Device-to-Device Load Balancing for Cellular Networks

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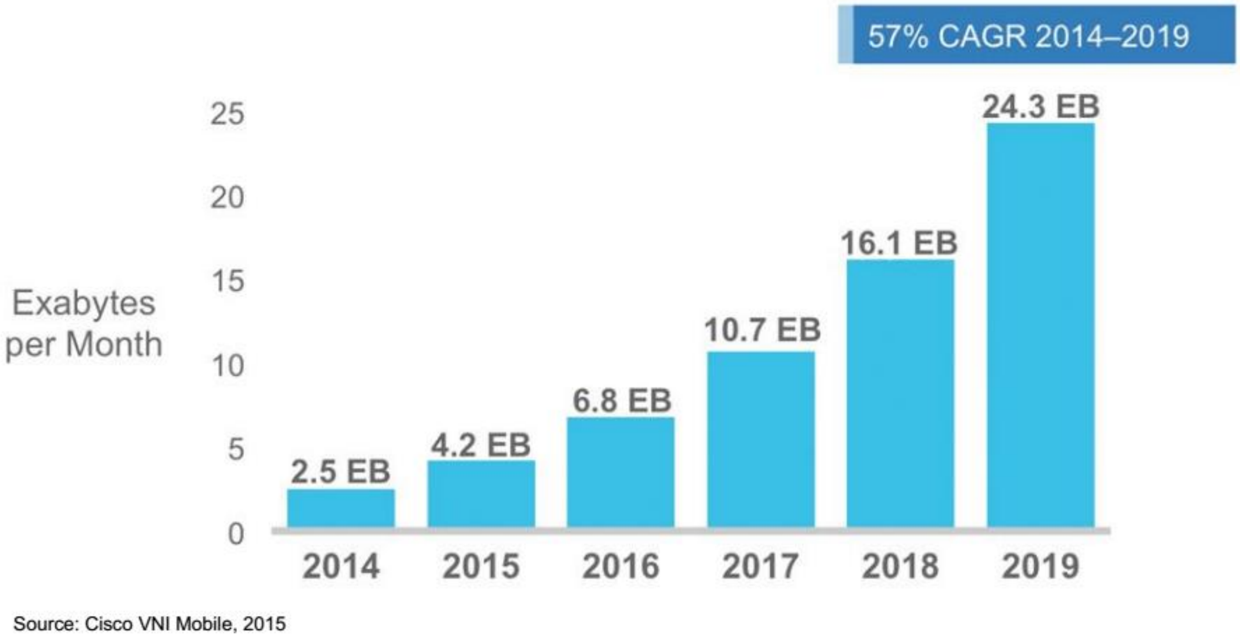
Mobile Data Traffic Is Skyrocketing



Increased Mobile Data

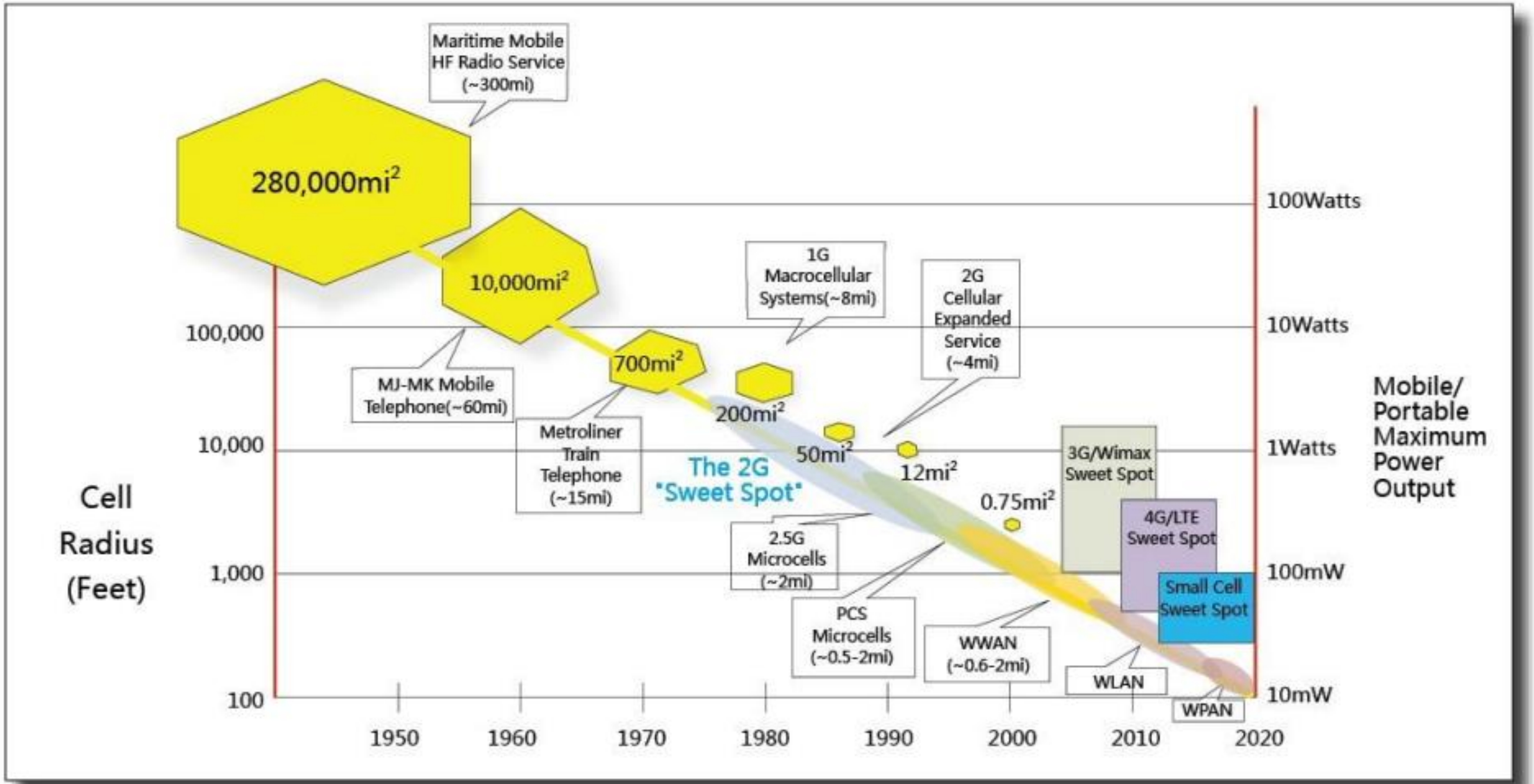
V.S.

