Device Access Control of Wireless Networks for Demand Response in Smart Grids

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Acknowledgement

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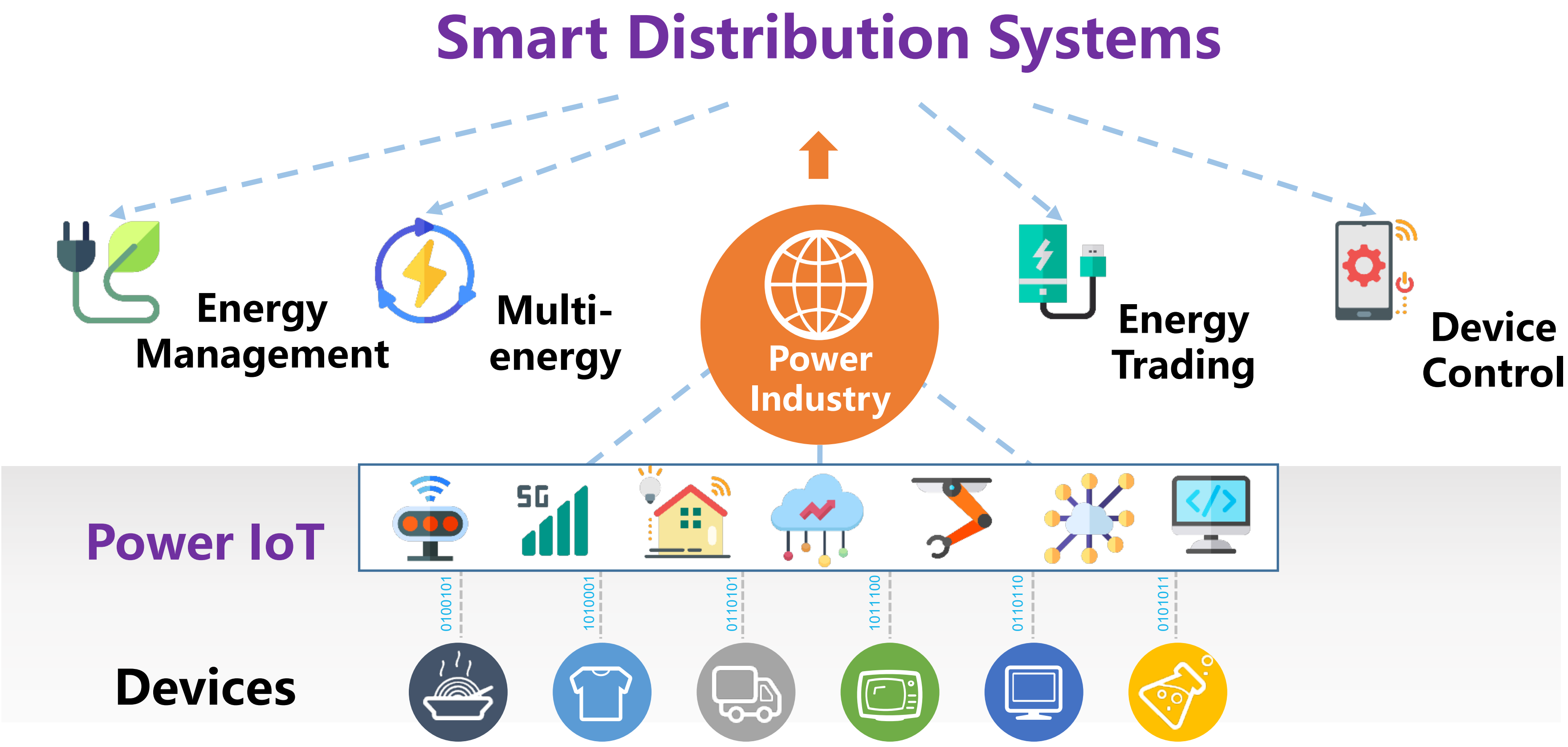
More details of the presentation can be found by:

- Cheng Feng, **Yi Wang***, Xuanyuan Wang, and Qixin Chen*, "Device Access Optimization for Virtual Power Plants in Heterogeneous Networks," *IEEE Transactions on Smart Grid*, in press.
- Chenyu Zhou, Cheng Feng, and **Yi Wang***, "Spatial-Temporal Energy Management of Base Stations in Cellular Networks," *IEEE Internet of Things Journal*, in press.

Outline

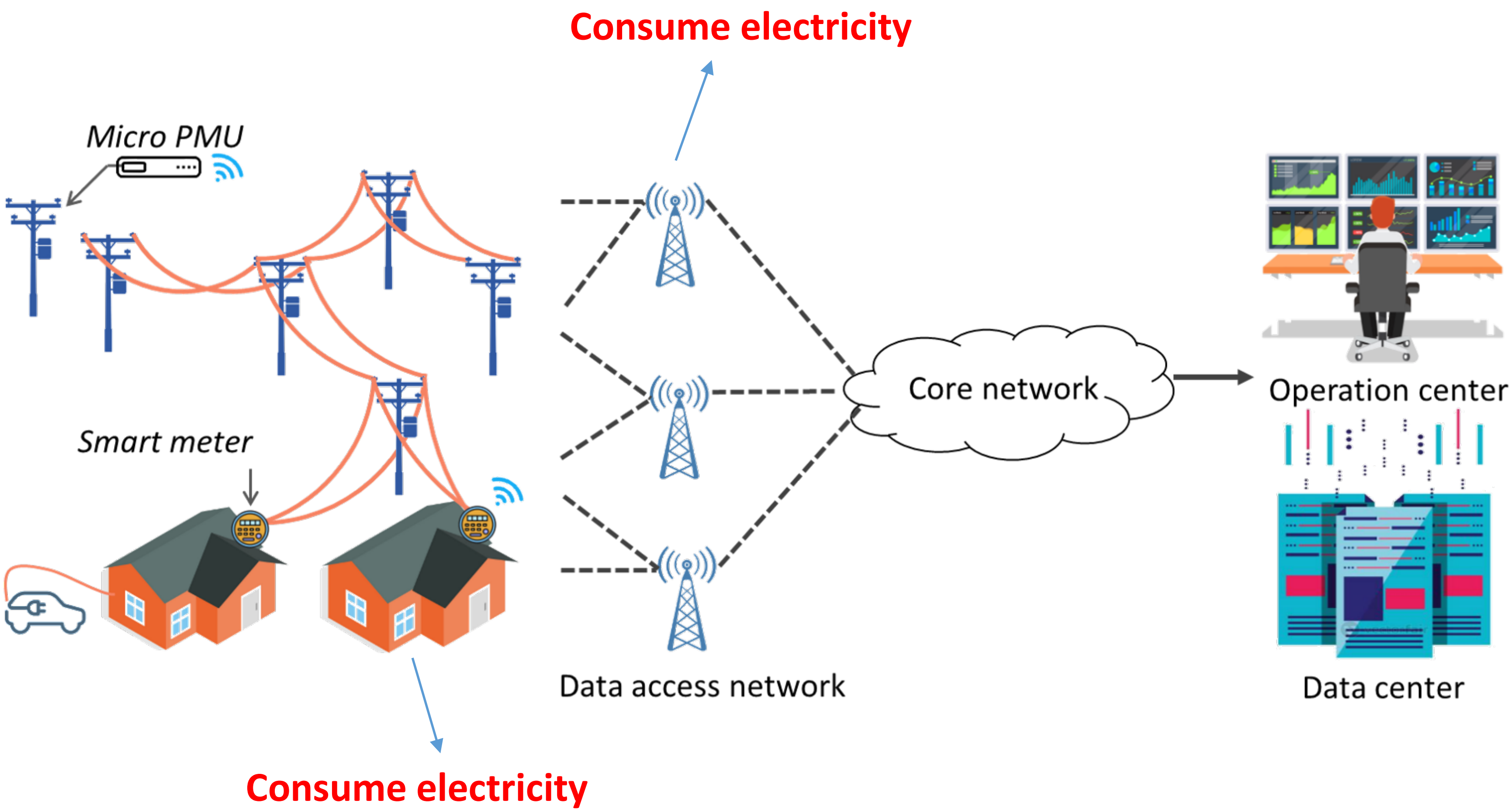
- Wireless Communication in Smart Grid
- Part 1: Energy Management of 5G Base Stations
- Part 2: Virtual Power Plant in Smart Grid
- Conclusions

Device Access Control



- Massive connections;
- Real-time monitoring and control.

