ultra-Dense Networks

Interferer locations converge to the user locations ($\hat{R} \to R$), under dormant mode operation [Ericsson13]



[Ericsson13] C. Hoymann, D. Larsson, H. Koorapaty, and J. Cheng, "A Lean Carrier for LTE," IEEE Comm. Mag., February 2013.

System Model

- BS locations ~ homogeneous Poisson point process (PPP) with density λ_b
- User locations ~ homogeneous PPP with density λ_u

- Maximum SNR (nearest) association
- Dormant operation when BSs being empty
- Uniformly random scheduler

- Path loss attenuation, Rayleigh fading
- Interference-limited regime (consider SIR instead SINR)

SE in Sparse and Ultra-Dense Networks

BS Density Increase Effect on SE

Sparse network SE

(w.o. multiple access)

$$\gamma_\alpha = \int_0^\infty \left[1 + \rho_t (e^t - 1)^{\frac{\alpha}{2}}\right]^{-1} dt$$

independent of BS density

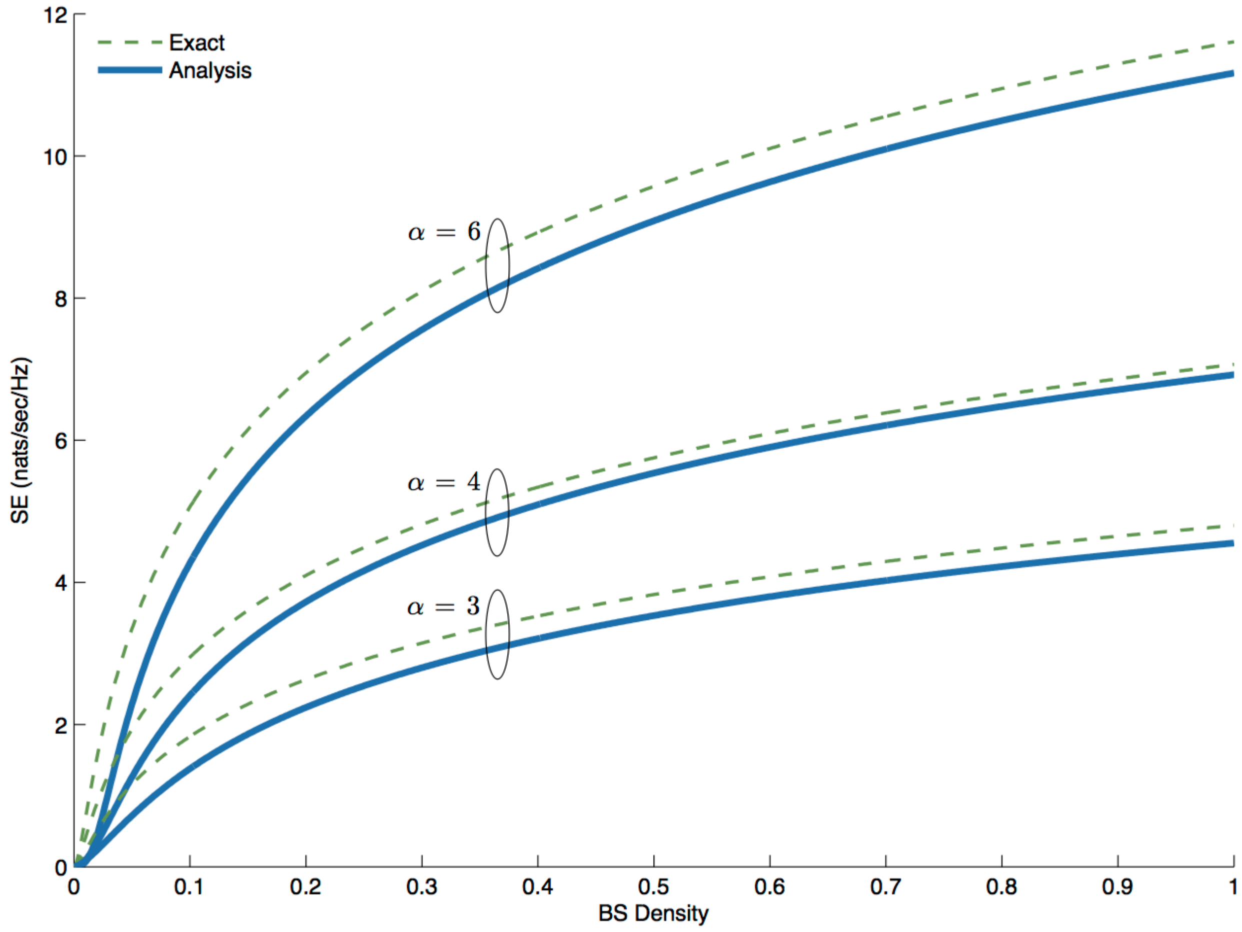
(w. multiple access)

$$\gamma \approx \frac{\boxed{\lambda_b}}{\lambda_u} \gamma_\alpha$$

Ultra-dense network SE

$$\gamma \gtrsim \log\left[1 + \left(\frac{\boxed{\lambda_b}}{\rho_0 \lambda_u}\right)^{\frac{\alpha}{2}}\right]$$

where $\rho_0 := \int_0^\infty 1/\left(1 + u^{\frac{\alpha}{2}}\right) du$



SE in Sparse and Ultra-Dense Networks (w. Multiple Access)

User Density Increase Effect on SE

Sparse network SE

(w.o. multiple access)

$$\gamma_\alpha = \int_0^\infty \left[1+\rho_t(e^t-1)^{\frac{\alpha}{2}}\right]^{-1} dt$$

(w. multiple access)

$$\gamma \approx \frac{\lambda_b}{\boxed{\lambda_u}}\gamma_\alpha$$

∵ **multiple access congestion**

Ultra-dense network SE

$$\gamma \gtrsim \log\left[1+\left(\frac{\lambda_b}{\rho_0\boxed{\lambda_u}}\right)^{\frac{\alpha}{2}}\right]$$

∵ **interference increment**

Profit Maximizing BS & Spectrum OPEX

User Demand Model

- Usage-based pricing: price *p* per bit
- Willingness-to-pay: *Θ* ~ *uniform*(0 , $\boxed{b}$)