Limited Radio Spectrum

- Cisco Forecasts 24.3 EB per Month of Mobile Data Traffic by 2019
- A **10x** Increase over 2014

24.3 EB (Exabyte) = **40%** of Monthly Global Fixed-Internet Traffic in 2014

The Cell Size Is Shrinking



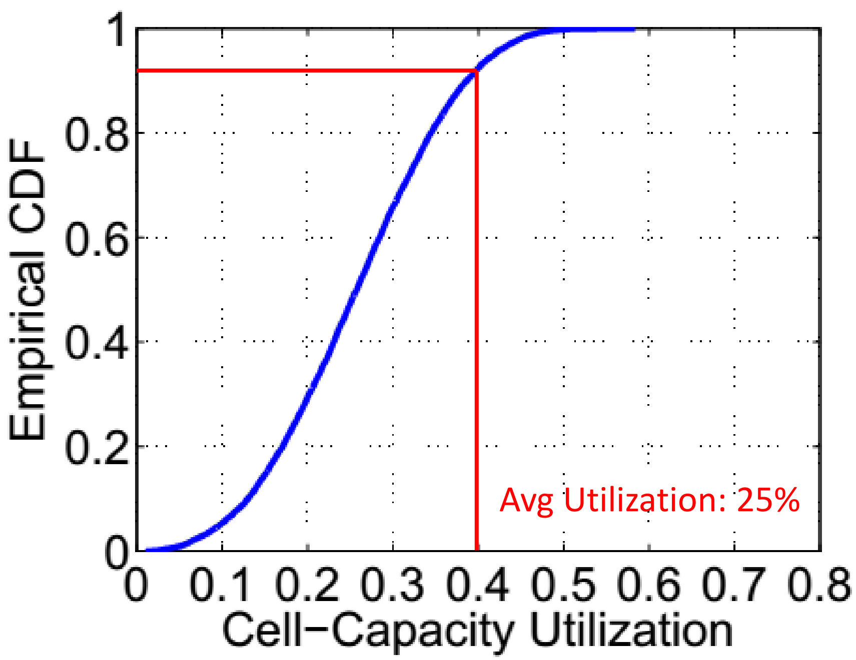
The Trend of Shrinking Cells (Source: ZTE Article)

Small Cell Improves Spectrum Spatial Efficiency

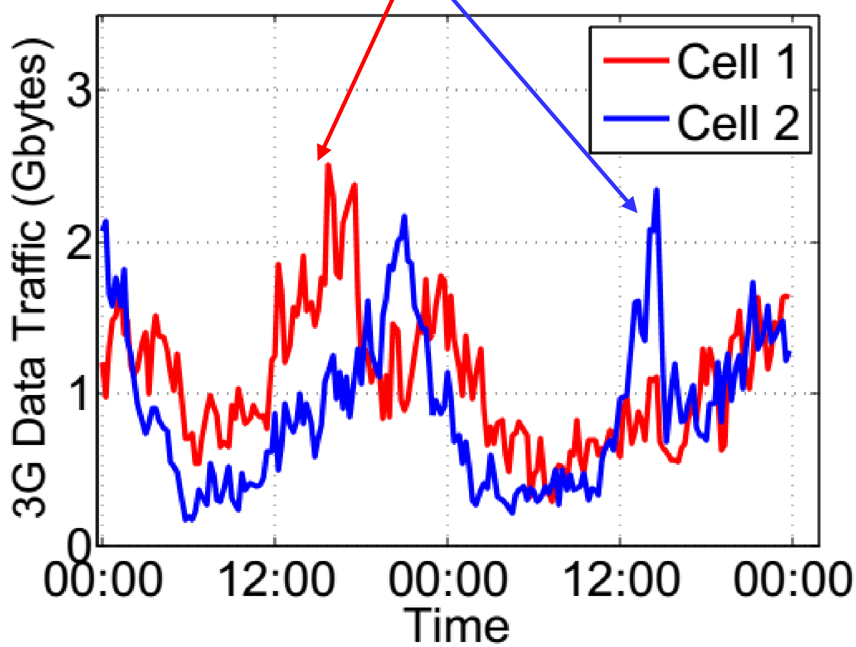
yet Degrades Spectrum Temporal Efficiency