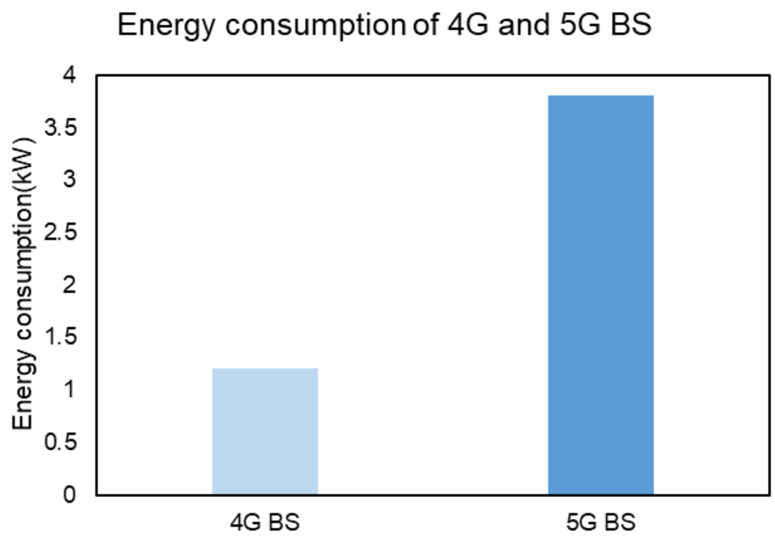
Device Access Control



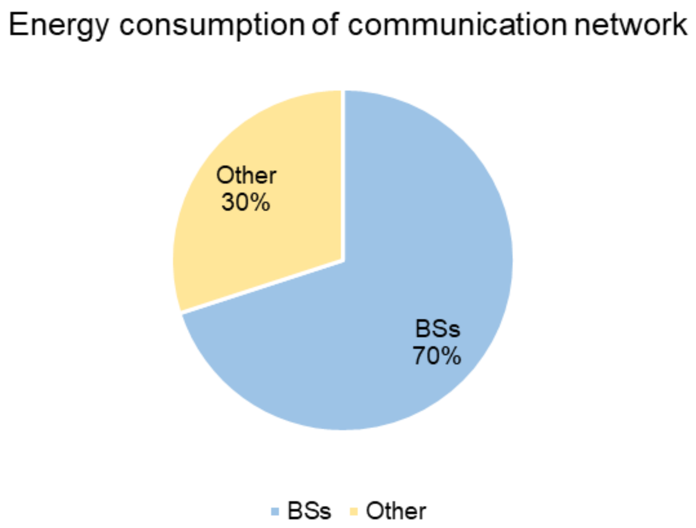
Energy Management of 5G Base Stations

Energy consumption of 5G base station (BS)

3 to 4 times higher than 4G BS[1]



Accounts for about **70%** of network[2]



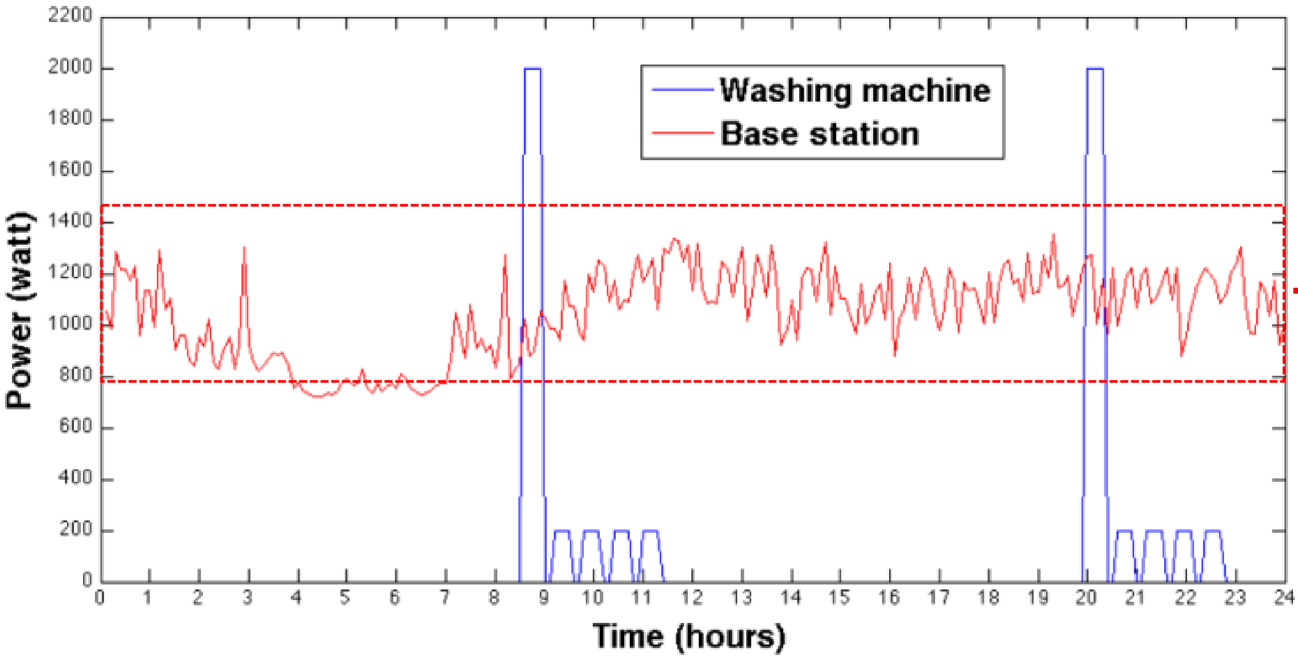
Reducing the high energy consumption of BSs is an effective way to reduce the overall cost for the cellular wireless network operators.

[1] China Mobile Research Institute. White paper on 5G base station energy saving technology [EB/OL]. (2020-8-28) . https://max.book118.com/html/2020/0913/8 105107075002142.shtm.

[2]D. Feng, C. Jiang, G. Lim, L. J. Cimini, G. Feng, and G. Y. Li, “A survey of energy-efficient wireless communications,” IEEE Communications Surveys Tutorials, vol. 15, no. 1, pp. 167–178, 2013.

Energy Management of 5G Base Stations

Demand response potential



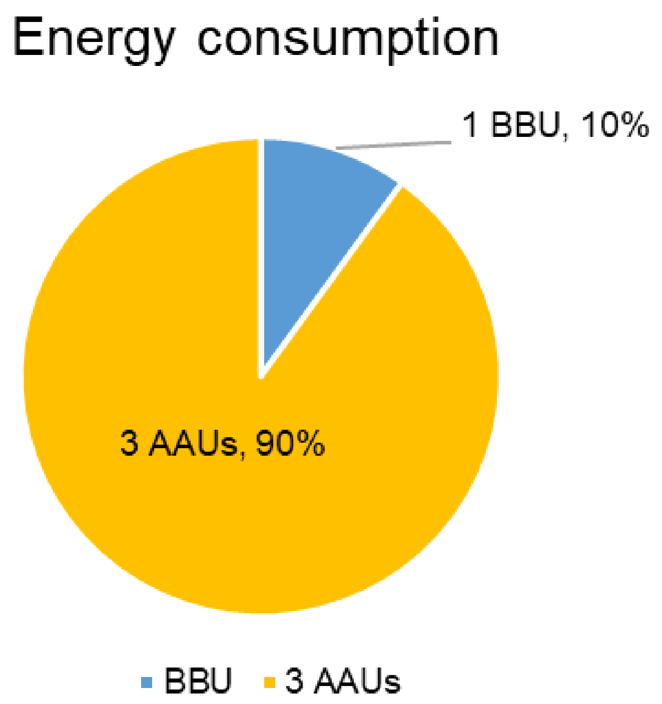
Power consumption of BS keeps at relatively higher level all day.

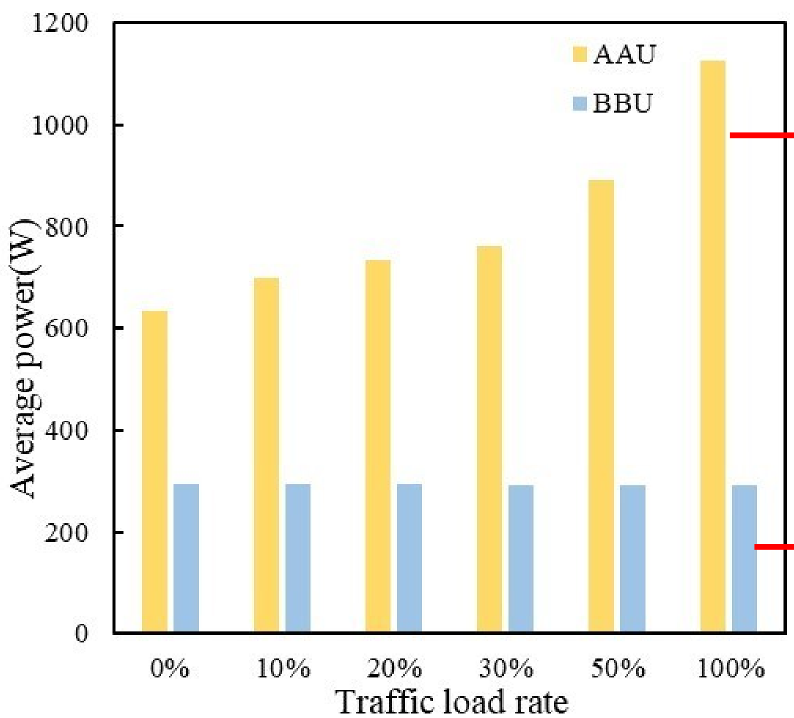
It seems that **BSs have greater potential for demand response**.

Energy Management of 5G Base Stations

Characteristics of 5G Base Station

Configuration of 5G BS: 1 baseband unit (BBU), 3 active antenna units (AAU)





AAU power is greatly affected by traffic load.