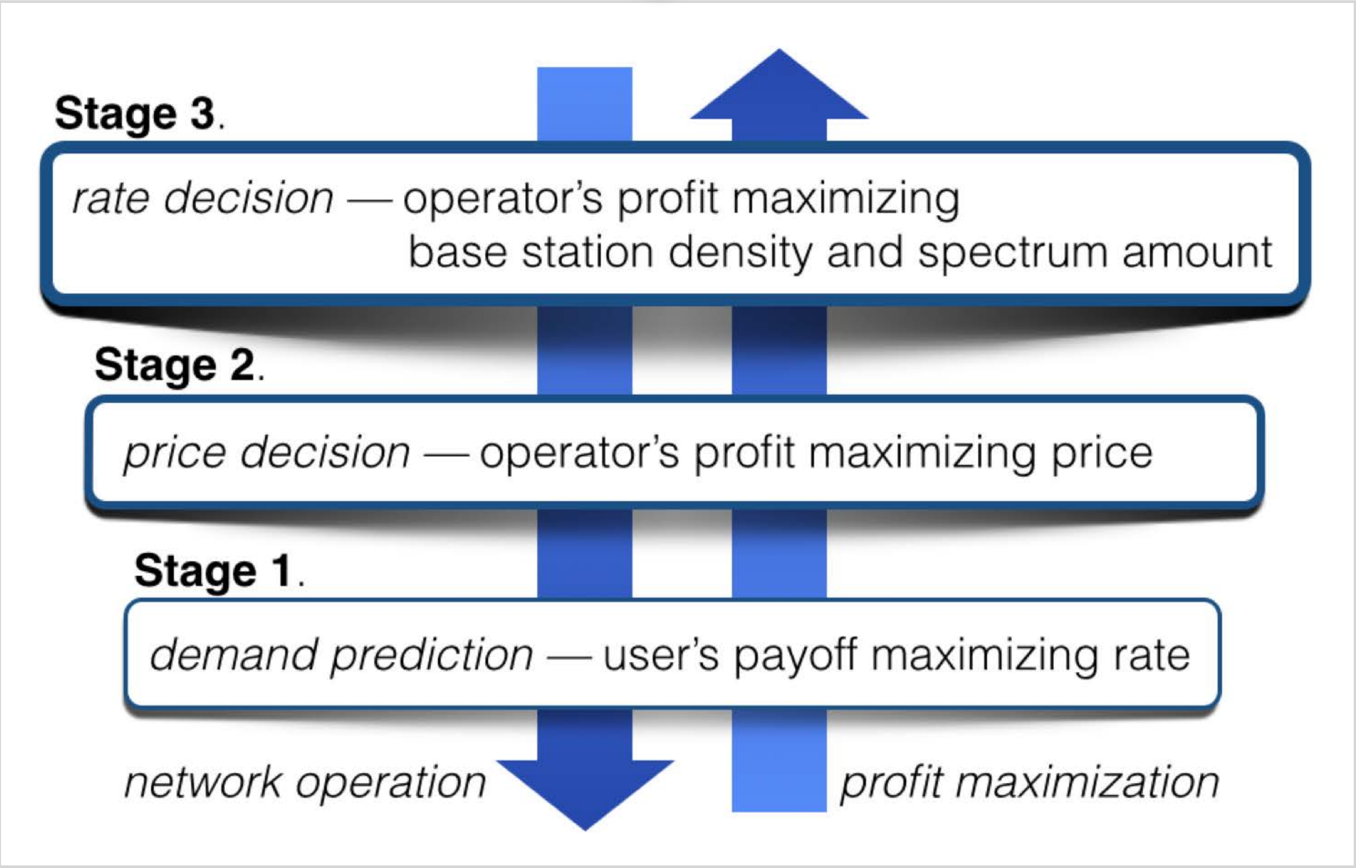
  where **rate sensitivity** *b* > *p*
- Rate (demand) per user*: X*
- Payoff function:

$$U = [\theta \log(1+X) - pX]^+$$

3-Stage Profit Maximization

$$\begin{aligned} (\texttt{P1}):\ \underset{\lambda_b,W,p}{\texttt{Maximize}}\quad & \overset{\text{revenue}}{p\lambda_u\bar{X}} - \overset{\text{OPEX}}{(c_b\lambda_b + c_wW)} \\ \texttt{subject to}\quad & \underset{\text{avg. demand}}{\bar{X}} \le \underset{\text{avg. rate (supply)}}{W\gamma} \end{aligned}$$

comprising 3 stages



Stage 3.

rate decision — operator's profit maximizing base station density and spectrum amount

Stage 2.

price decision — operator's profit maximizing price

Stage 1.

demand prediction — user's payoff maximizing rate

Optimal Price (Stages 1 & 2)

Demand Prediction

- avg. user demand per user) at Stage 1

$$\bar{X} = \frac{(b-p)^2}{2bp}$$

- per-user demand *decreases with p* ($\because$ *b* > *p*)

- its resultant profit in (P1) also *decreases with p*

revenue OPEX

$$\text{(P1)}: \underset{\lambda_b, W, p}{\texttt{Maximize}} \quad p\lambda_u\bar{X} - (c_b\lambda_b + c_w W)$$

$$\texttt{subject to} \quad \bar{X} \boxed{\leq} W\gamma$$

avg. demand avg. rate (supply)

*optimal price occurs when the (P1) constraint's **equality** holds*

Optimal Price at Stage 2

$$p^* \approx \frac{b}{2(1+W\gamma)}$$

Profit Optimal BS Density & Spectrum Amount (Stage 3)

OPEX Effect

Result 1. (Unit Cost) Optimal BS density and spectrum amount are:

- inversely proportional to their unit costs
- proportional to their counter resource unit costs

$$
\textit{Sparse:}\begin{cases}
\lambda_b^* = \left[\dfrac{b\boxed{c_w}}{2\gamma_\alpha}\left(\dfrac{\lambda_u}{\boxed{c_b}}\right)^2\right]^{\frac{1}{3}} \\[2ex]
W^* = \left[\dfrac{b\boxed{c_b}}{2\gamma_\alpha}\left(\dfrac{\lambda_u}{\boxed{c_w}}\right)^2\right]^{\frac{1}{3}}
\end{cases}
$$

$$
\textit{Ultra-Dense:}\begin{cases}
\lambda_b^* \approx \left[\left(\dfrac{\alpha}{2^{2.5}\boxed{c_b}}\right)^8 (b\boxed{c_w})^4 {\rho_0}^\alpha {\lambda_u}^{\alpha+4}\right]^{\frac{1}{\alpha+8}} \\[2ex]
W^* \approx \left[2^{2(\alpha-2)}\dfrac{\boxed{c_b}^\alpha}{\boxed{c_u}^{\alpha+4}} b^4 {\rho_0}^\alpha {\lambda_u}^{\alpha+4}\right]^{\frac{1}{\alpha+8}}
\end{cases}
$$