Case Study: SmarTone

Average Cell Radius: 200m



Non-synchronized Peak Traffic

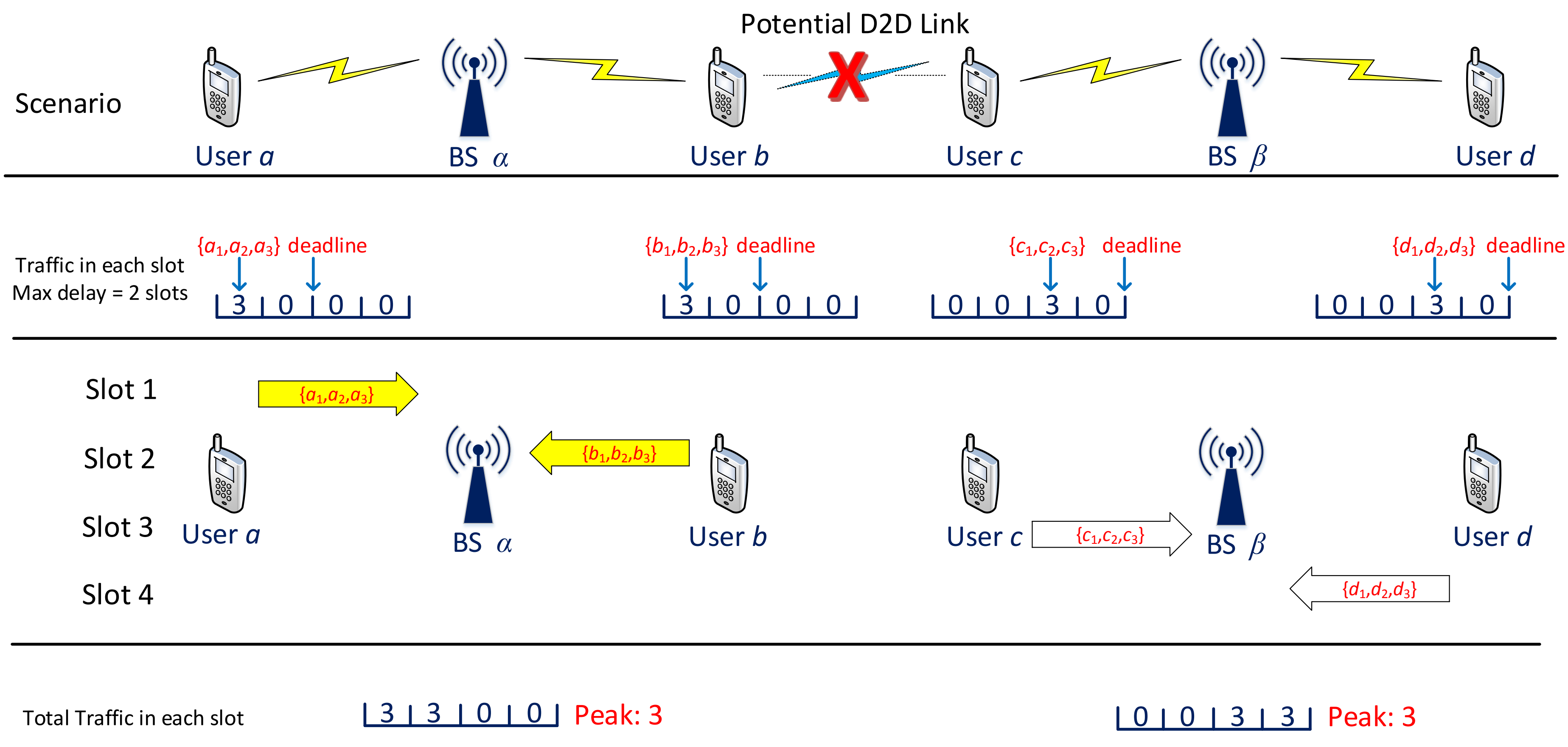


Low Spectrum Temporal Efficiency!