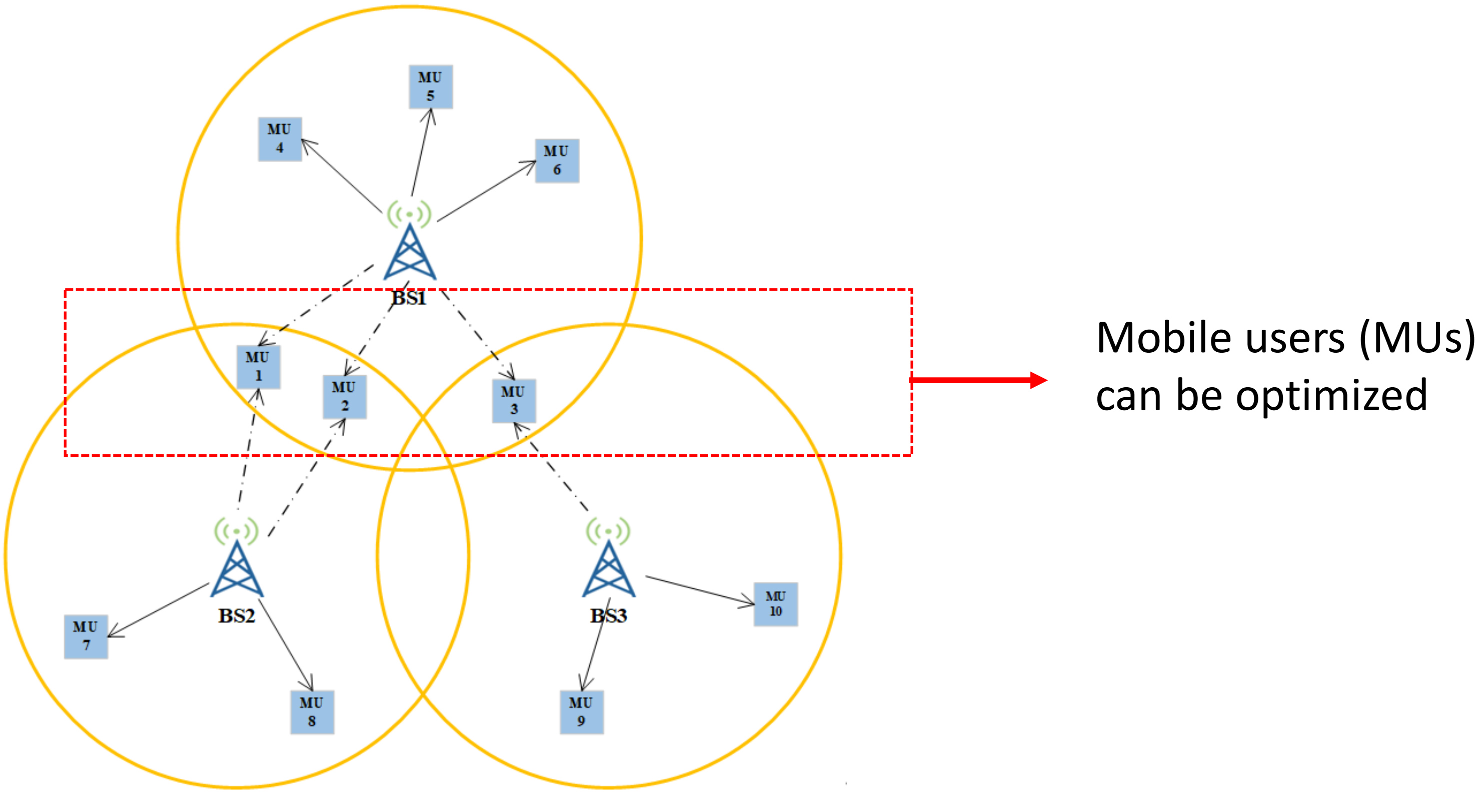
BBU power is relatively stable

The **adjustable energy consumption** based on traffic load accounts for about **40%** of the total.

Energy Management of 5G Base Stations

Spatial-temporal demand response

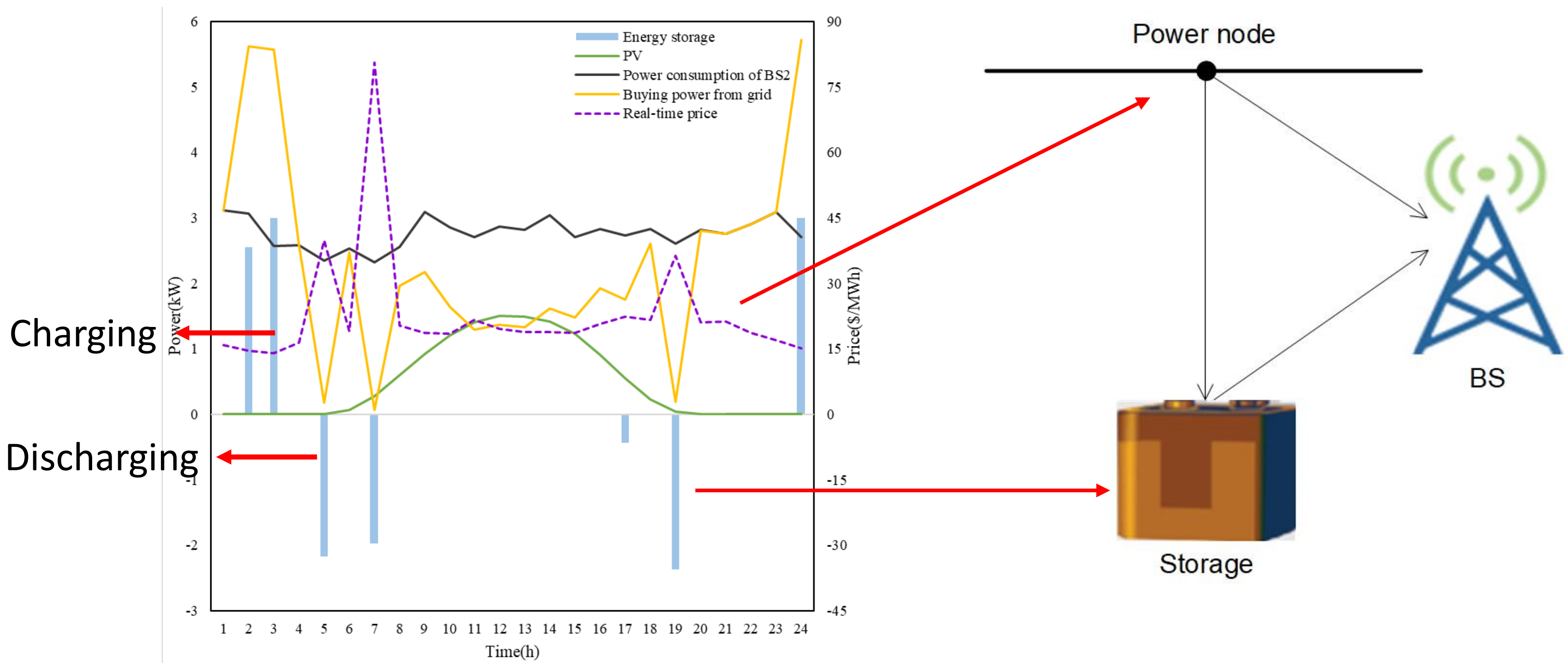
- **Spatial:** BSs can reasonably allocate the communication traffic load in the cellular network according to the real-time price differences among BSs.



Energy Management of 5G Base Stations

Spatial-temporal demand response

- **Temporal:** The operations of BSs which are equipped with energy storage are temporally coupled by the charging/discharging behavior of energy storage.



Energy Management of 5G Base Stations

Optimization Model

	BSs	MUs	Time periods
Number	I	M	T
Set	B	M	T
Index	i	m	t

Objective function

To minimize the total electricity bill of all the BSs B during time periods T

$$\min_{\boldsymbol{P},\boldsymbol{E},\boldsymbol{X},\boldsymbol{W}} \sum_{i\in \mathrm{B}} \sum_{t\in \mathrm{T}} p_{i,t} P_{i,t}^{N}$$

Variable matrices

Net electricity demand of BS *i* at time *t*

Real-time price of BS *i* at time *t*

Energy Management of 5G Base Stations

Optimization Model

Energy constraints

BS

BS power consumption :

Static Dynamic

$$P_{i,t}^{B} = P_{i,t}^{S} + \beta P_{i,t}^{D}, \forall i,t \qquad (1)$$

Energy efficiency

Range of dynamic power consumption:

$$0 \le P_{i,t}^{D} \le P_{i}^{D,\max}, \forall i,t \qquad (2)$$

PV

Output of renewable energy:

$$0 \le P_{i,t}^{R} \le P_{i,t}^{R,\max}, \forall i,t \qquad (3)$$

Storage

Limits on charging/discharging power:

$$\begin{aligned} &0 \le P_{i,t}^{c,S} \le P_{i}^{S,\max}, \forall i,t \\ &0 \le P_{i,t}^{d,S} \le P_{i}^{S,\max}, \forall i,t \end{aligned} \qquad (4)$$

Energy Management of 5G Base Stations

Optimization Model

Energy constraints

SoC of energy storage: **Storage**

$$E^S_{i,t+1} = E^S_{i,t} + \eta_{i,c} P^{c,S}_{i,t} - P^{d,S}_{i,t} / \eta_{i,d}, \forall i,t \tag{5}$$

Range of SoC:

$$0 \le E^S_{i,t} \le E^{S,\max}_i, \forall i,t \tag{6}$$

SoC at starting time and ending time:

$$E^S_{i,1} = E^S_{i,T} = 0.5 E^{S,\max}_i, \forall i,t \tag{7}$$

Net electricity demand of BS: **BS**

$$P^N_{i.t} = \overset{\text{BS}}{P^B_{i,t}} - \underset{\text{PV}}{P^R_{i,t}} + \overbrace{P^{c,S}_{i,t} - P^{d,S}_{i,t}}^{\text{Storage}}, \forall i,t \tag{8}$$