Profit Optimal BS Density & Spectrum Amount (Stage 3)

OPEX Effect

Result 2. (OPEX Ratio) Operators should invest in BS OPEX:

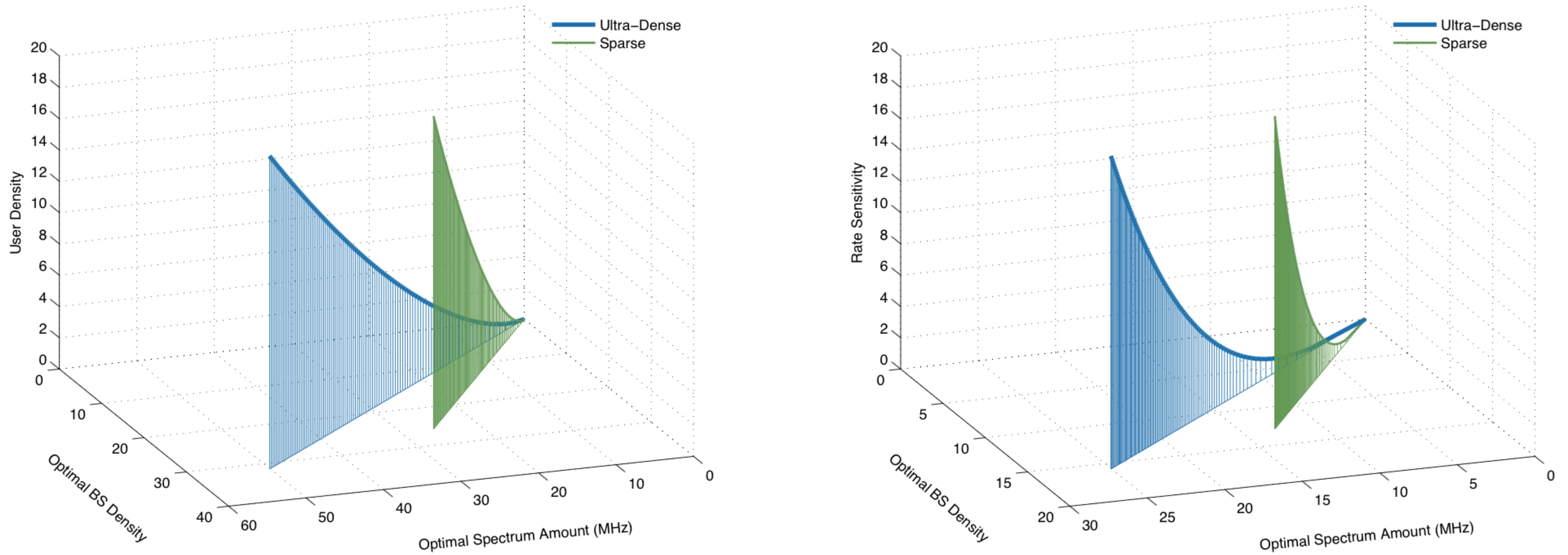
1) as much as spectrum OPEX for sparse networks

$$\boxed{\textit{Sparse:} \quad \frac{c_b\lambda_b^*}{c_w W^*} = 1}$$

2) less than spectrum OPEX for ultra-dense networks

$$\boxed{\textit{Ultra-Dense:} \quad \frac{c_b\lambda_b^*}{c_w W^*} \approx 2^{-2}\alpha^{\frac{8}{\alpha+8}}}$$

0.43 ~ 0.71



(a) For user density λ_u for $b = 10$

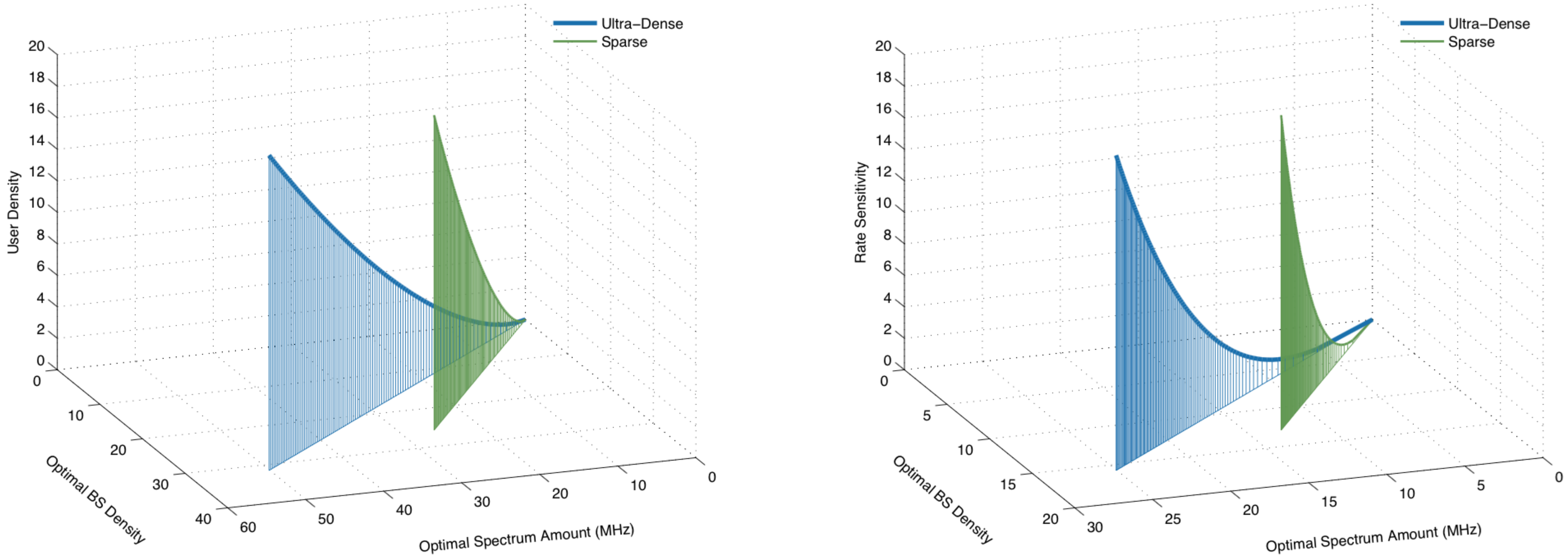
(b) For per-user rate sensitivity b for $\lambda_u = 5$

Fig. 3. Profit optimal BS density λ_b^* and spectrum amount W^* ($\alpha = 4$, $c_b = c_w = 0.1$).

