LTE-A Spectral Resource Management

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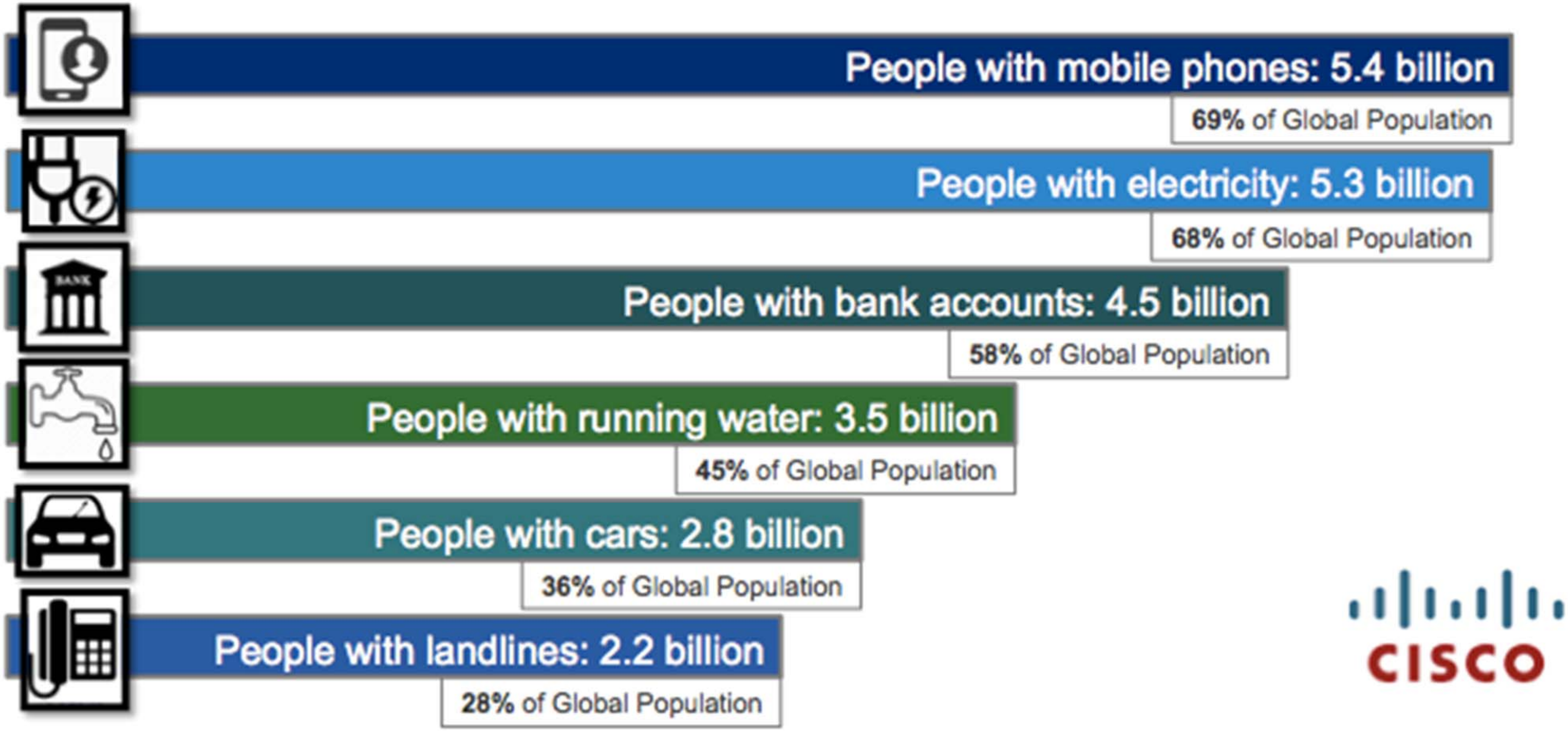
Outline

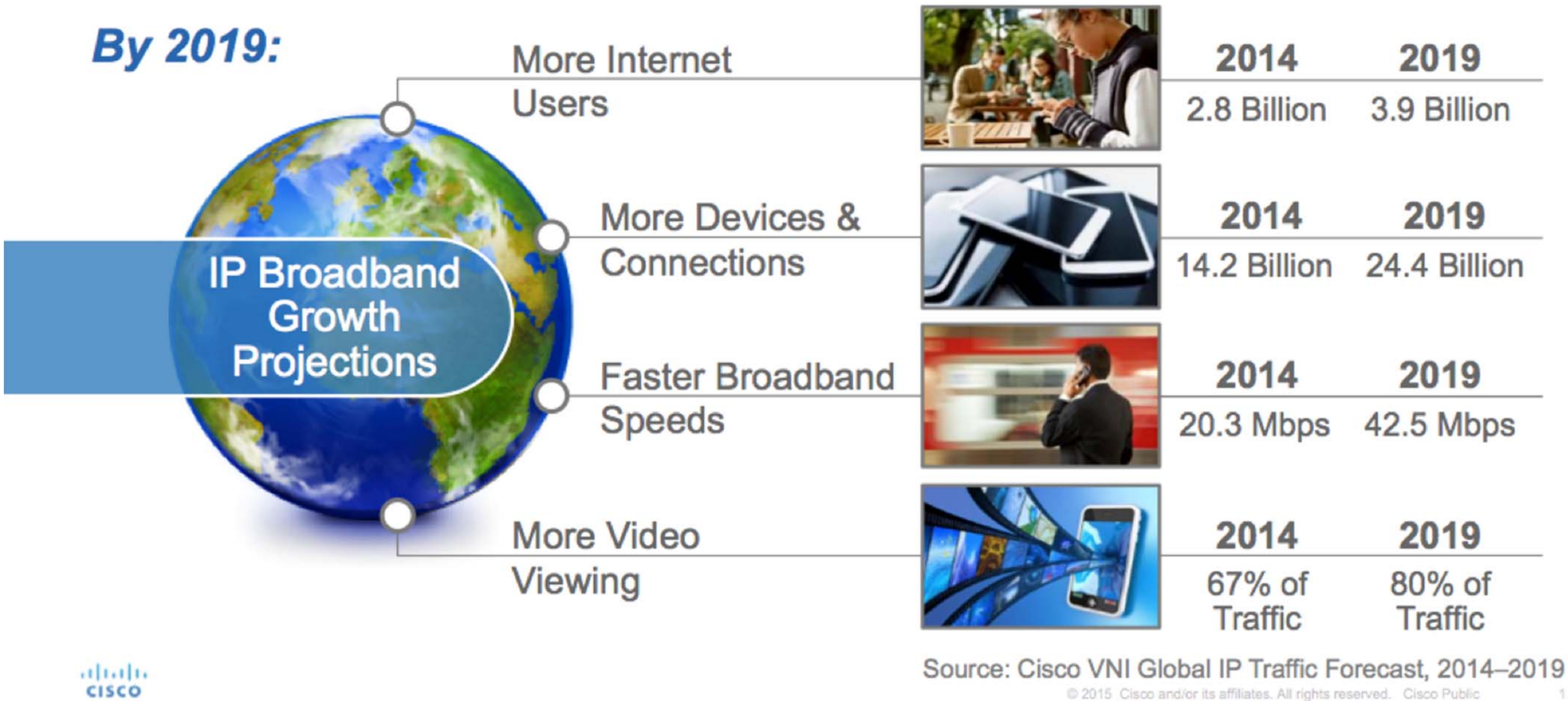
- Brief introduction to LTE-A
- A 4-guideline downlink scheduling strategy
- Downlink resource management for green communication