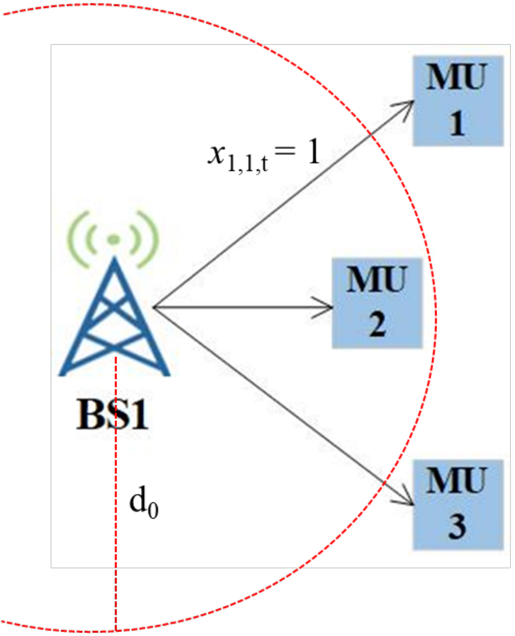
Reversible charging not allowed:

$$P^N_{i.t} \ge 0, \forall i,t \tag{9}$$

Energy Management of 5G Base Stations

Optimization Model

Communication constraints



User association binary variable:

$$x_{i,m,t} \in \{0,1\}, \forall i,m,t \tag{10}$$

Each MU connected to one and only one BS:

$$\sum_{i \in \mathrm{B}} x_{i,m,t} = 1, \forall i,m,t \tag{11}$$

Signal-to-interference-plus-noise ratio (SINR):

$$\phi_{i,m,t} = \frac{\overbrace{P_{i,t}^{D} g_{i,m}}^{\text{Signal power}}}{\underbrace{\sigma^2}_{\text{Noise power}} + \underbrace{\sum_{j \in \mathrm{B}, j \neq i} P_{j,t}^{D} g_{j,m}}_{\text{Interference power}}}, \forall i,m,t \tag{12}$$

Channel gain:

$$g_{i,m} = \begin{cases} A\left(\dfrac{d_{i,m}}{d_0}\right)^{-\alpha}, & d_{i,m} \geq d_0, \\ A, & 0 \leq d_{i,m} < d_0, \end{cases} \quad \forall i,m \tag{13}$$

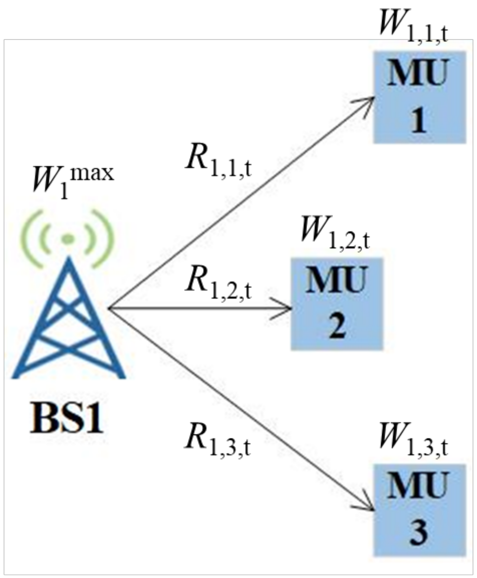
Path loss exponent

Fixed path loss

Energy Management of 5G Base Stations

Optimization Model

Communication constraints



SINR $\phi_{i,m,t} = \dfrac{P_{i,t}^{D} g_{i,m}}{\sigma^2 + \sum_{j \in \mathrm{B}, j \neq i} P_{j,t}^{D} g_{j,m}}, \forall i,m,t$

Shannon's Theorem:

$$R_{i,m,t} = W_{i,m,t} \log_2\left(1 + \phi_{i,m,t}\right), \forall i,m,t \quad (14)$$

Required transmission rate of MU must be satisfied:

$$R_{i,m,t} \geq R_{m,t}^{req} x_{i,m,t}, \forall i,m,t \quad (15)$$

MU obtain bandwidth resource from BS connected:

$$0 \leq W_{i,m,t} \leq x_{i,m,t} W_i^{\max}, x_{i,m,t} \in \{0,1\} \; \forall i,m,t \quad (16)$$

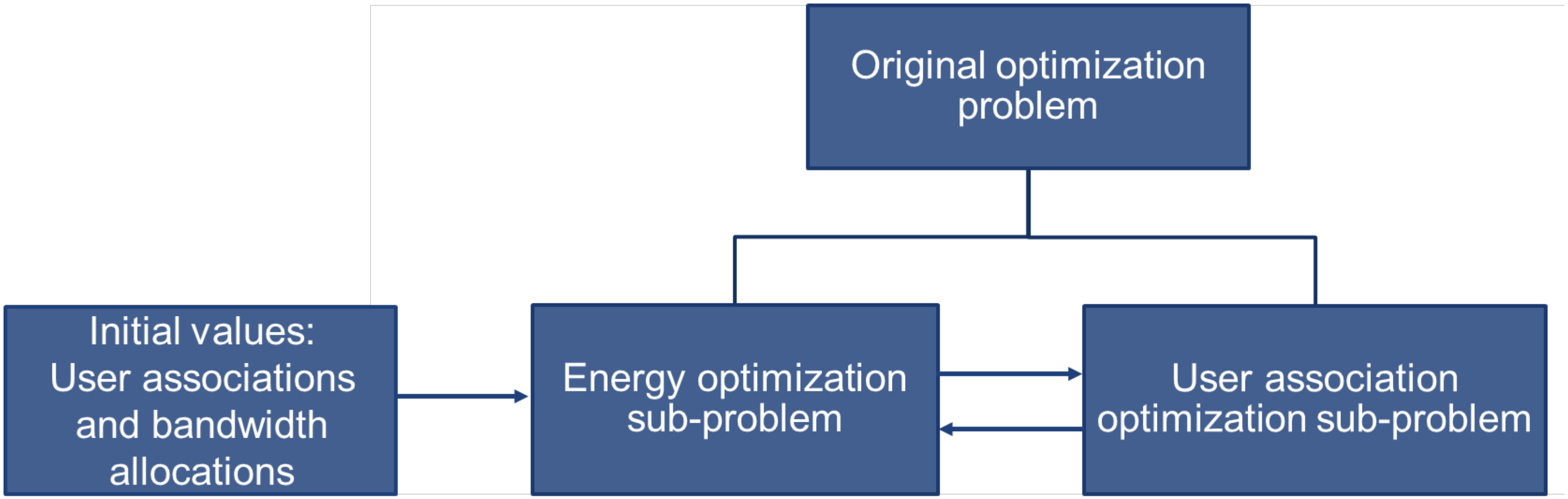
Assigned bandwidth cannot exceed total bandwidth of BS:

$$\sum_{m \in \mathrm{M}} x_{i,m,t} W_{i,m,t} \leq W_i^{\max}, \forall i,t \quad (17)$$

Energy Management of 5G Base Stations

Iterative algorithm

Decomposes the original optimization problem into two sub-problems. The two sub-problems are solved iteratively until convergence to find the local optimal solution of the original optimization problem.



Energy Management of 5G Base Stations

Solution Methodology

Solving process of iterative algorithm

Energy Optimization Sub-problem (LP problem):

Decision variable: dynamic power consumptions, output of renewable energy, charging/discharging power and SoC of energy storage

Parameter: user associations, bandwidth allocations

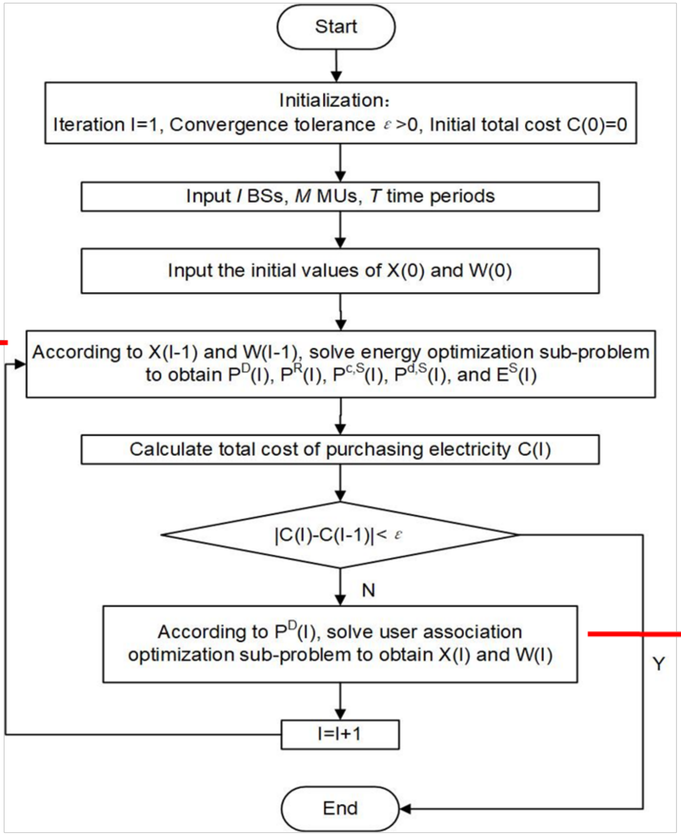
Objective: minimize total cost

$$\min_{\boldsymbol{P},\boldsymbol{E}} \sum_{i\in \mathrm{B}}\sum_{t\in \mathrm{T}} p_{i,t} P^{N}_{i,t}$$

$$s.t.\ (1)\text{-}(9), (12)\text{-}(15)$$

energy constraints (1)-(9)

transmission rate constraints (12)-(15)