Profit Optimal BS Density & Spectrum Amount (Stage 3)

User Demand Effect: User Density vs. Rate Sensitivity

Result 3. (Increasing Rate) Both profit optimal BS density and spectrum amount increase with user density higher than rate sensitivity



(a) For user density λ_u for $b = 10$

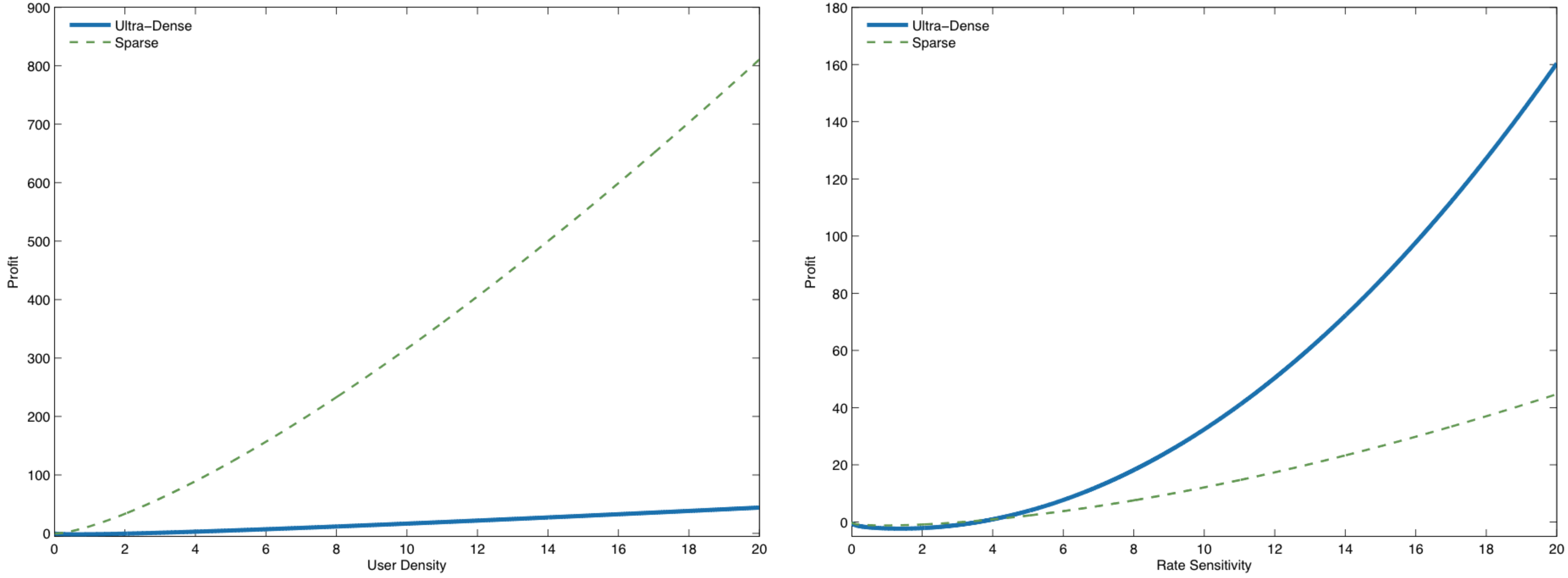
(b) For per-user rate sensitivity b for $\lambda_u = 5$

Fig. 3. Profit optimal BS density λ_b^* and spectrum amount W^* ($\alpha = 4$, $c_b = c_w = 0.1$).

Profit Optimal BS Density & Spectrum Amount (Stage 3)

User Demand Effect: User Density vs. Rate Sensitivity

Result 4. (Ultra-Dense Network Profitability) Ultra-densification is not preferable for user density increase but for rate sensitivity increase



(a) For user density λ_u for $b = 10$

(b) For per-user rate sensitivity b for $\lambda_u = 1$

Fig. 4. Maximized profit with optimal BS density λ_b^* and spectrum amount W^* ($\alpha = 4$, $c_b = c_w = 0.1$).

Part II.

Resource Management and Cell Planning in Milimeter-Wave Overlaid Ultra-Dense Cellular Networks [JSAC14]

- mmWave overlaid ultra-dense cellular network design
- Uplink/downlink SE
- Uplink/downlink resource allocations
- Required BS density scaling law