Cisco forecast (1/2)

- By 2020:



Cisco forecast (2/2)



Evolution of cellular communication

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Market impact	2003	2006	2009	2010	2016
Peak rate	384 kbps	7 Mbps	42 Mbps	~150 Mbps	~1 Gbps
Typical user rate downlink	~200 kbps	1–2 Mbps	2–10 Mbps	10–20 Mbps	~30–100 Mbps
Typical user rate uplink	64 kbps	64–884 Mbps	0.5–4.5 Mbps	5–10 Mbps	~10–60 Mbps

Support of LTE-A in the world

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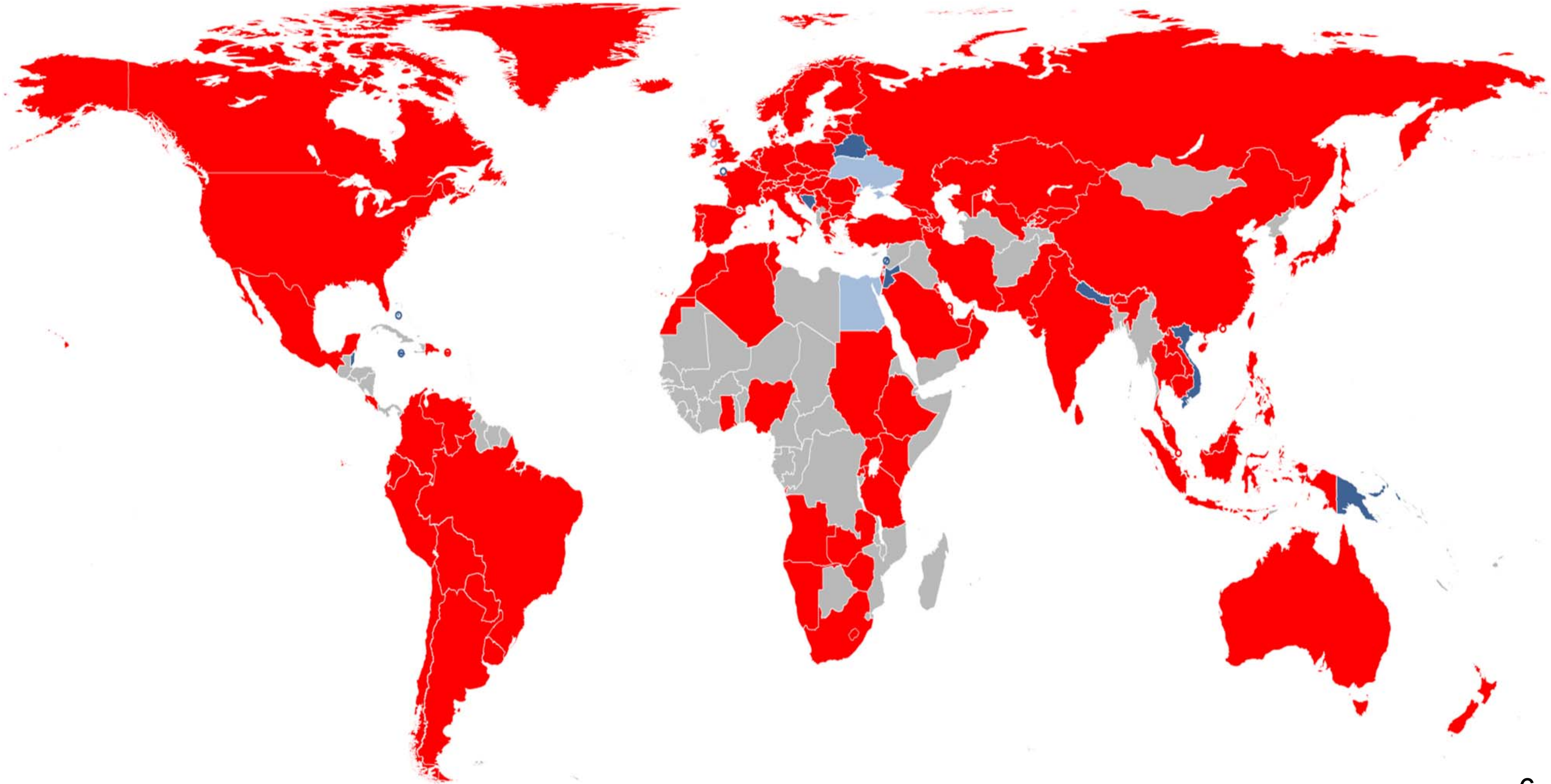
- Red: in operation; blue: in planning



Transmission technology in LTE-A

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- LTE-A uses **OFDMA** and **SC-FDMA** for downlink and uplink communication, respectively.
  - OFDMA: Orthogonal frequency division multiple access
  - SC-FDMA: Single carrier FDMA
- Comparing with OFDMA, SC-FDMA has a lower PAP (peak to average power) ratio, which can save the *energy consumption* of mobile phones.