User Association Optimization Sub-problem (MILP problem):

Decision variable: user associations, bandwidth allocations

Parameter: dynamic power consumptions

Objective: maximize each MU's transmission rate, provide more optimization space for the energy optimization sub-problem

$$\max_{\boldsymbol{X},\boldsymbol{W},\varphi\ge 0} \varphi$$

$$s.t.\ \sum_{i\in \mathrm{B}} R_{i,m,t} \ge R^{req}_{m,t} + \varphi, \forall m,t$$

$$(10)\text{-}(14), (16)\text{-}(17)$$

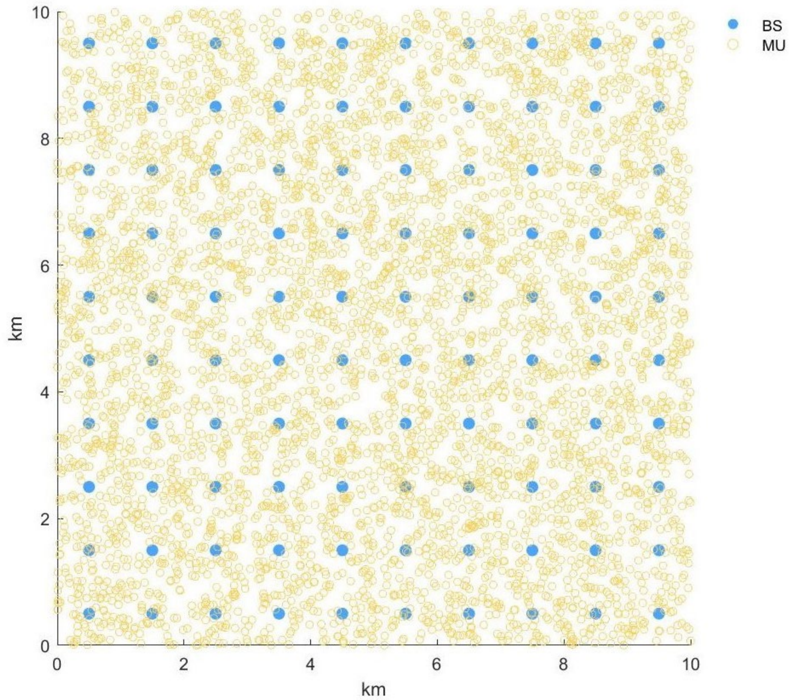
communication constraints

Energy Management of 5G Base Stations

Case Studies

Traditional case study

I = 100, M = 5000, T = 24. In 100 km^2 area, BSs are uniformly distributed, MUs are randomly distributed. Distance between two BSs is 1km. Coverage radius of each BS is 750m. User associations of **3236** MUs can be optimized.



Energy Management of 5G Base Stations

Case Studies

Results and analysis

Four scenarios are proposed, which have the same background and parameters.

Scenario	Initial value type	User associations	Bandwidth allocations
1	Distance-prioritized	Can be optimized	Can be optimized
2	Price-prioritized	Can be optimized	Can be optimized
3	Distance-prioritized	Fixed	Can be optimized
4	Price-prioritized	Fixed	Can be optimized

Energy Management of 5G Base Stations

Case Studies

Results and analysis

Consider distance and real-time price factors for user associations comprehensively

Scenario	Type of initial value	Total cost ($)	Total electricity (kWh)	Cost of dynamic power consumption ($)	Electricity of dynamic power consumption (kWh)	Calculation time (min)
1	Distance-prioritized (δ=0.5)	166.49	6927.74	34.01	1407.74	48.91
3	Distance-prioritized	186.34	7753.14	53.86	2233.14	19.82

Only consider distance factor for user associations

Compared with scenario 3, total cost and total electricity of scenario 1 are reduced by about **10.6%**.

Energy Management of 5G Base Stations

Case Studies

Results and analysis

Consider real-time price and distance factors for user associations comprehensively

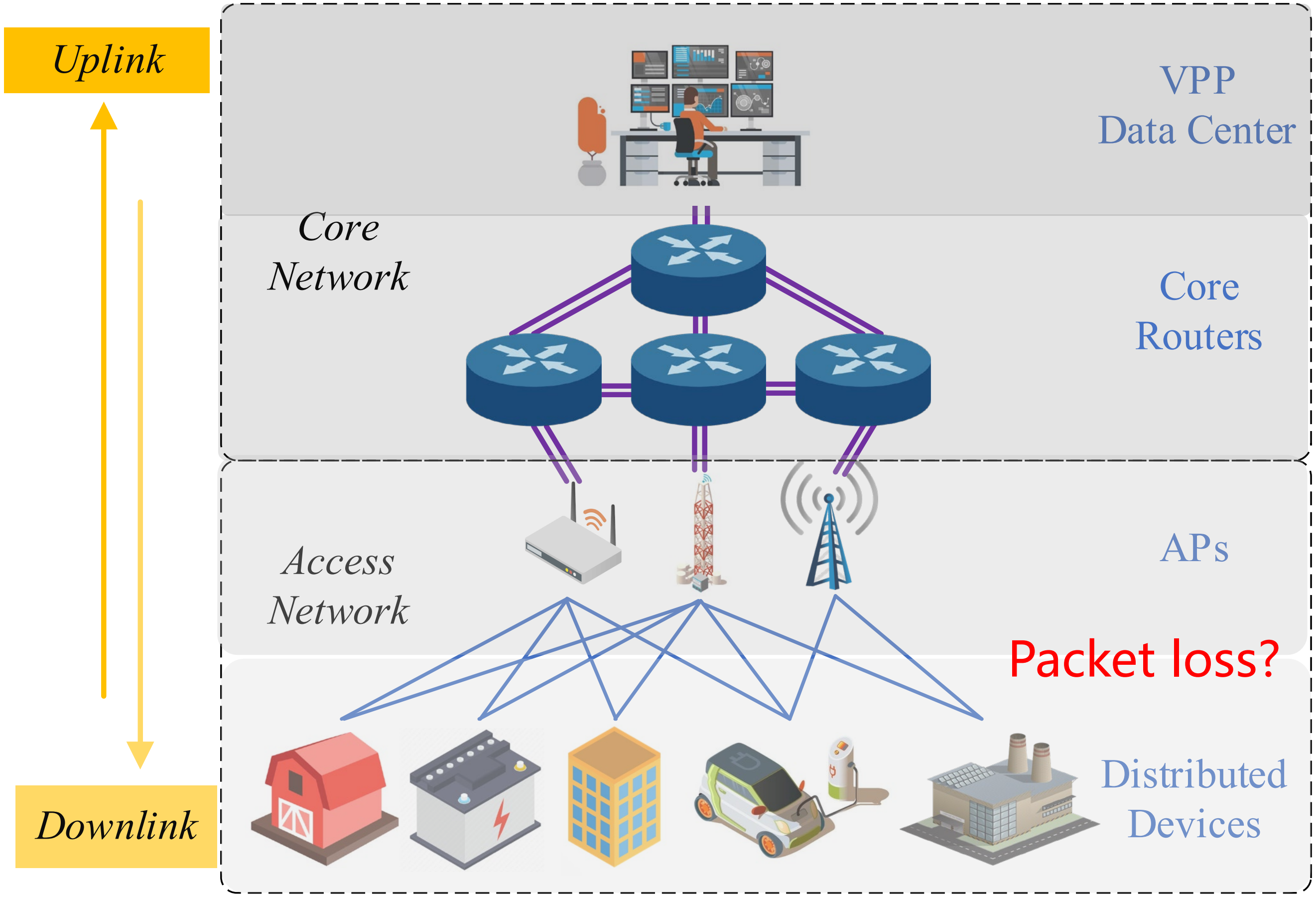
Scenario	Type of initial value	Total cost ($)	Total electricity (kWh)	Cost of dynamic power consumption ($)	Electricity of dynamic power consumption (kWh)	Calculation time (min)
2	Price-prioritized	177.8	7759.42	45.32	2239.42	21.78
4	Price-prioritized	197.05	8599.58	64.58	3079.58	14.45

Only consider real-time price factor for user associations

Compared to scenario 4, the total cost and total electricity of scenario 2 are reduced by about **9.8%**.