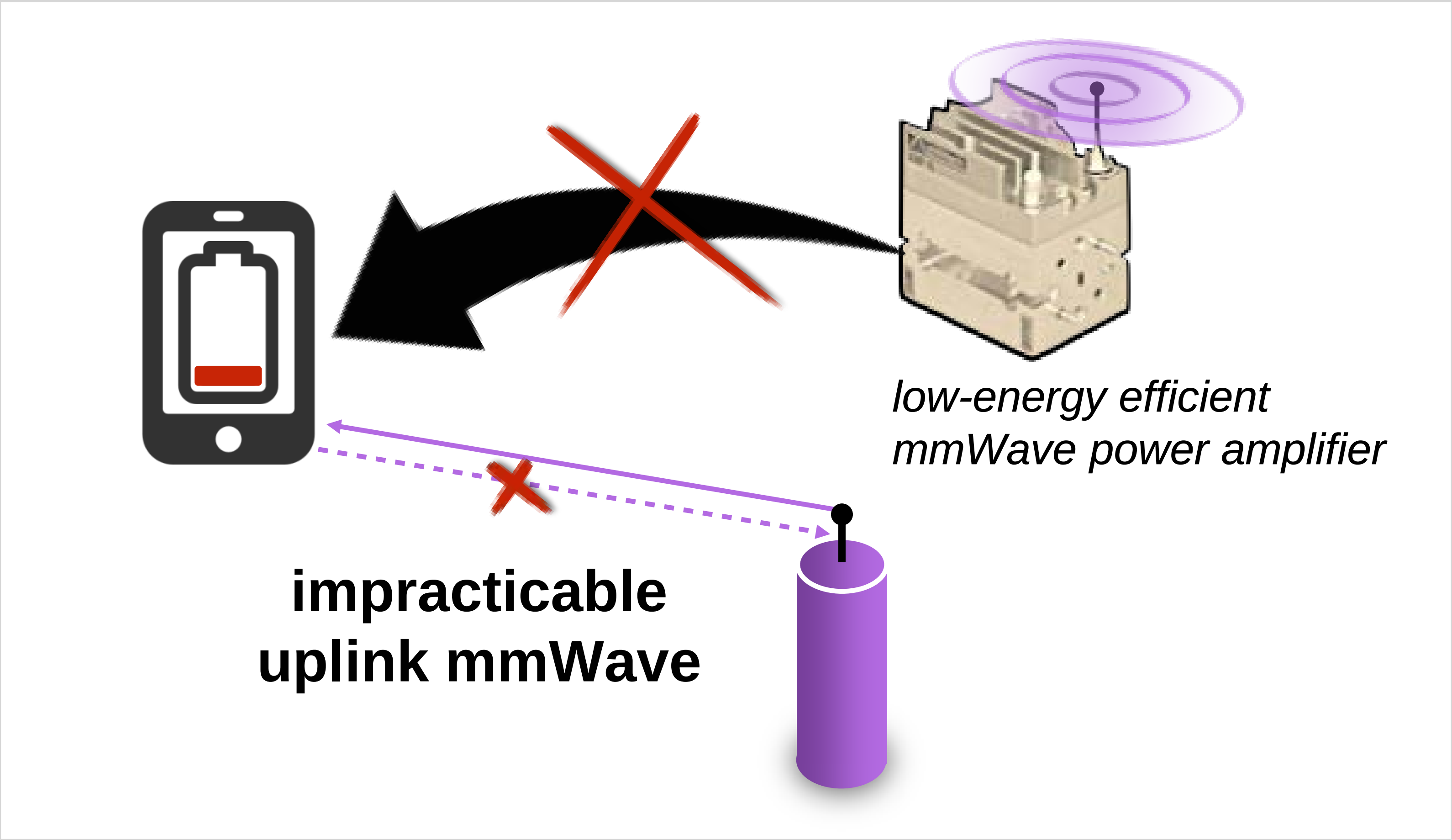
[JSAC14] J. Park, S.-L. Kim, and J. Zander, “Resource Management and Cell Planning in Milimeter-Wave Overlaid Ultra-Dense Cellular Networks,” submitted to IEEE JSAC.

Motivation

- No micro-wave (μWave) & mmWave coexisting network analysis
- No closed-form uplink/downlink SE

* **Uplink/downlink rate asymmetry** [Samsung11, 13]

mmWave resorts to be implemented for downlink transmission only



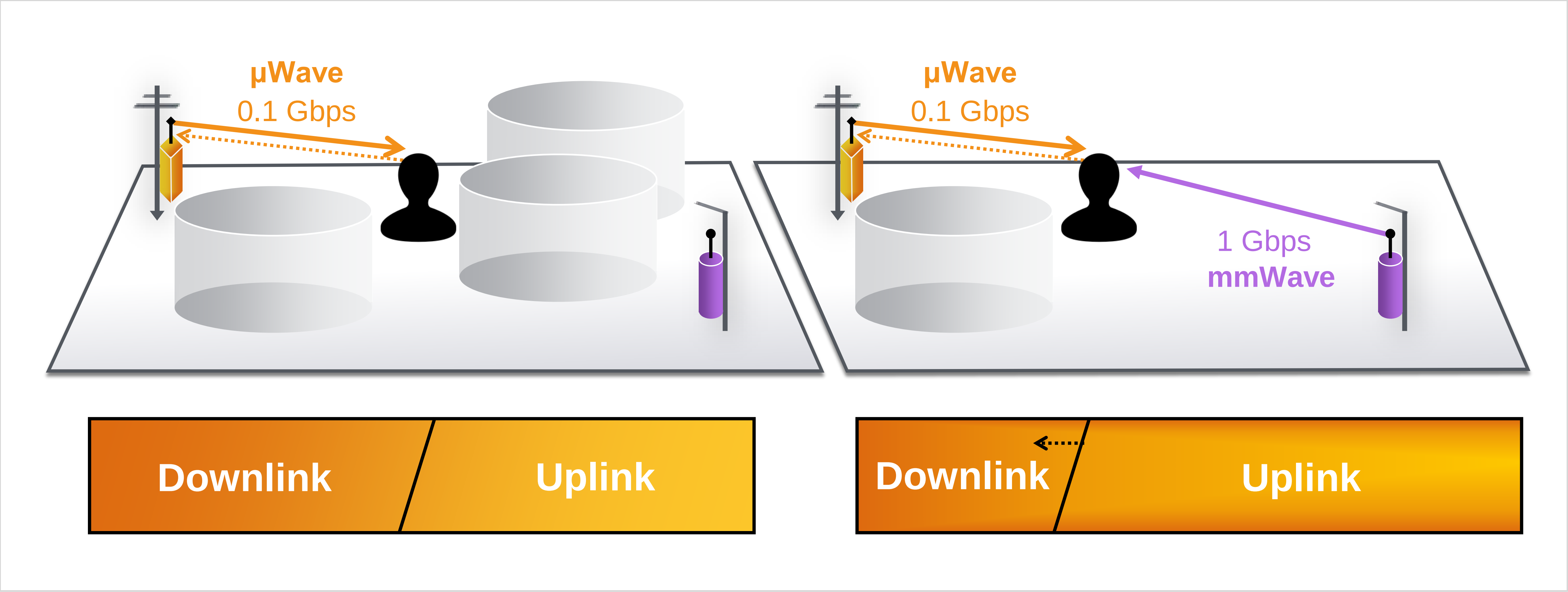
[Samsung11] Z. Pi and F. Khan, "An Introduction to Milimeter-Wave Mobile Broadband Systems," IEEE Comm. Mag., June 2011.

[Samsung13] W. Roh, "Performances and Feasibiliy of mmWave Beamforming Prototype for 5G Cellular Communications," IEEE ICC Keynote, June 2013.