OFDMA vs. SC-FDMA

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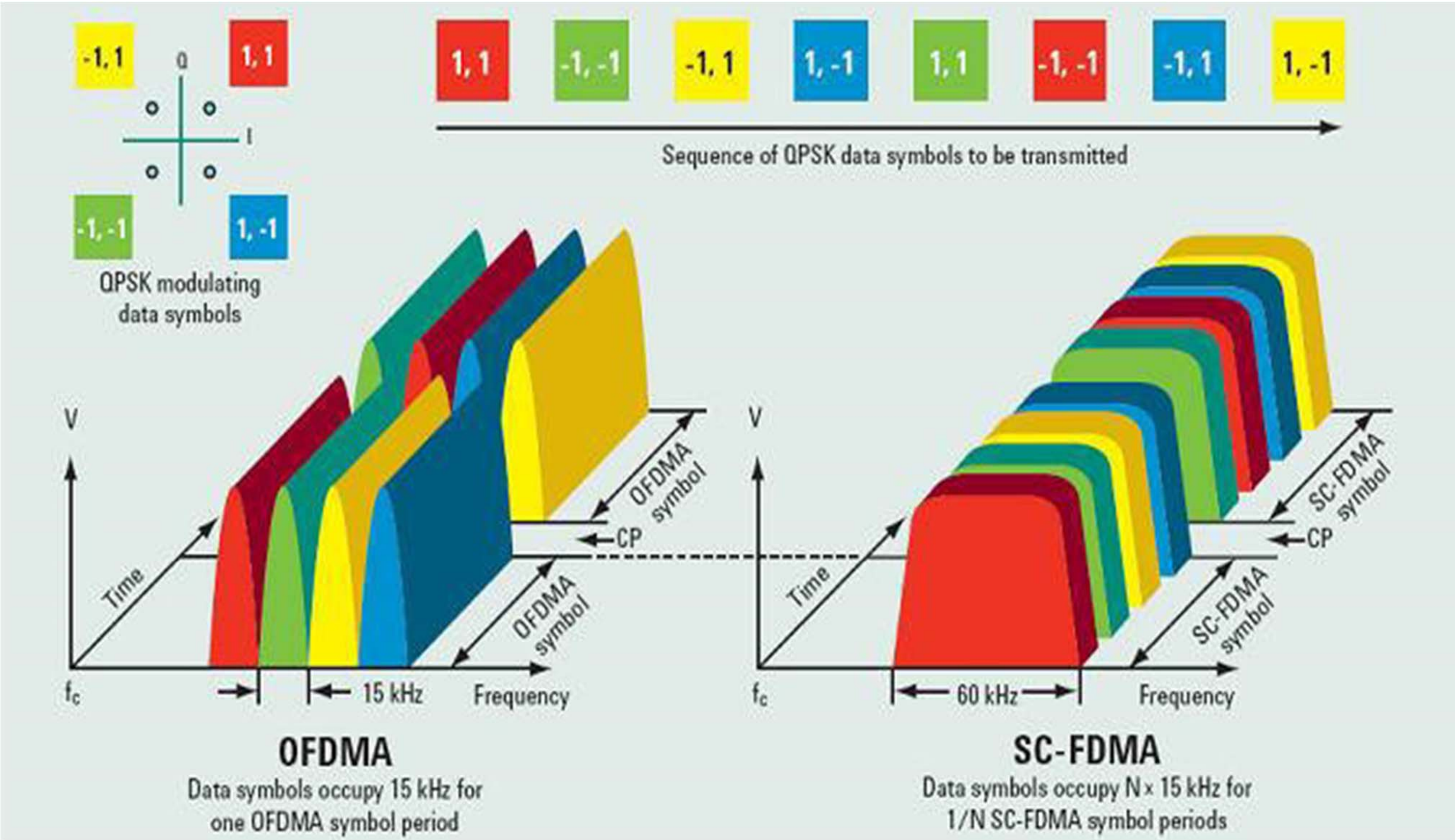
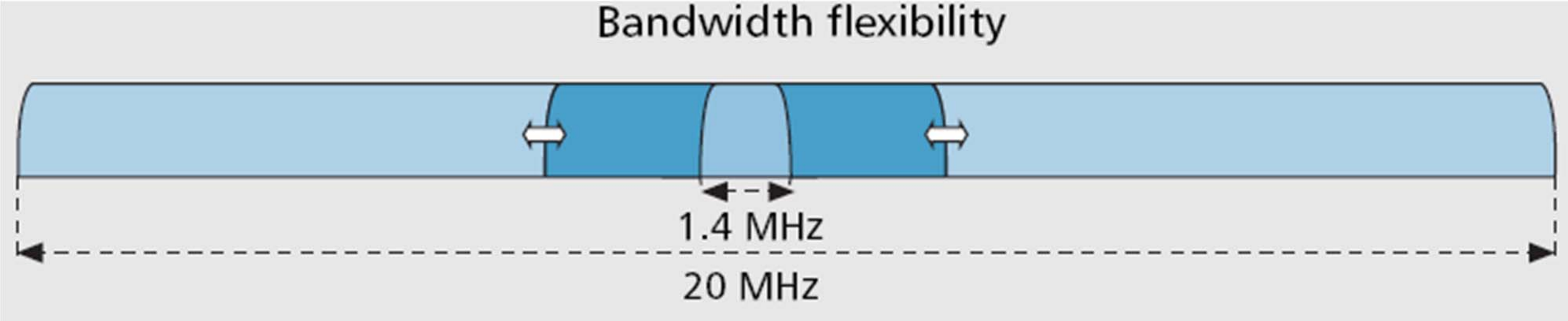


LTE-A channel bandwidth

- LTE-A supports six types of channel bandwidth, including 1.4, 3, 5, 10, 15, and 20MHz.



- With *carrier aggregation*, a base station can combine different channels to provide much larger bandwidth (to **100MHz**).