Virtual Power Plant in Smart Grid

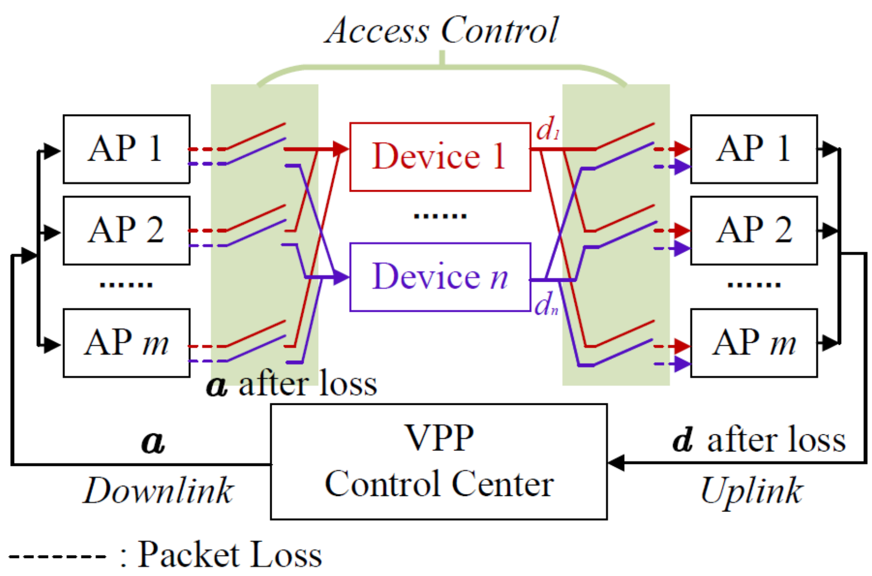
Communication Structure of VPP



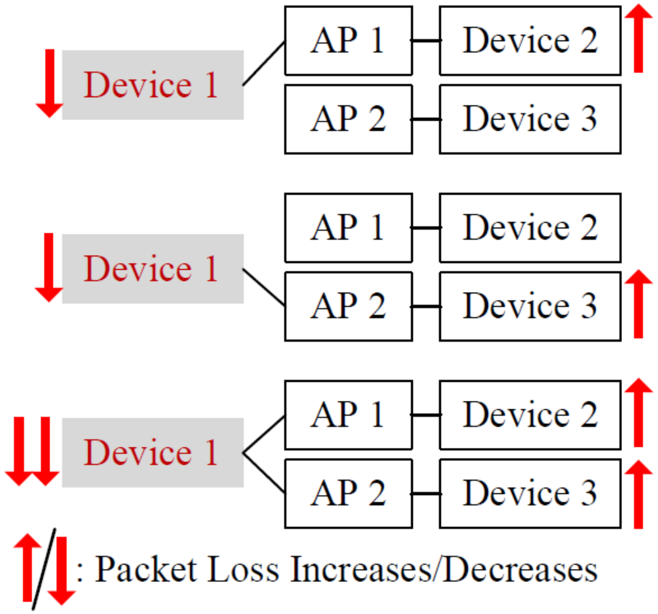
Uplink: Status of distributed energy resources
Downlink: dispatch order

Virtual Power Plant in Smart Grid

Communication Structure of VPP



The control perspective diagram



Why need device access optimization?

Virtual Power Plant in Smart Grid

Problem Formulation

$$\min \ C = \begin{bmatrix} \boldsymbol{p}_{\text{up}} \odot (\mathbf{1}_N - \boldsymbol{p}_{\text{down}}) \\ (\mathbf{1}_N - \boldsymbol{p}_{\text{up}}) \odot \boldsymbol{p}_{\text{down}} \\ \boldsymbol{p}_{\text{up}} \odot \boldsymbol{p}_{\text{down}} \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{up}} \\ \boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{down}} \\ \boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{updown}} \end{bmatrix}^{\text{T}}$$

$$\approx \underbrace{\boldsymbol{p}_{\text{up}} (\boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{up}})^{\text{T}}}_{C_{\text{up}}} + \underbrace{\boldsymbol{p}_{\text{down}} (\boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{down}})^{\text{T}}}_{C_{\text{down}}}$$

$$U_{n,\text{pe}} = \mathbb{E}_{d_n} \left[\max_{a_n} \ U(a_n, d_n) \right]$$

$$U_{n,\text{up}} = \max_{a_n} \mathbb{E}_{d_n} \left[U(a_n, d_n) \right]$$

$$U_{n,\text{down}} = \mathbb{E}_{d_n} \left[U(\phi_n, d_n) \right]$$

Adverse Effects of Packet Loss

- Objective: to minimize the total expected revenue reduction due to packet loss C.

Virtual Power Plant in Smart Grid

Adverse Effects of Packet Loss

Perfect transmission:

$$U\left(a_n, d_n\right) \xrightarrow{\text{Receiving status data}} \max_{a_n} U\left(a_n, d_n\right) \xrightarrow{\text{Sending dispatch order}} \mathbb{E}_{d_n}\left[\max_{a_n} U\left(a_n, d_n\right)\right]$$

dispatch order   Status data

Virtual Power Plant in Smart Grid

Adverse Effects of Packet Loss

Uplink packet loss:

$$U\left(a_n, d_n\right) \longrightarrow \max_{a_n} U\left(a_n, d_n\right) \longrightarrow \mathbb{E}_{d_n}\left[\max_{a_n} U\left(a_n, d_n\right)\right]$$

dispatch order — Status data

Sending dispatch order

$$U_{n,\mathrm{up}} = \max_{a_n} \mathbb{E}_{d_n}\left[U\left(a_n, d_n\right)\right]$$

Virtual Power Plant in Smart Grid

Adverse Effects of Packet Loss

Downlink packet loss:

$$U(\underbrace{a_n}_{\text{dispatch order}}, \underbrace{d_n}_{\text{Status data}}) \xrightarrow{\text{Receiving status data}} \max_{a_n} U(a_n, d_n) \not\longrightarrow \mathbb{E}_{d_n}\left[\max_{a_n} U(a_n, d_n)\right]$$

$$\max_{a_n} U(a_n, d_n) \longrightarrow U_{n,\mathrm{down}} = \mathbb{E}_{d_n}\left[U(\underbrace{\phi_n}_{\text{null control order}}, d_n)\right]$$

Virtual Power Plant in Smart Grid

Problem Formulation

$$\min\ C = \begin{bmatrix} \boldsymbol{p}_{\text{up}} \odot (\mathbf{1}_N - \boldsymbol{p}_{\text{down}}) \\ (\mathbf{1}_N - \boldsymbol{p}_{\text{up}}) \odot \boldsymbol{p}_{\text{down}} \\ \boldsymbol{p}_{\text{up}} \odot \boldsymbol{p}_{\text{down}} \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{up}} \\ \boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{down}} \\ \boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{updown}} \end{bmatrix}^{\mathrm{T}}$$

$$\approx \underbrace{\boldsymbol{p}_{\text{up}} (\boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{up}})^{\mathrm{T}}}_{C_{\text{up}}} + \underbrace{\boldsymbol{p}_{\text{down}} (\boldsymbol{U}_{\text{pe}} - \boldsymbol{U}_{\text{down}})^{\mathrm{T}}}_{C_{\text{down}}}$$

$$U_{n,\text{pe}} = \mathbb{E}_{d_n}\left[\max_{a_n}\ U(a_n, d_n)\right]$$

$$U_{n,\text{up}} = \max_{a_n} \mathbb{E}_{d_n}\left[U(a_n, d_n)\right]$$

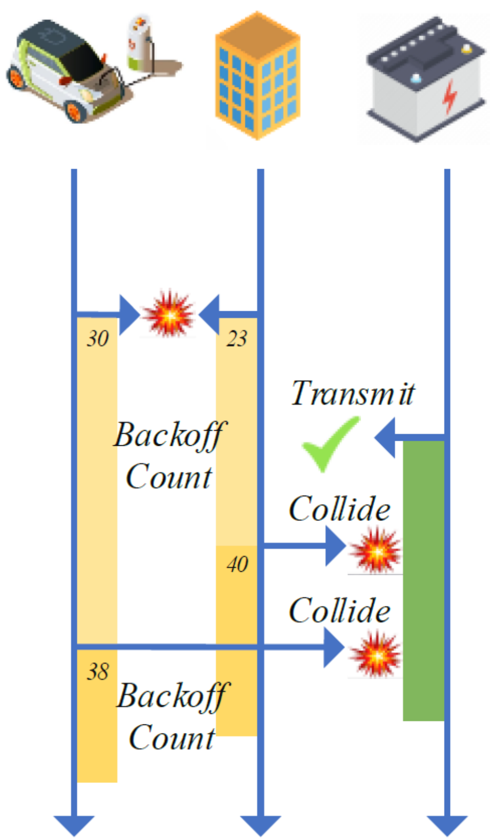
$$U_{n,\text{down}} = \mathbb{E}_{d_n}\left[U(\phi_n, d_n)\right]$$

Adverse Effects of Packet Loss

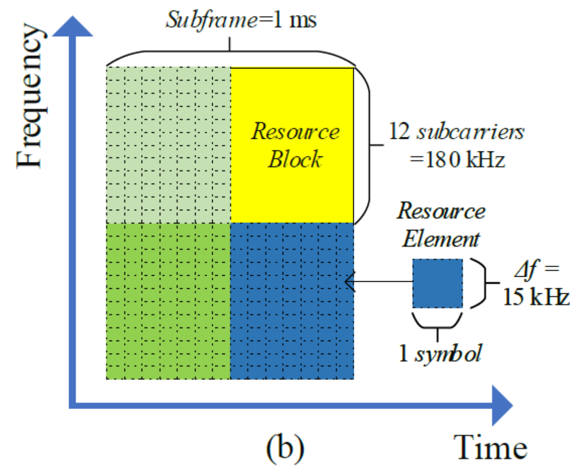
- Objective: to minimize the total expected revenue reduction due to packet loss C.