Load Balancing Can Potentially Increase Spectrum Temporal Efficiency

We Advocate ***Device-to-Device Load Balancing (D2D LB)*** Scheme

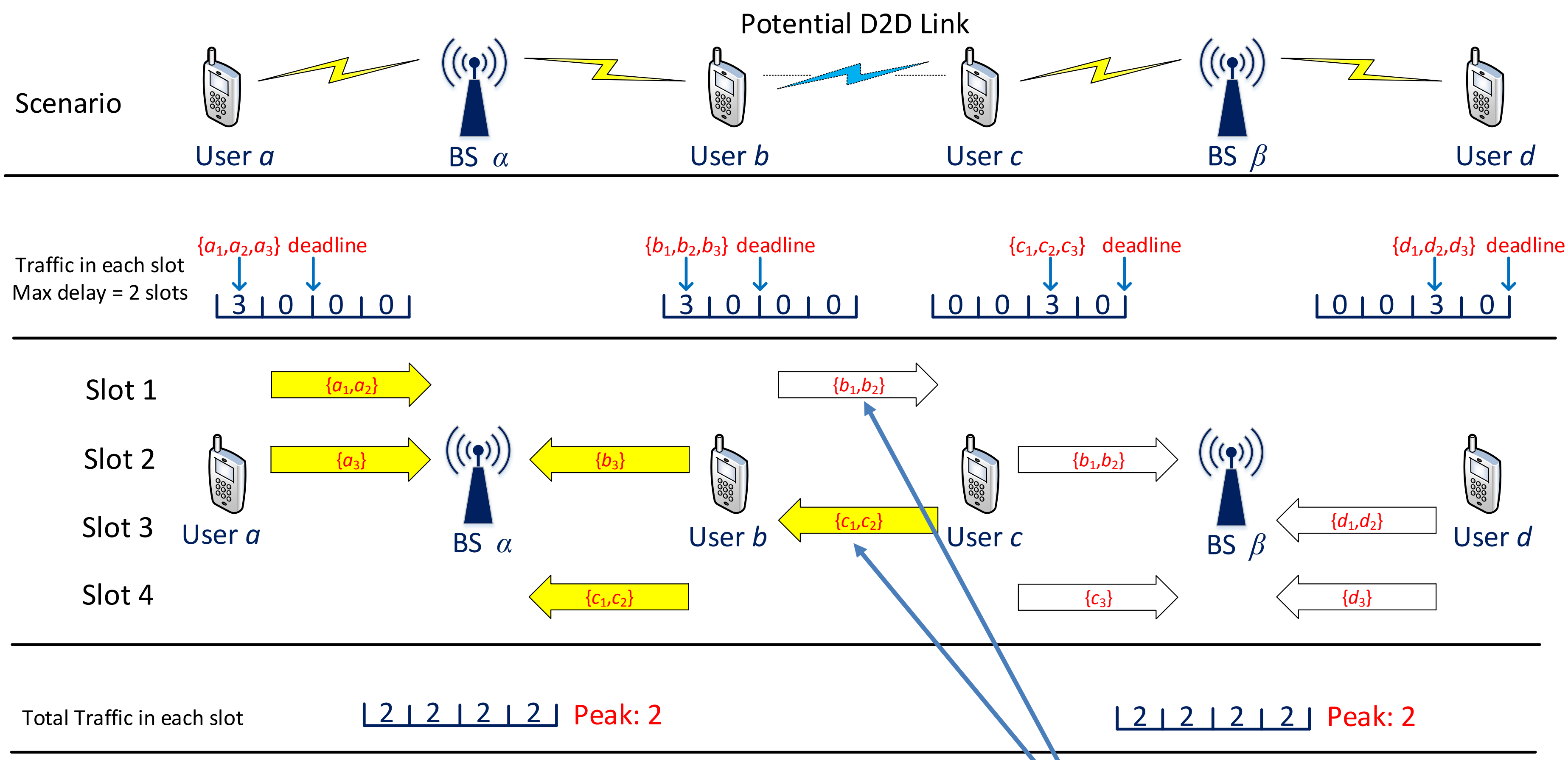
Example: Without D2D Load Balancing



Peak Traffic: 3

Spectrum Temporal Utilization: 50%

Example: With D2D Load Balancing



Peak Traffic: **3** → **2**

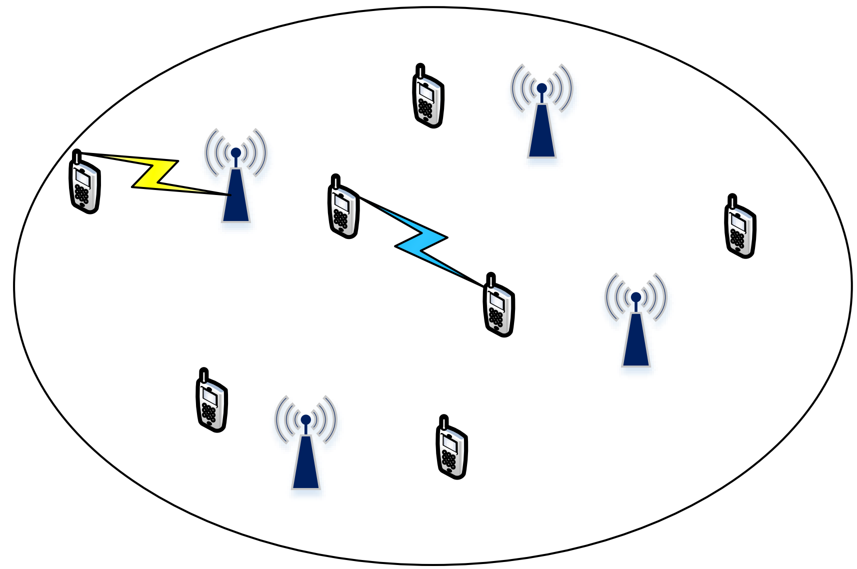
Spectrum Temporal Utilization: **50%** → **100%**