LTE-A resource

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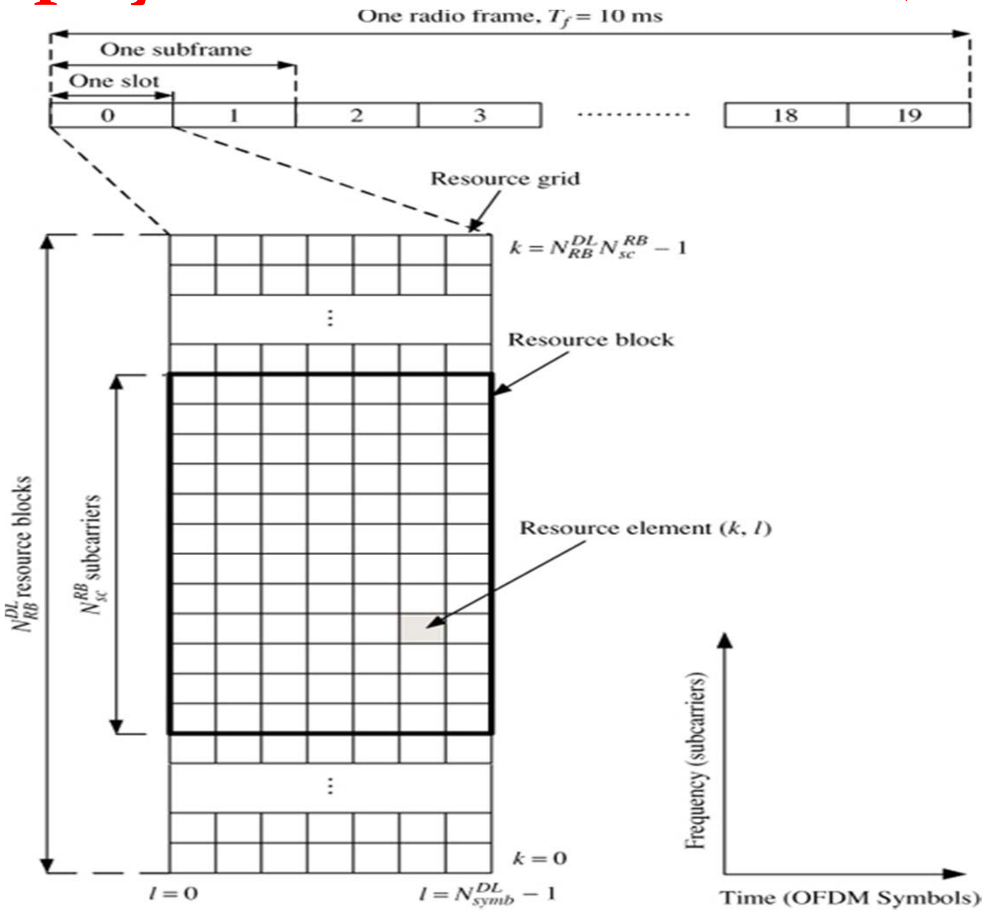
- The basic unit of LTE-A resource is called **physical resource block (PRB)**.



One PRB
Time: 0.5ms
Frequency: 12 subcarriers

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Related work

- Many downlink scheduling methods are proposed to allocate PRBs.
  - Max-CQI: (CQI – channel quality indicator)
    - Improve network throughput, but could *starve* UEs with bad channel quality.
  - Proportional Fair (PF):
    - Keep fairness by considering *current rate* r_i and *average rate* r_i^{avg} (i.e., pick UE with max r_i / r_i^{avg}).
      - Modified Largest Weighted Delay First (M-LWDF)
      - Exponential Proportional Fair (EXP/PF)

Observations

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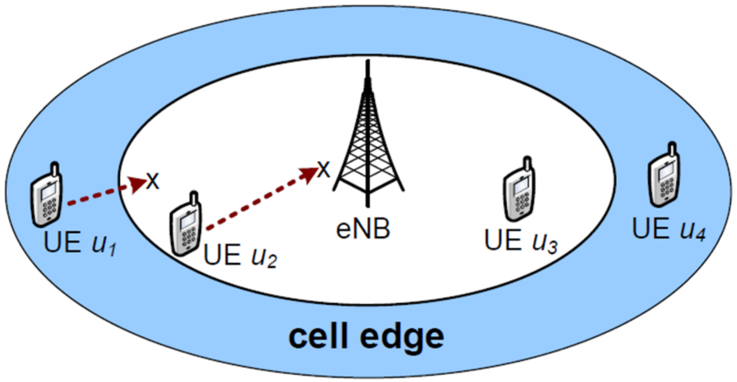

- Unfair transmission by PF (for **cell-edge** UEs):
  - Two UEs move and $r_1 / r_1^{avg} < r_2 / r_2^{avg}$, so u_2 is preferred by PF (but u_1 requires more resource).
  - Two UEs stay and $r_3 / r_3^{avg} \approx r_4 / r_4^{avg}$, so u_3 and u_4 are treated as *no difference* (but u_4 requires more resource).

Network model (1/2)

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- We consider SU-MIMO, so PRBs are *non-sharable*.
- LTE supports three modulations:
  - **QPSK** (CQI: 1~6), **16QAM** (CQI: 7~9), and **64QAM** (CQI: 10~15).

CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

Network model (2/2)

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- Given CQI and demand of each UE, our problem asks how to allocate PRBs to UEs such that
  - Network *throughput* is increased.
  - System *fairness* is improved.
  - Real-time packet *dropping* is reduced.

4G-LDS strategy

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- We develop a *4-guideline LTE downlink scheduling (4G-LDS) strategy* to solve the problem.
  ① Credit-based guideline
  ② Cell-division guideline
  ③ Flow-weight guideline
  ④ Packet-fitness guideline

Credit-based guideline (1/2)

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- Motivated by *weighted fair queuing*, we expect that each UE can get t_i resource in every TTI.
  - If all UEs each exactly receives kt_i amount of data in k TTIs, for any k, we say that the network is **fair**.

- We use D_i to record the difference between *data actually received* by a UE u_i and *resource that it is expected to obtain*.
  - $D_i > 0$: u_i uses more resource than expectation.
  - $D_i < 0$: u_i does not receive enough resource.

Credit-based guideline (2/2)

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- The variation of D_i may be large, especially when some UEs have *much better channel quality* but others do not.

- We thus translate D_i into a **normalized** credit:

$$\hat{C}_i = 2 - \frac{D_i - D_{\min}}{D_{\max} - D_{\min}}$$

  - This normalized credit will be limited to [1, 2].

Cell-division guideline (1/2)

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- Cell-edge UEs do not have good channel quality and may be **starved** (e.g., max-CQI).
- We thus reserve a number of PRBs for them:

$$\gamma = \left\lceil \min\left\{ \frac{\sum_{u_i \in \mathcal{U}_e} \alpha_i}{\sum_{u_i \in \mathcal{U}} \alpha_i}, \beta \right\} \times m \right\rceil$$

  - *U* and U_e are sets of *all* UEs and *cell-edge* UEs.
  - α_i is the demand of a UE.
  - β avoids keeping too many PRBs for cell-edge UEs.
  - *m* is the number of available PRBs.