Joint Uplink/Downlink µWave Resource Allocation

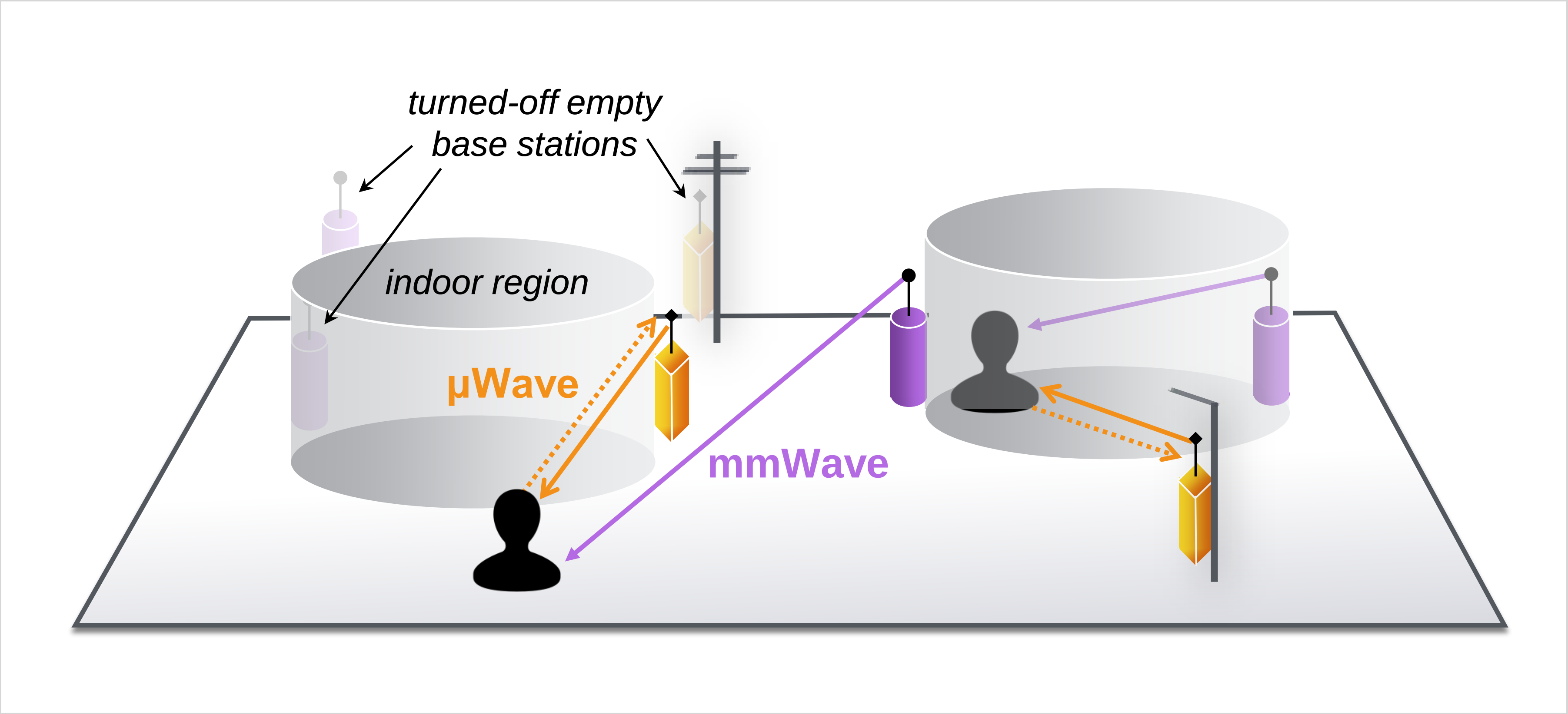
Uplink QoS Guaranteeing µWave Uplink/Downlink Resource Allocation

When (downlink) mmWave is highly available, µWave resource should be more allocated to uplink in order to balance the uplink/downlink rates



Network Model

- mmWave BS locations ~ homogeneous PPP with density λ_m
- μWave BS locations ~ homogeneous PPP with density λ_μ
- User locations ~ homogeneous PPP with density λ_u
- Downlink only mmWave
- Dormant mode operation for empty BSs
- Maximum SNR association
- Heterogeneous carrier aggregation: receiving from both μWave and mmWave if available



Channel Model

- Boolean indoor/outdoor model with indoor grain density λ_g and avg. area S
- μWave penetrable / mmWave impenetrable walls
- **mmWave**:

  - Path loss exponents: 2 for indoor / $\alpha_m > 2$ for outdoor

  - No fading

  - Directional beam with main lobe width Θ

  - Gaussian angle-of-arrival estimation error [Rappaport13]

    → (approx.) directivity gain ~ *exp(1)*
- **μWave**:

  - Path loss exponent: α_μ for both indoor and outdoor

  - Rayleigh fading
- Interference-limited regime

[Rappaport13] T. S. Rappaport, et al., "Milimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEEE Access, 2013.

Uplink/Downlink SEs

µWave SE

- Uplink/downlink reciprocity holds in ultra-dense networks
- Both Uplink and downlink SE are represented as:

$$\gamma_\mu > \log\left(1 + \left[\frac{\boxed{\lambda_\mu}}{\rho_\mu \lambda_\mathrm{u}}\right]^{\alpha_\mu/2}\right)$$

where $\rho_\mu := \int_0^\infty 1/(1+u^{\alpha_\mu/2})du$

mmWave Downlink SE

$$\gamma_\mathrm{m} > \log\left(1 + \frac{\pi \boxed{\lambda_\mathrm{m}}^{\left(\frac{\alpha_\mathrm{m}}{2}-1\right)e^{-\lambda_g S}+1}}{\sigma^2}\left[\frac{2\sigma^2}{\theta}\left(\frac{e^{\lambda_g S}}{\rho_\mathrm{m}\lambda_\mathrm{u}}\right)^{\frac{\alpha_\mathrm{m}}{2}}\right]^{e^{-\lambda_g S}}\right)$$

where $\rho_\mathrm{m} := \int_0^\infty 1/(1+u^{\alpha_\mathrm{m}/2})du$

Downlink Rate Maximization While Guaranteeing Minimum Uplink Rate

Uplink/Downlink Resource Allocation

- Average rate maximizing μWave allocation
- guaranteeing the minimum uplink rate ratio *T*

$$\text{P1.}\ \max_{W_\mu}\ R_\text{d}$$
$$\text{subject to}$$
$$R_\text{u}/R_\text{d} \geq T$$
$$W_{\mu.\text{d}} + W_{\mu.\text{u}} = W.$$

optimization

downlink mmWave SE

$$W^*_{\mu.\text{u}} = \frac{T}{1+T}\left(W + \frac{W_\text{m}\boxed{\gamma_\text{m}}}{\gamma_\mu}\right)$$

$$W^*_{\mu.\text{d}} = \frac{1}{1+T}\left(W - \frac{TW_\text{m}\gamma_\text{m}}{\gamma_\mu}\right)$$