4 Extra D2D Transmissions

System Model

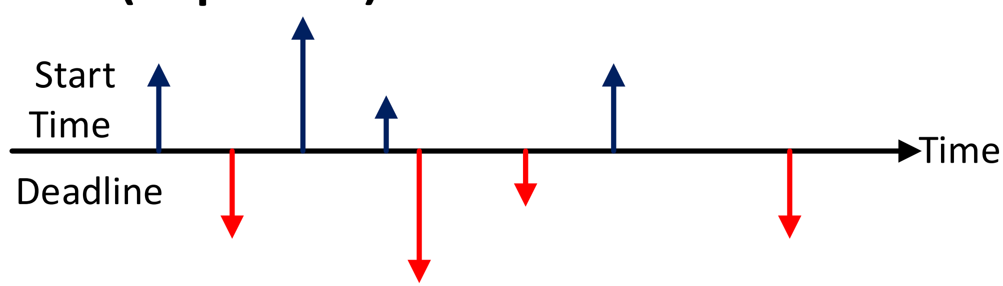
- Network topology
  - Directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$
  - Link rate R_{uv}

    $$\text{Transmitted Volume per Slot} = \text{Link Rate} \times \text{Assigned Resources}$$



- Traffic demand pattern (Uplink)
  - $z^{s\tau} = (x^{s\tau}, d^{s\tau})$

    user start-time volume deadline



All traffic should reach **any** BSs before expiration!

Performance Metrics

- □ Sum peak traffic/resource reduction (Benefit)

$$\rho = \frac{P_{ND} - P_D}{P_{ND}} \in [0, 1)$$

  - P_{ND} is the minimal sum peak traffic without D2D
  - P_D is the minimal sum peak traffic with D2D LB

- □ D2D traffic overhead ratio (Cost)

$$\eta = \frac{V_{D2D}}{V_{D2D} + V_{BS}} \in [0, 1)$$

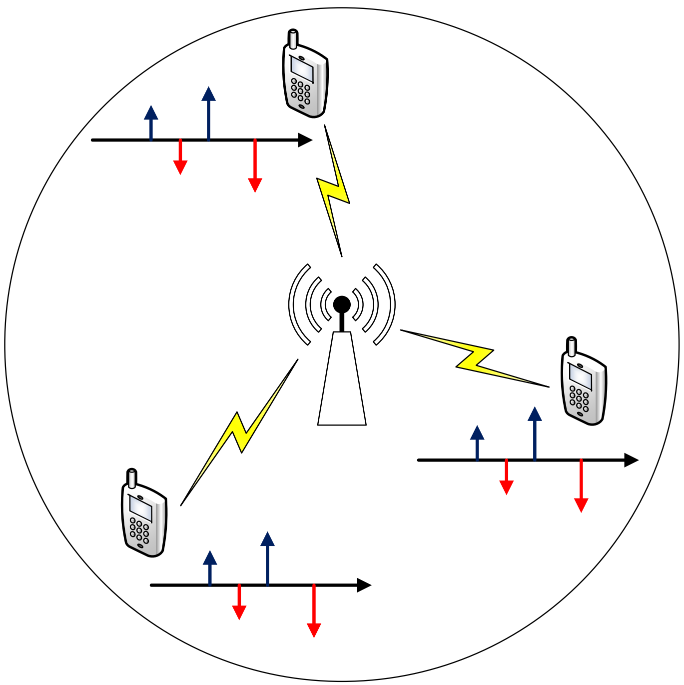
  - V_{D2D} is the sum volume of all D2D traffic
  - V_{BS} is the sum volume of all user-BS traffic

We optimize the benefit and characterize the corresponding cost

Minimize Sum Peak Traffic: No D2D

- We can use YDS algorithm to get the minimal peak traffic of any BS b
- Define the *intensity* of an interval $I = [z, z']$ as