Cell-division guideline (2/2)

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- How to find cell-edge UEs?
  - One solution is to use the *distance*, but it requires the knowledge of UEs' locations.
- We propose a simple solution by **CQI**.
  - A UE is viewed as a cell-edge UE if it has CQI $\leqq$ 6.
  - This solution adds *no overhead*, since every UE has to report its CQI in each TTI.
  - When CQI $\leqq$ 6, the UE can use only the simplest **QPSK** modulation.

Flow-weight guideline

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- We assign different **weights** for real-time and non-real-time flows.
  - Real-time flows: (modified *M-LWDF*)

    $$\hat{W}_{i,j} = w_{i,j} \times d_{i,j} \times r_i$$

    - $d_{i,j}$: HOL packet delay of the flow
    - r_i: data rate of the UE
  - Non-real-time flows: (modified *max-CQI*)

    $$\hat{W}_{i,j} = r_i$$

Packet-fitness guideline (1/2)

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- We use a *fitness degree* to check if the PRB is **suitable** to send the flow's packet.
  - $l_{i,j}$ is the size of the flow's HOL packet.
  - θ_i is the PRB's capacity (i.e., # of bits carried).
  - Θ_{64QAM} and Θ_{16QAM} are the minimum capacity of an PRB when 64QAM and 16QAM are adopted.
- Three cases are discussed below.

Packet-fitness guideline (2/2)

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- $\theta_i \geq \Theta_{64QAM}$ (large-capacity PRB):
  - Prefer matching the PRB with a *large-size packet*.
  - Fitness degree: $\hat{F}_{i,j} = \min\{l_{i,j}/\theta_i, 1\}$
- θ_i is in $[\Theta_{16QAM}, \Theta_{64QAM})$:
  - Fitness degree = $\theta_i / \Theta_{64QAM}$ if $l_{i,j} \geq \Theta_{64QAM}$.
  - Otherwise, $\hat{F}_{i,j} = \min\{l_{i,j}/\theta_i, 1\}$
- $\theta_i < \Theta_{16QAM}$:
  - Fitness degree = $\theta_i / \Theta_{16QAM}$ if $l_{i,j} \geq \Theta_{16QAM}$.
  - Otherwise, $\hat{F}_{i,j} = \min\{l_{i,j}/\theta_i, 1\}$

Discussion

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- Our 4G-LDS strategy will conduct these steps:
  - Discard those **overdue** packets (i.e., cannot meet their deadlines even if we *send them out now*) in advance to save bandwidth.
  - Reserve γ PRBs for cell-edge UEs, and allow **all** UEs to compete for the remaining (m - γ) PRBs.
  - Select a flow to receive each PRB by

$$f_{i,j} = \arg\max_{i,j} \begin{cases} \hat{C}_i \times \hat{F}_{i,j} \times r_i & \text{if } u_i \in \mathcal{U}_e, \\ \hat{C}_i \times \hat{F}_{i,j} \times \hat{W}_{i,j} & \text{otherwise.} \end{cases}$$

Simulation parameters

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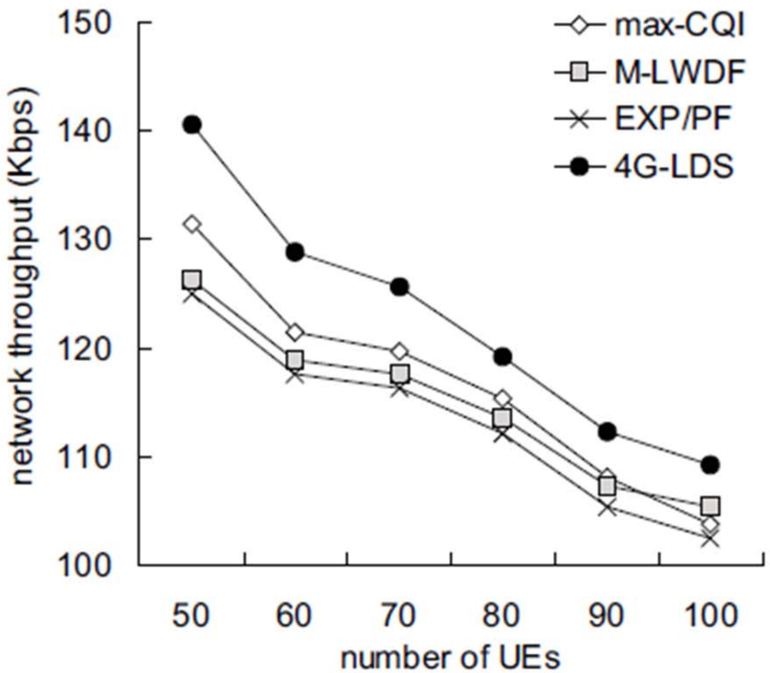
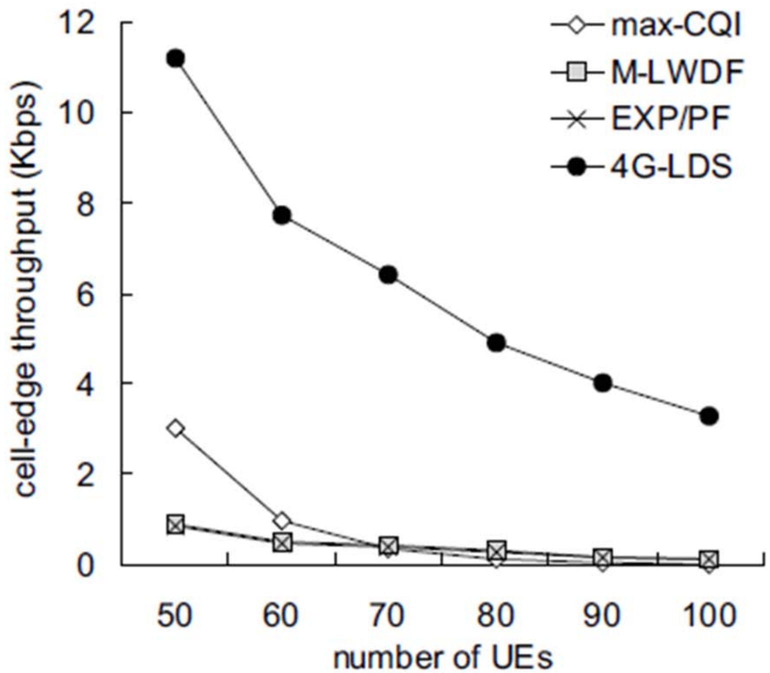
- We use **LTE-Sim** to simulate an LTE macro-cell.
  - A 20MHz downlink channel with 100 PRBs
  - 50 ~ 100 UEs in the cell
  - Mobility model:
    random walking with 3km/h speed
  - Each UE has two flows:
    - Video streaming (242Kbps)
    - Constant-bit-rate (CBR, 12Kbps)
  - Comparison: max-CQI, M-LWDF, and EXP/PF

Simulation results (1/2)





- 4G-LDS improves network throughput, especially for those *cell-edge UEs*.