Virtual Power Plant in Smart Grid

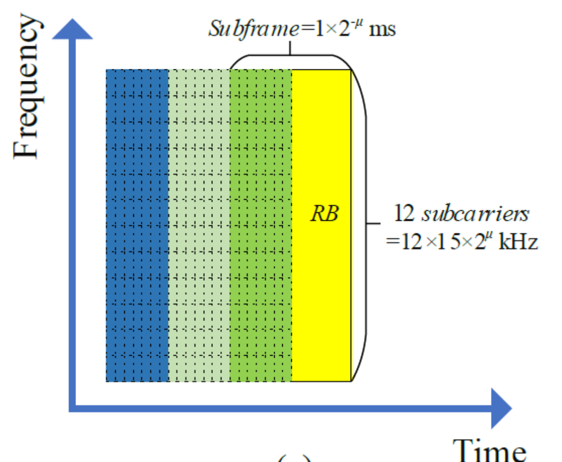
Packet Loss Rate



(a)



(b)



(c)

(a): The protocol of **Wi-Fi**. If devices collide, they backoff and set counter to wait for next re-transmission.
(b): The **LTE** resource grid map.
(c): The **5G** New Radio resource grid map.

PLR:

$$\theta_m = \mathscr{L}_m\left(k + N_m, r, r_{\mathrm{am}}\right)$$

total number of connected devices and users

device rate requirements

users rate requirements

Virtual Power Plant in Smart Grid

Packet Loss Rate of Wifi:

The probability of collision

$$\begin{cases} \tau = 2\left(1-2\pi\right)\left(1-\pi^{i_{\max}+1}\right)/B \\ B = \ W_0\left(1-\left(2\pi\right)^{i'_{\max}+1}\right)\left(1-\pi\right)+ \\ \left(1-2\pi\right)\left[W_0 2^{i'_{\max}}\pi^{i'_{\max}+1}\left(1-\pi^{i_{\max}-i'_{\max}}\right)+1-\pi^{i_{\max}+1}\right] \\ \pi = 1-\left(1-\tau\right)^{N-1} \end{cases} \Rightarrow \theta_{m,\mathrm{co}} = \pi^{i_{\max}+1}$$

Due to the fact that Wi-Fi uses an unlicensed spectrum, it may suffer a low signal-to-noise ratio (SNR) and so induce packet loss when the SNR ratio falls below the outage threshold.

$$\boxed{\theta_m = \theta_{m,\mathrm{co}} + \theta_{m,\mathrm{SNR}} - \theta_{m,\mathrm{co}}\theta_{m,\mathrm{SNR}}}$$

Virtual Power Plant in Smart Grid

Packet Loss Rate of Cellular:

The total frequency-time resources are finite. When the number of devices that need to be served increases, a device will wait for longer periods of time for BSs to get its required resources.

Then the probability that devices get unserved and its packet is abandoned as

$$\boxed{\theta_m = \left(N_m - \min\left(\lfloor\frac{b_{\text{remain}}}{b_{\text{device}}}\rfloor, N_m\right)\right)/N_m}$$

$$b_{\text{device}} = \lceil r/r_{\text{RB}}\rceil \; b_{\text{user}} = \lceil r_m/r_{\text{RB}}\rceil$$

$$b_{\text{remain}} = t_{\text{d}} b_{\text{RB-sfr}}^{(\text{share})} - k b_{\text{user}}$$

Virtual Power Plant in Smart Grid

Problem Formulation

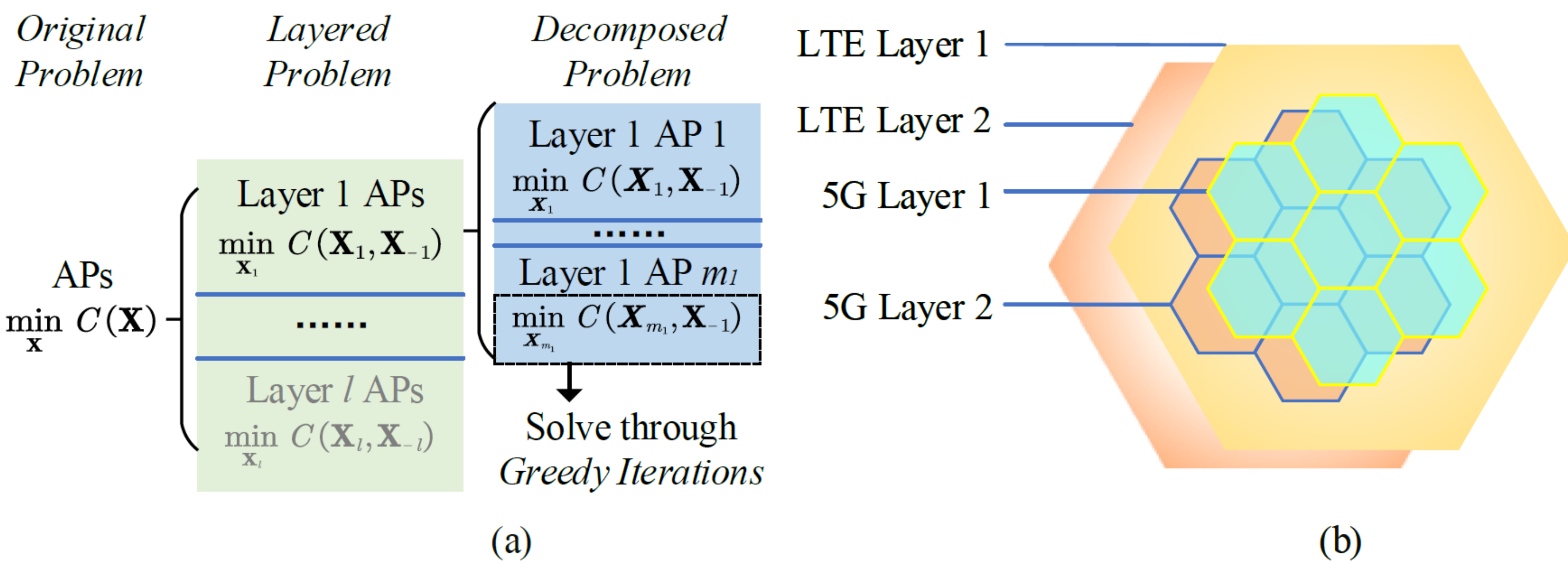
$$\min\ C = \begin{bmatrix} \boldsymbol{p}_{\mathrm{up}} \odot (\mathbf{1}_N - \boldsymbol{p}_{\mathrm{down}}) \\ (\mathbf{1}_N - \boldsymbol{p}_{\mathrm{up}}) \odot \boldsymbol{p}_{\mathrm{down}} \\ \boldsymbol{p}_{\mathrm{up}} \odot \boldsymbol{p}_{\mathrm{down}} \end{bmatrix} \begin{bmatrix} \boldsymbol{U}_{\mathrm{pe}} - \boldsymbol{U}_{\mathrm{up}} \\ \boldsymbol{U}_{\mathrm{pe}} - \boldsymbol{U}_{\mathrm{down}} \\ \boldsymbol{U}_{\mathrm{pe}} - \boldsymbol{U}_{\mathrm{updown}} \end{bmatrix}^{\mathrm{T}}$$

$$\approx \underbrace{\boldsymbol{p}_{\mathrm{up}} (\boldsymbol{U}_{\mathrm{pe}} - \boldsymbol{U}_{\mathrm{up}})^{\mathrm{T}}}_{C_{\mathrm{up}}} + \underbrace{\boldsymbol{p}_{\mathrm{down}} (\boldsymbol{U}_{\mathrm{pe}} - \boldsymbol{U}_{\mathrm{down}})^{\mathrm{T}}}_{C_{\mathrm{down}}}$$