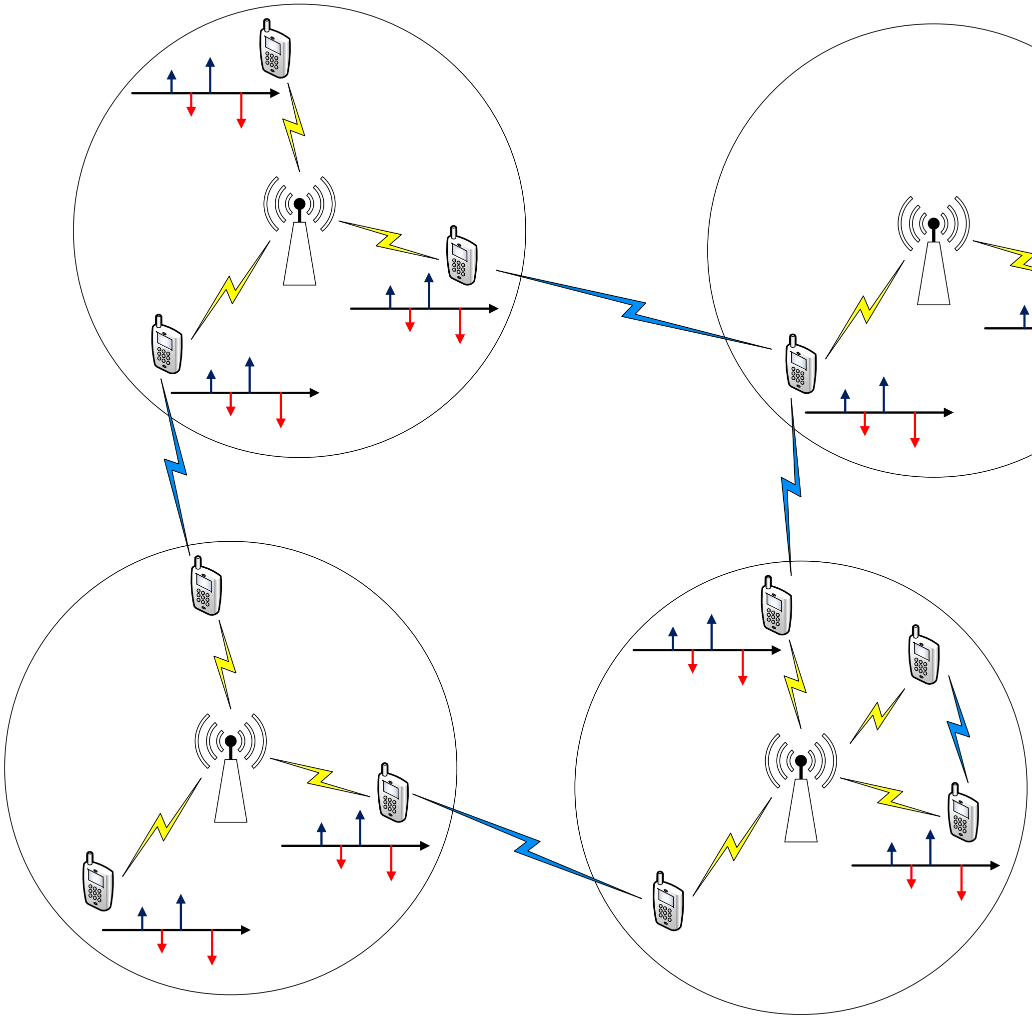
$$g_b(I) = \frac{\sum_{(s,\tau)\in\mathcal{A}_b(I)} \frac{x^{s\tau}}{R_{sb}}}{z' - z + 1}$$



- **Theorem**: $P_b^* = \max_{I\subset[1,T]} g_b(I).$

F. Yao, A. Demers and S. Shenker, "A scheduling model for reduced CPU energy," in *Proc IEEE FOCS*, 1995.

Minimize Sum Peak Traffic: D2D LB



All BSs Are Coupled!

A Large-Scale LP

No Efficient Algorithm Now

Limitations of Conceivable Approach

- No closed-form expression
  - Minimal sum peak traffic with/without D2D LB
  - Sum peak traffic reduction
- No efficient algorithm
  - Minimal sum peak traffic with D2D LB
- Hard to get **insights** of the benefit of D2D LB

Sum Peak Traffic Reduction: Upper Bound

- **Theorem**: For an arbitrary network topology and an arbitrary traffic pattern,

$$\rho = \frac{P_{ND} - P_D}{P_{ND}} \leq \frac{\max\{r, 1\} + \tilde{r}\Delta^- - 1}{\max\{r, 1\} + \tilde{r}\Delta^-}.$$

Captures the link-rate advantages of **intra-cell D2D links** over the **user-BS links**

Captures the link-rate advantages of **inter-cell D2D links** over the **user-BS links**

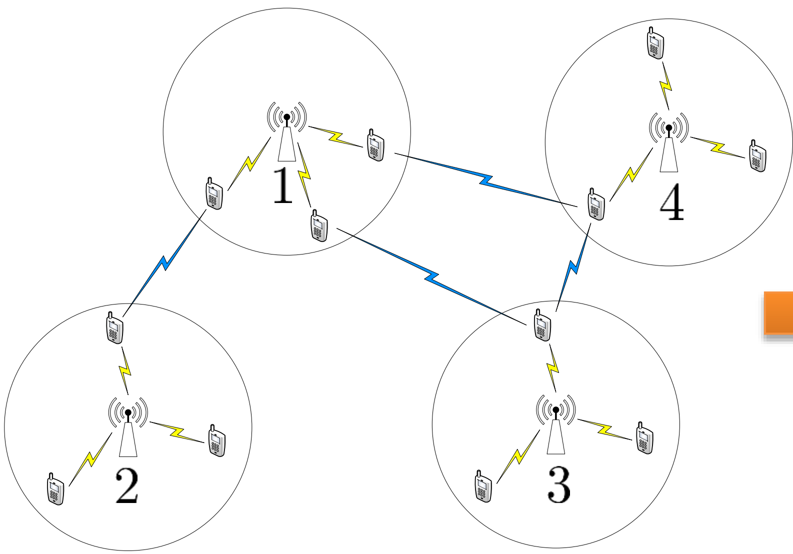
Captures the BS-level network connectivity and **traffic aggregation** capability