Simulation results (2/2)

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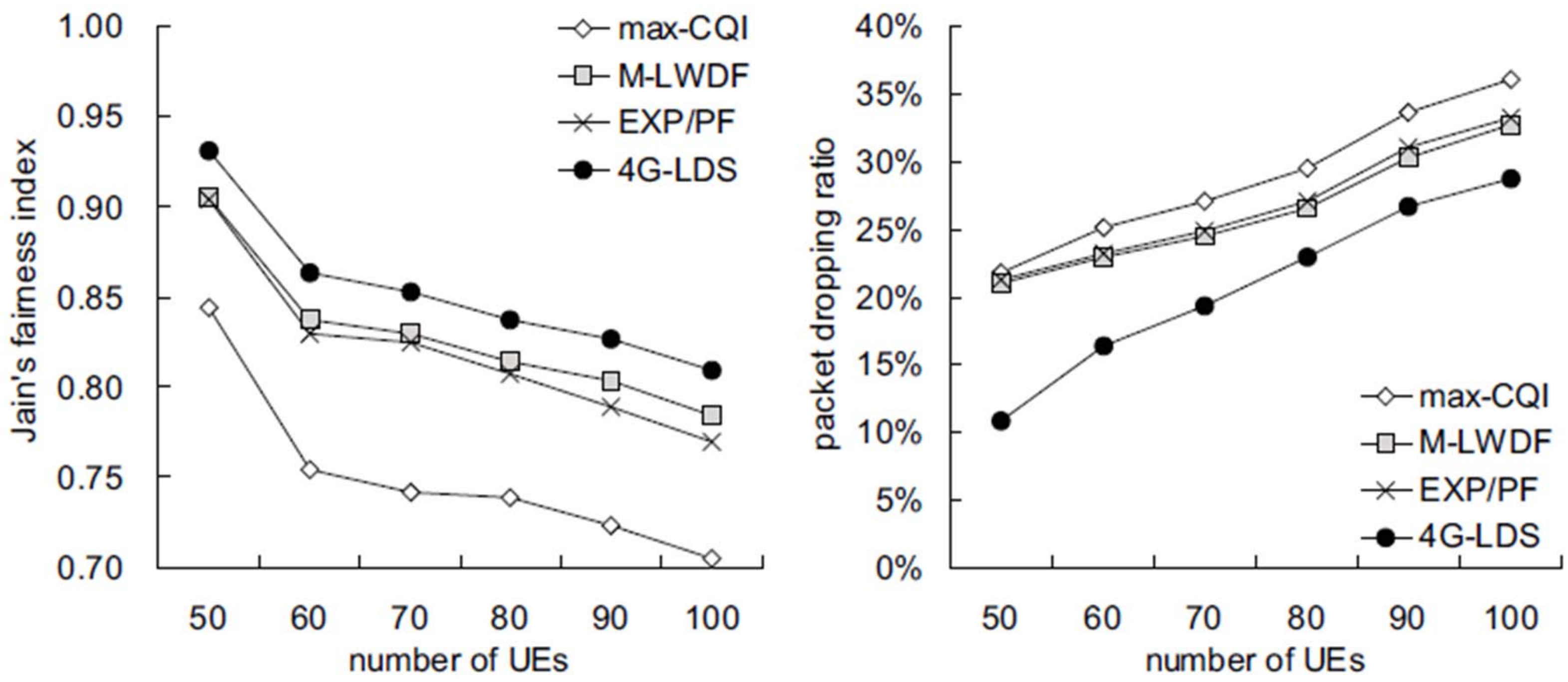

- 4G-LDS not only improves *fairness*, but also reduces real-time *packet dropping*.

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Carrier aggregation (CA)

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- LTE-A supports channel bandwidth to 100MHz.
  - However, many bands in **microwave** spectrum have been used by 2G and 3G systems.
  - LTE-A uses CA to combine different *component carriers* (CCs) to get larger bandwidth.
    - Ex: Combine five 20MHz CCs to get 100MHz bandwidth.

- LTE-A allows *contiguous* and *non-contiguous* CA.
  - However, user equipment will consume more energy when non-contiguous CA is used.

Related work

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- Existing methods are classified into two groups.
  - CC selection:
    - How to *balance the loads* of different CCs to improve the overall throughput?
  - PRB assignment:
    - How to allocate PRBs to each user equipment (UE) to improve throughput, or *reduce packet delay*?
  - However, the issue of saving **energy** on communication is not well addressed.

Problem formulation

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- Energy-reduction LTE-A resource management (ELRM) problem asks to allocate RBs such that
  - *Energy consumption* of each UE is minimized.
  - BS's *transmission power* is minimized.
- ELRM has two constraints:
  - Total power on all CCs cannot exceed the BS's *maximum power* $P_{\max}$.
  - *Traffic demand* of each UE should be met.
- ELRM is **NP-hard**.

The proposed solution (1/4)

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- Given a set **U** of UEs (each with demand r_i) and a set **C** of CCs, our solution has the following steps.

① Set an *initial power* of $P_{max}/|\mathbf{C}|$ on each CC.

② BS then sends a *reference signal* to let each UE compute its **CQI** (channel quality indicator).

③ With CQI, BS can find **MCS** (modulation & coding scheme) for each (UE, CC) pair.

- It thus builds a table where each tuple (u_i, c_j) is *the number of bits* sent by CC c_j for UE u_i.

The proposed solution (2/4)

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④ We also use Q_i to record the **backlog** of each UE (i.e., the number of bits *not satisfied yet*).

⑤ BS picks a UE with maximum Q_i and assigns one CC by its **weight**.

- Weight is the *sum of data bits* supported by c_j for all UEs (except u_i) with positive backlog.
- A large weight indicates that other UEs may have *good channel quality* on c_j, so we should keep it for later assignment.

The proposed solution (3/4)

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⑤ (Cont.) BS will select the CC with *largest data rate* but *smallest weight* to serve the UE.