Maximum Downlink Average Rate

$$R_\text{d}{}^* = \frac{1}{1+T}\log\left(1 + c_\text{d}\boxed{\lambda_\text{m}}^{W_\text{m}\left(1-\sqrt{\frac{S}{\lambda_\text{m}}}\right)\left[\left(\frac{\alpha_\text{m}}{2}\right)e^{-\lambda_g S}+1\right]}\lambda_\mu{}^{\frac{W\alpha_\mu}{2}}\right)$$

where

$$c_\text{d} = \left[\frac{\pi}{\sigma^2}\left\{\frac{2\sigma^2}{\theta}\left(\rho_m e^{-\lambda_g S}\lambda_\text{u}\right)^{-\frac{\alpha_\text{m}}{2}}\right\}^{e^{-\lambda_g S}}\right]^{W_\text{m}\left(1-\sqrt{\frac{S}{\lambda_\text{m}}}\right)} \cdot \left(\rho_\mu\lambda_\text{u}\right)^{-\frac{\alpha_\mu W}{2}}$$

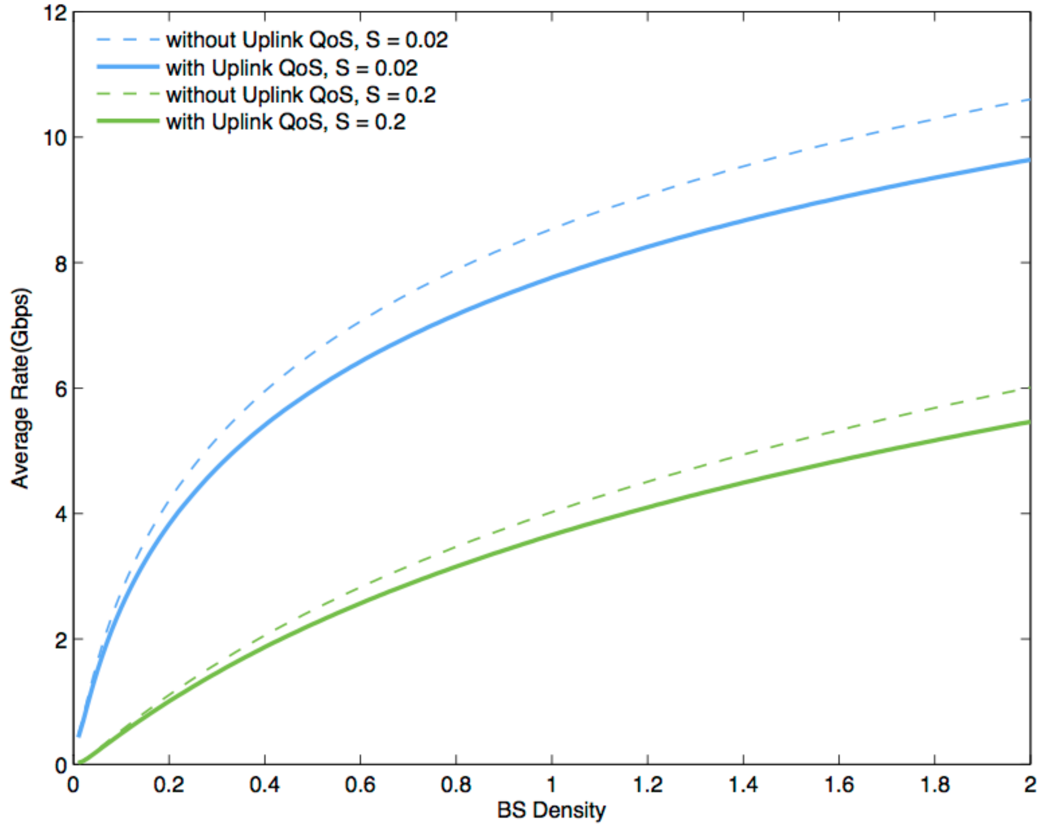


Fig. 6. Maximized downlink average rate with and without the uplink QoS $T = 0.1$ under μWave bandwidth 20 MHz and mmWave bandwidth 500 MHz ($\lambda_\text{u} = 0.02$, $\alpha_\mu = 4.58$, $\alpha_\text{m} = 5.76$, $\lambda_g = 0.1$, $\theta = 10°$, $\sigma^2 = 1$).

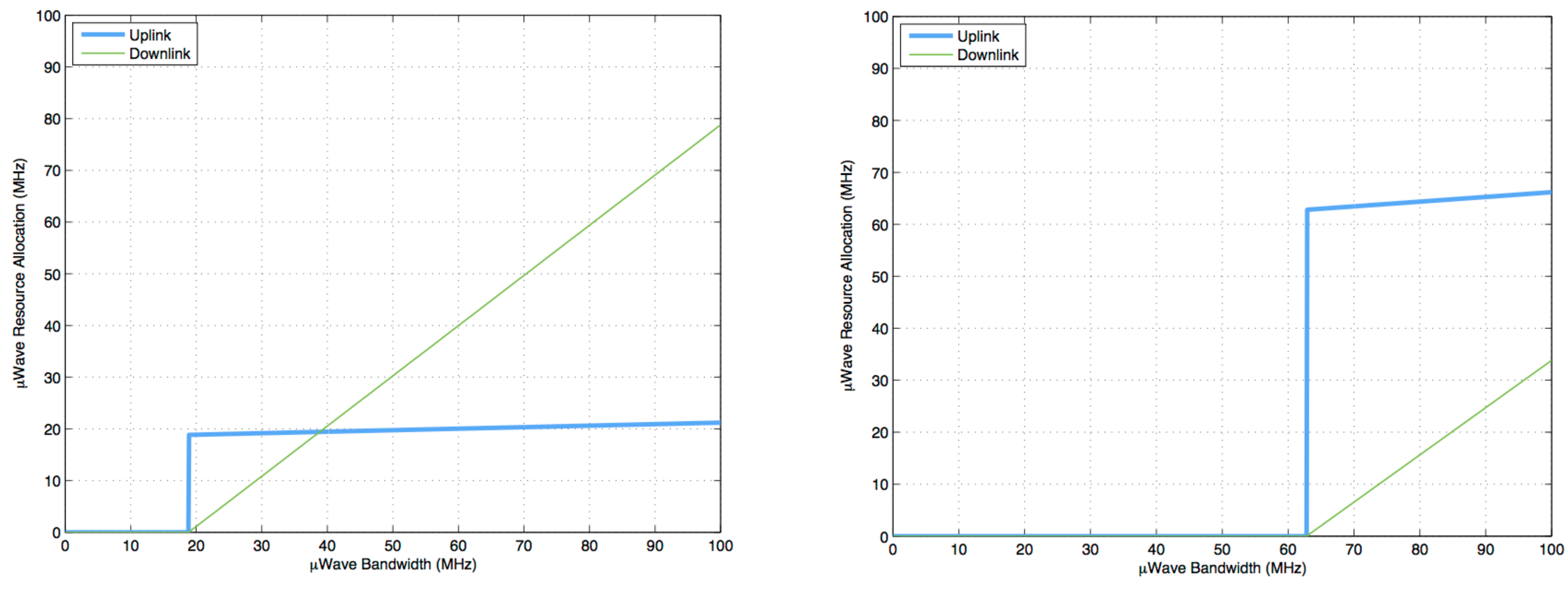
Downlink Rate Maximization While Guaranteeing Minimum Uplink Rate