Sum Peak Traffic Reduction: Upper Bound

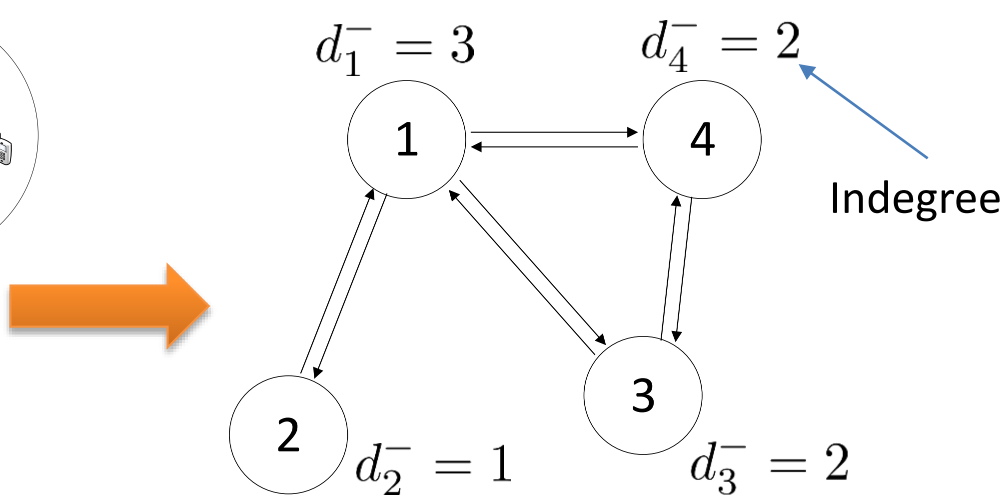
- **Corollary**: If $r = \tilde{r} = 1$, then we have

$$\rho = \frac{P_{ND} - P_D}{P_{ND}} \leq \frac{\Delta^-}{\Delta^- + 1}$$

Network Topology



D2D Communication Graph (BS-level)



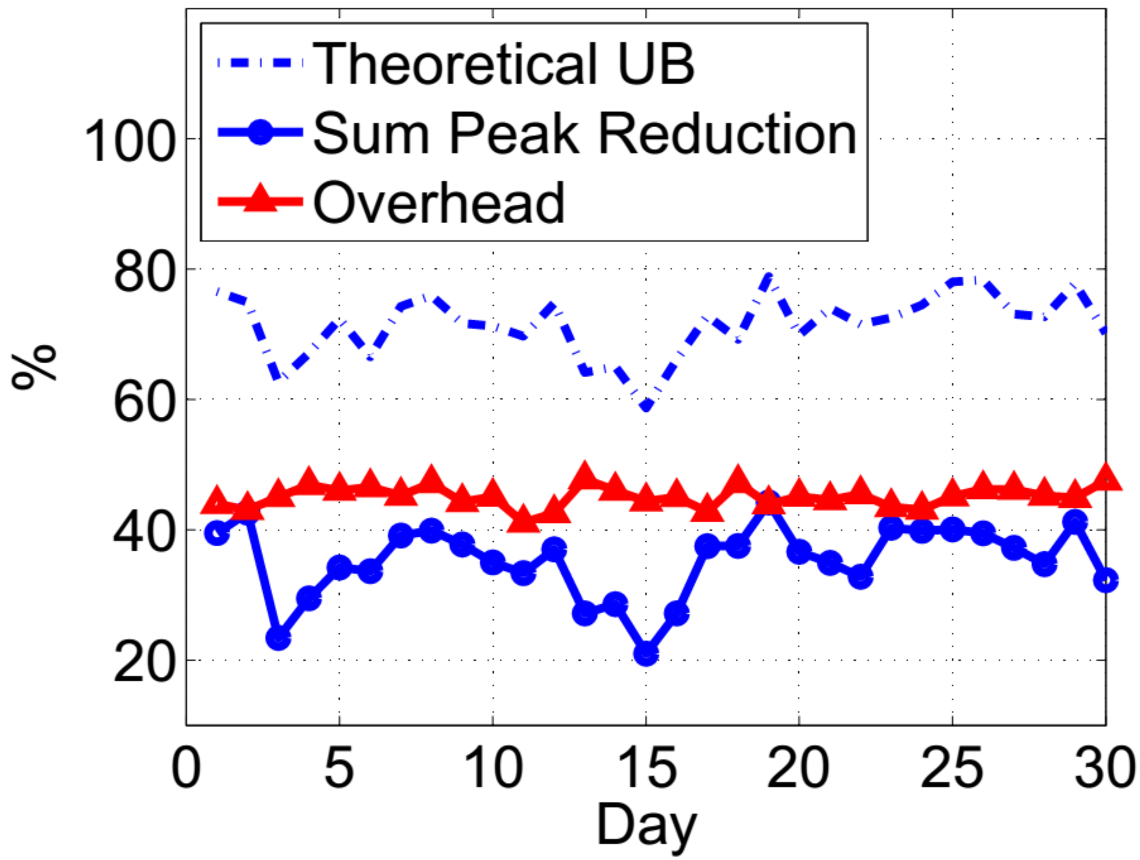
Max Indegree: $\Delta^- = \max_i d_i^- = 3$

$$\rho \leq \frac{\Delta^-}{\Delta^- + 1} = 75\%$$

Discussions

- **Corollary**: $\rho = \frac{P_{ND} - P_D}{P_{ND}} \leq \frac{\Delta^-}{\Delta^- + 1}$
- Δ^- evaluates the traffic aggregation capability
- The more traffic each BS aggregates for other BSs, the more statistical multiplexing gain
- How good is this upper bound?
  - $\rho \to \frac{2}{3} = \frac{\Delta^-}{\Delta^- + 1}$ in the ring topology
  - i.e., tight under ring topology ($\Delta^- = 2$)