- We then update Q_i (backlog) and corresponding tuples in the table.

⑥ We repeat step 5 until any of two cases occurs:

- The demand of each UE is satisfied.
  → Go to step 7 to save *BS's transmission power*.
- All CCs are used but some UEs have backlog.
  → Algorithm **finishes** as there is no enough resource.

The proposed solution (4/4)

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⑦ We check if some CCs can be given with less **power** to meet UEs' demands.

- Suppose that a CC c_j is assigned to a UE u_i with MCS $m(i, j)$.
- We try a new MCS $m'(i, j) < m(i, j)$ and check if c_j has *enough PRBs* to satisfy u_i's demand.
- If so, we can lower down the power on c_j such that the MCS becomes $m'(i, j)$.

Example (1/3)

UE	Demand	c_1	c_2	c_3	c_4	c_5
u_1	1150	380	884	**0**	380	380
u_2	550	236	380	**0**	884	153
u_3	**594**	380	606	**0**	236	606
weight						

① Pick u_3 and CC c_2, c_3, and c_5 are candidates.

- Select c_3 and update Q_3 by 1200 - 606 = 594.

② Pick u_1 and CC c_2 is the only candidate.

- Assign c_2 to u_1 and update Q_3 by 1150 - 884 = 266.

Example (2/3)

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UE	Demand	c_1	c_2	c_3	c_4	c_5
u_1	266	380	0	0	**126**	0
u_2	**0**	236	0	0	**294**	0
u_3	0	380	0	0	**78**	0

③ Pick u_3 again and CC c_5 is the candidate.
- Assign c_5 and update Q_3 by zero.

④ Pick u_2 and CC c_4 is the only candidate.
- UE u_2 only uses 8 PRBs in CC c_4.

Example (3/3)

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UE	Demand	c_1	c_2	c_3	c_4	c_5
u_1	**0**	**0**	0	0	126	0
u_2	0	**0**	0	0	294	0
u_3	0	**0**	0	0	78	0

⑤ Assign c_1 to u_1.

- CC assignment:
  $\{c_1, c_2\} \rightarrow u_1$
  $\{c_4\} \rightarrow u_2$ **We can lower down MCS in c_4.**
  $\{c_3, c_5\} \rightarrow u_3$

Simulation parameters

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- Path loss: PL = 128.1 + 37.6 log D(BS, u_i)
- Two communication bands:
  - Band 1 (2110~2170 MHz)
    → cut in twelve 5MHz CCs
  - Band 5 (869~894 MHz)
    → cut in two 5MHz CCs and five 3MHz CCs
- Each UE has 50Mbps real-time traffic and 35Mbps non-real-time traffic.
- BS's maximum power: 40W

Comparison

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- Two methods for comparison:
  - Greedy-PF: Find a **weighted** rate of each UE and selects the pair of UE and CC with the maximum rate. To keep fairness, a larger weight is given to a UE that *sent less data* in the past.
  - Greedy: Similar with greedy-PF but set all weights to one.
- For each experiment, we repeat 1000 simulations and take their average.

Experimental results (1/3)

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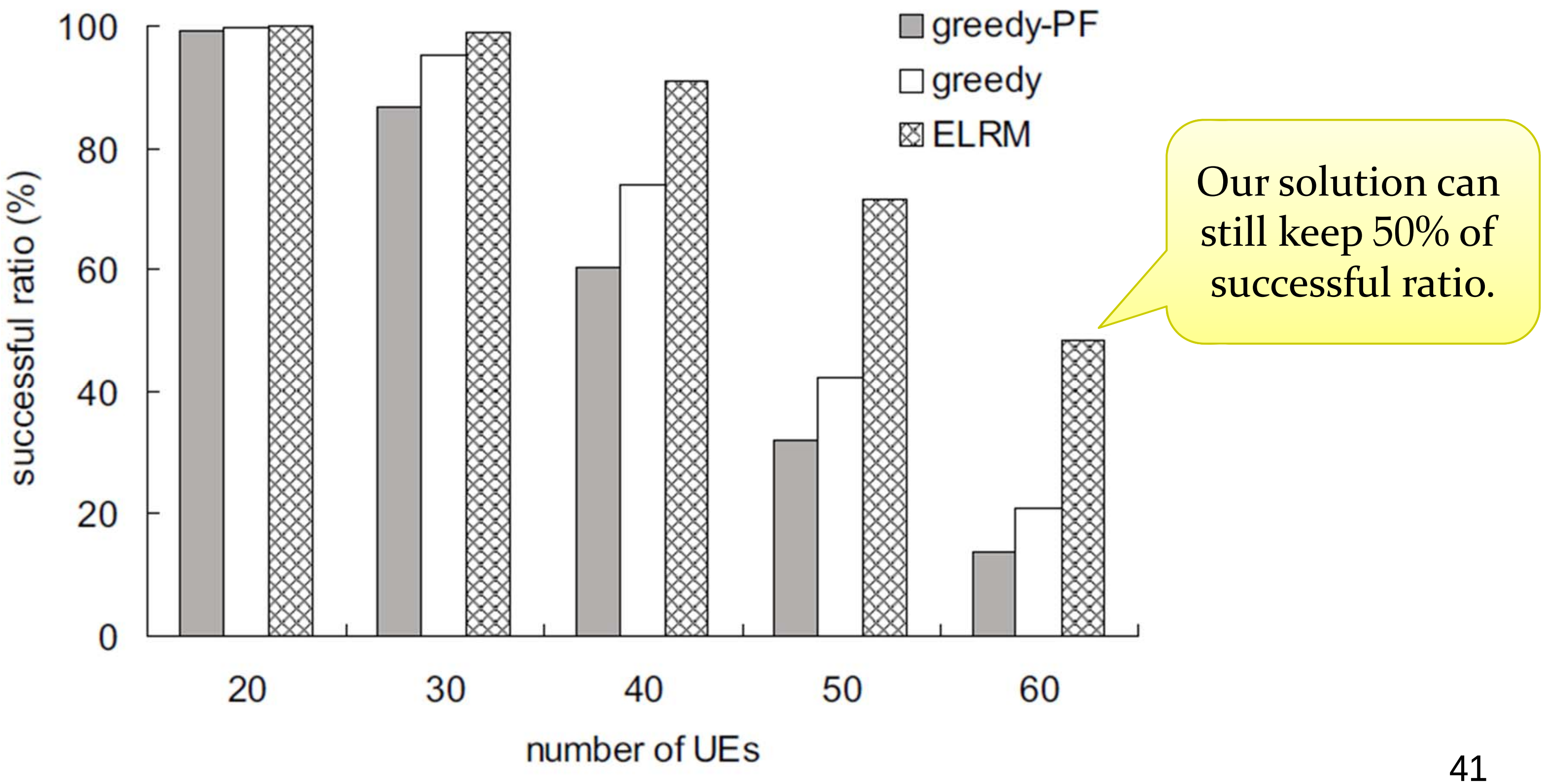
- Successful ratio of resource scheduling:
  - # of successful experiments / 1,000 experiments