$$p_n = \prod_{x_{m,n} \neq 0} \boxed{x_{m,n}} \theta_m$$

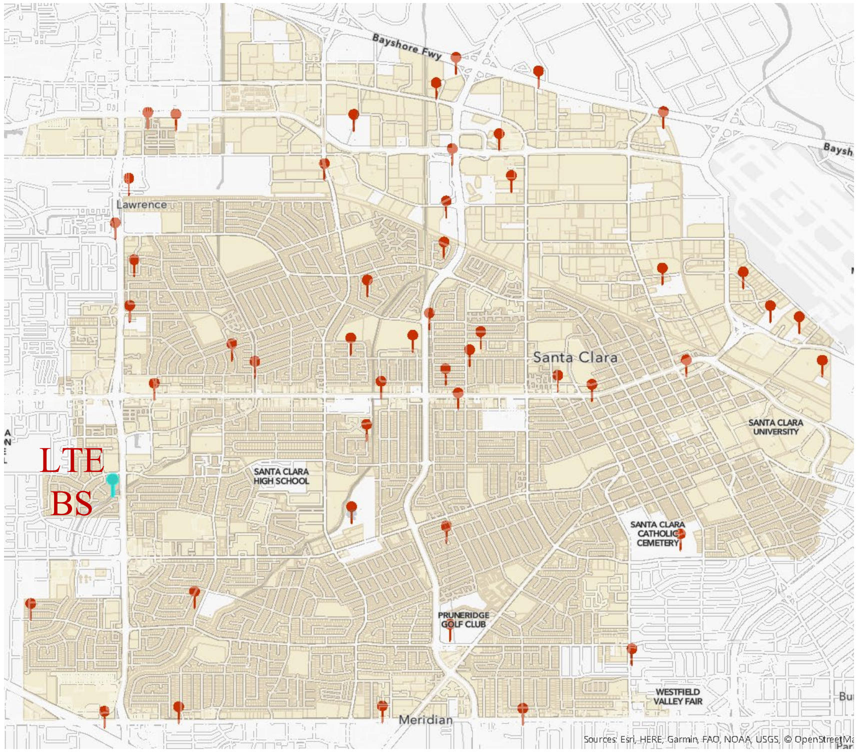
Virtual Power Plant in Smart Grid

Solution Algorithm

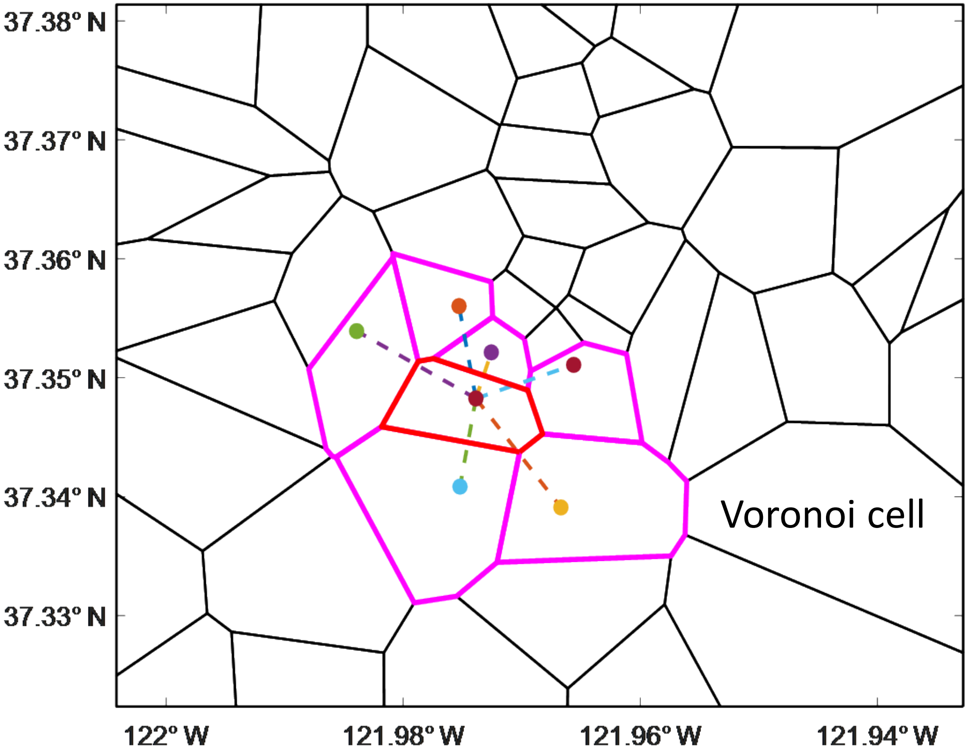


Virtual Power Plant in Smart Grid

Case Studies



(a)



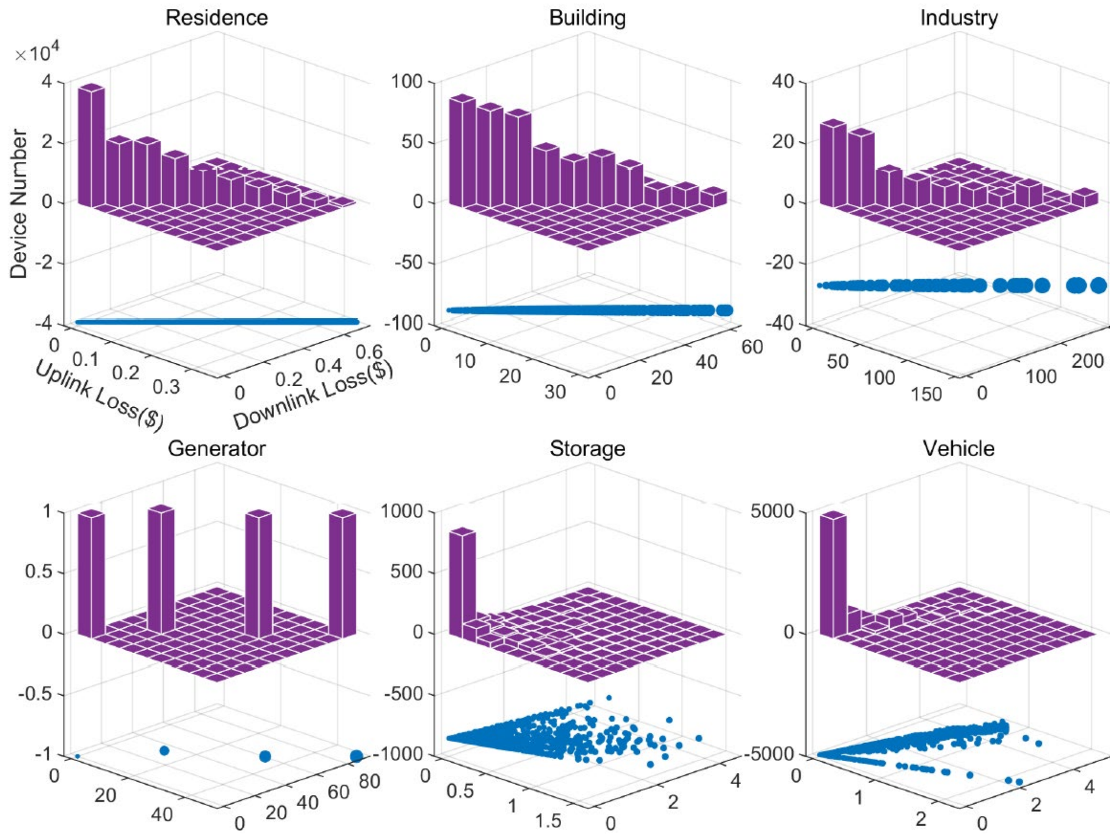
(b)

Virtual Power Plant in Smart Grid

Case Studies

TABLE I
DISTRIBUTED DEVICE SETTING

Type	Device Quantity	q_n(kW)	Connectable AP Wi-Fi	LTE	5G	Area
Residence Load	45000×3	0.5-2	1	1	2	Res.
Building Load	45×10	50-200	1	1	2	All
Industrial Load	10×10	$100\text{-}10^3$	1	1	2	Ind.
Generator	4	$100\text{-}2\times10^3$	0	1	2	All
Energy Storage	2000	10-20	1	1	2	All
Charging Station	8000	5-20	1	1	2	All



Virtual Power Plant in Smart Grid

Case Studies

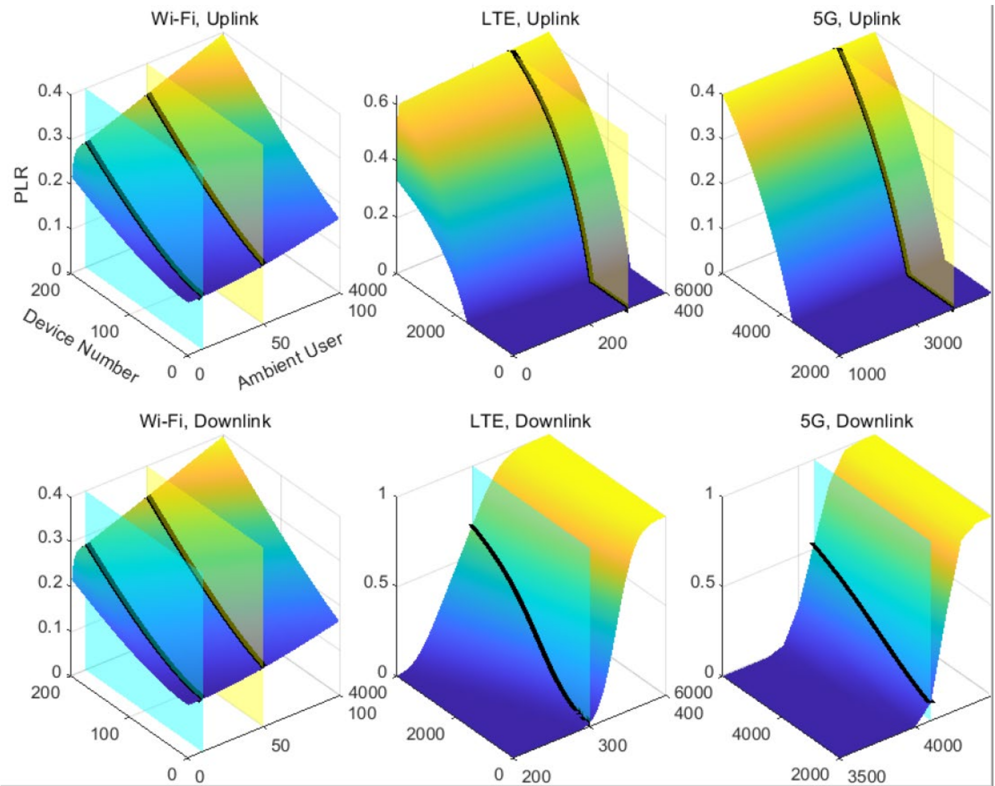


TABLE II
ITERATION RESULTS

Scenario	Uplink		Downlink		Cost
	PLR	PLR (filtered)	PLR	PLR (filtered)	C($)
Full	0.0159	0.0159	0.0241	0.0241	1267.7
IM	0.1101	0.1101	0.1101	0.1101	4762.2
Case A	0.1014	0.0125	0.1107	0.0227	402.3
Case B	0.1583	0.0139	0.165	0.0217	420.6
Case C	0.1000	0.0110	0.110	0.0220	390.2

Conclusions

- Relationship between power flow and information flow?
  - Information flow -> virtual power flow
  - Information flow failure -> power flow unbalance
- Whose demand response?
  - For communication networks
  - For power networks
- What can be done in the future?
  - Network slicing for smart grid?
  - Joint planning of power and communication networks?

Thanks for your attention!

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