Uplink/Downlink Resource Allocation

Result 1. (Rate Optimal µWave Allocation with QoS) In a mmWave overlaid cellular network in 5G,

µWave uplink/downlink allocation should be:

1) mostly dedicated to the uplink; or 2) it resort to procuring additional µWave spectrum



(a) Small uplink QoS requirement ($T = 0.03$)

(b) Large uplink QoS requirement ($T = 0.1$)

Fig. 5. Uplink and downlink μWave resource allocations with mmWave bandwidth 500 MHz ($\lambda_{\mathrm{u}} = 0.02$, $\alpha_{\mu} = 4.58$, $\alpha_{\mathrm{m}} = 5.76$, $\lambda_g = 0.1$, $\theta = 10^\circ$, $\sigma^2 = 1$).

Downlink Rate Maximization While Guaranteeing Minimum Uplink Rate

Minimum Required μWave BS densify for Guaranteeing Uplink Rate QoS

Result 2. (Required μWave BS) μWave BS densification cannot be a sole remedy for the minimum uplink QoS problem, but should be in conjunction with procuring more μWave resources

$$O(\lambda_{\mathrm{m}}) = \lambda_\mu^{\frac{\alpha_\mu W}{T W_{\mathrm{m}}\left[(\alpha_{\mathrm{m}}-2)e^{-\lambda_g S}+2\right]}}$$

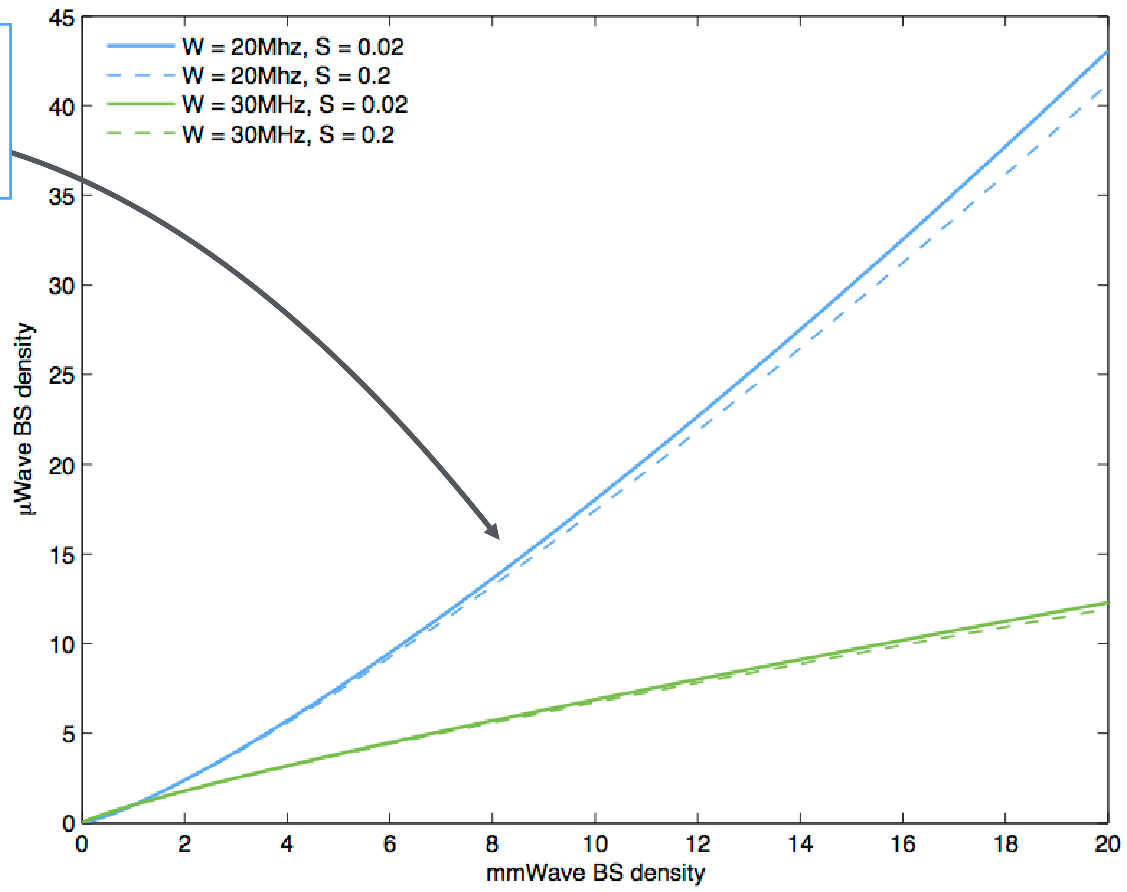


Fig. 7. Minimum required μWave BS density as mmWave BS density increases for μWave bandwidths 20 MHz (blue) and 30 MHz (green) under mmWave bandwidth 500 MHz ($T = 0.04$, $\lambda_{\mathrm{u}} = 0.02$, $\alpha_\mu = 4.58$, $\alpha_{\mathrm{m}} = 5.76$, $\lambda_g = 0.1$, $\theta = 10^\circ$, $\sigma^2 = 1$).