Experimental results (2/3)

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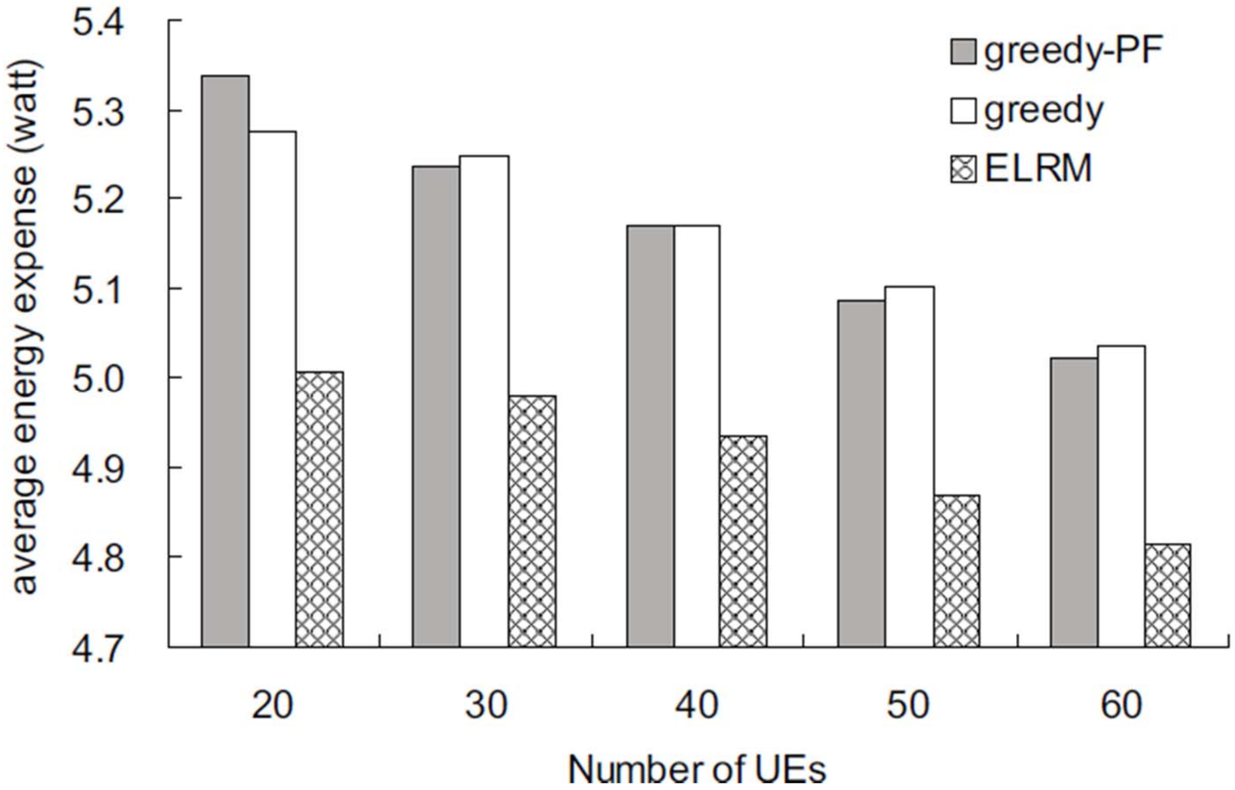
- Average energy expense of UEs:
  - Decrease as the number of UEs grows.



Experimental results (3/3)

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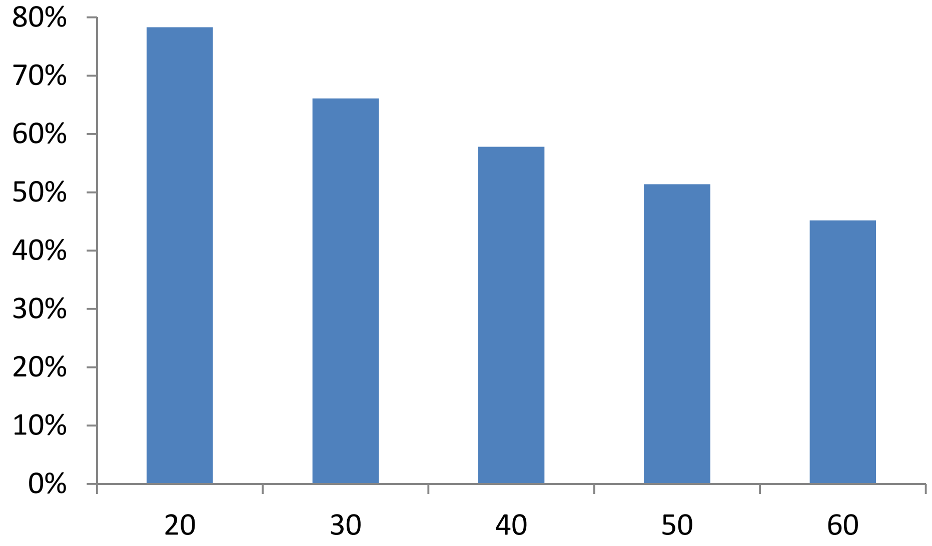
- Saving ratio of the BS's transmission power by our ELRM solution:

UEs	20	30	40	50	60
ratio	78.3%	66.1%	57.8%	51.4%	45.2%



Conclusion

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- LTE-A is a world-wide standard for 4G cellular communication.
- We have developed two downlink resource scheduling methods for LTE-A networks.
  - 4-guildeline strategy
  - Green communication

References

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- You-Chiun Wang* and Hung-Yi Ko, "Energy-efficient downlink resource scheduling for LTE-A networks with carrier aggregation," ***Journal of Information Science and Engineering***, vol. 33, no. 1, pp. 123-141, Jan. 2017.