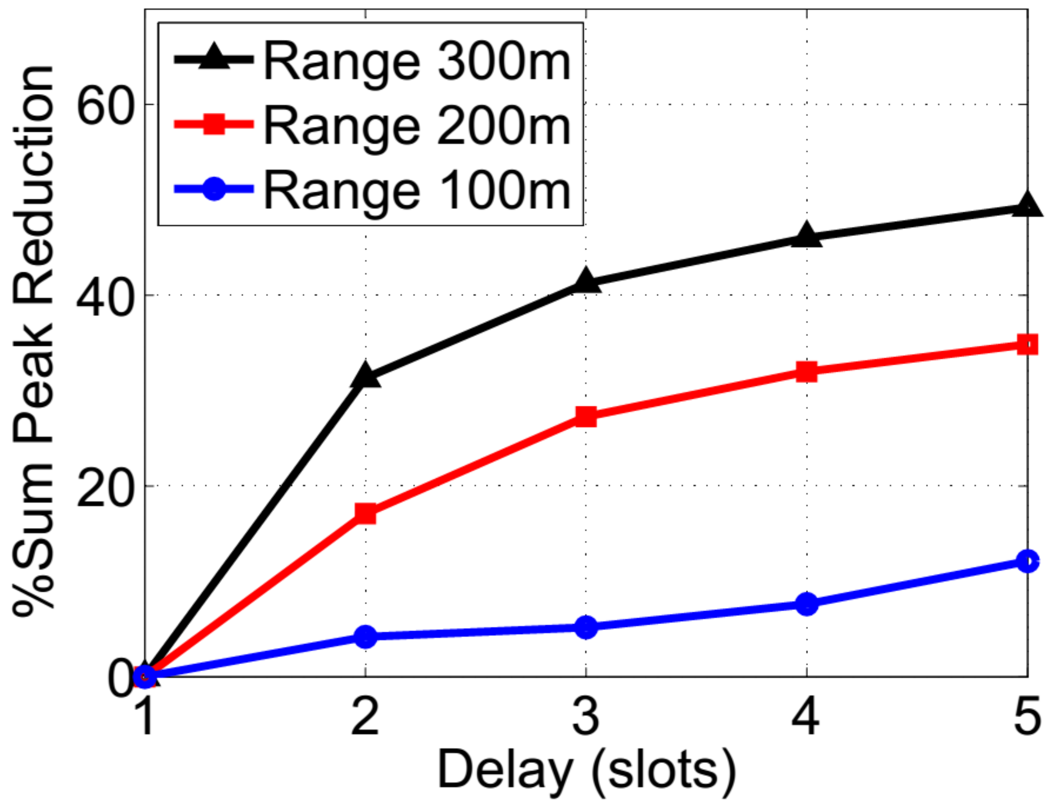
Trace-driven Simulation: Benefit and Cost



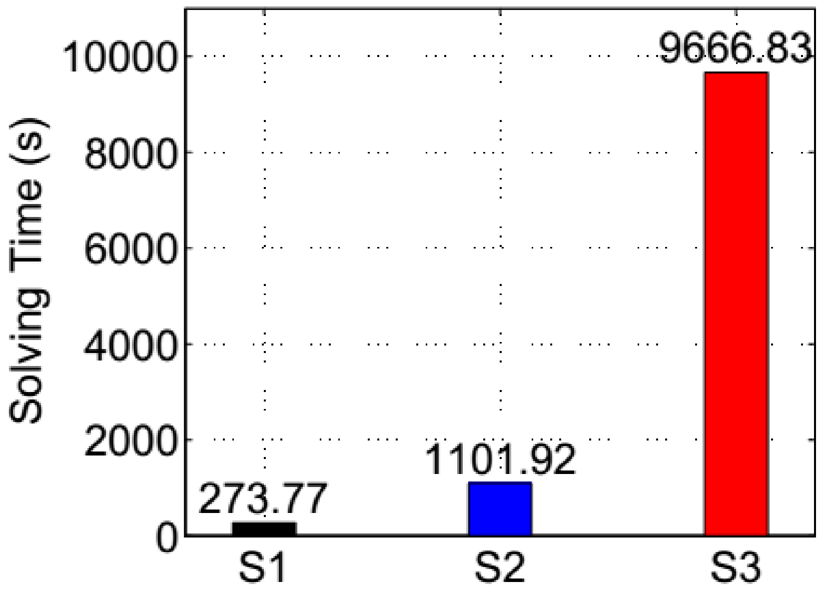
Benefit: 35%

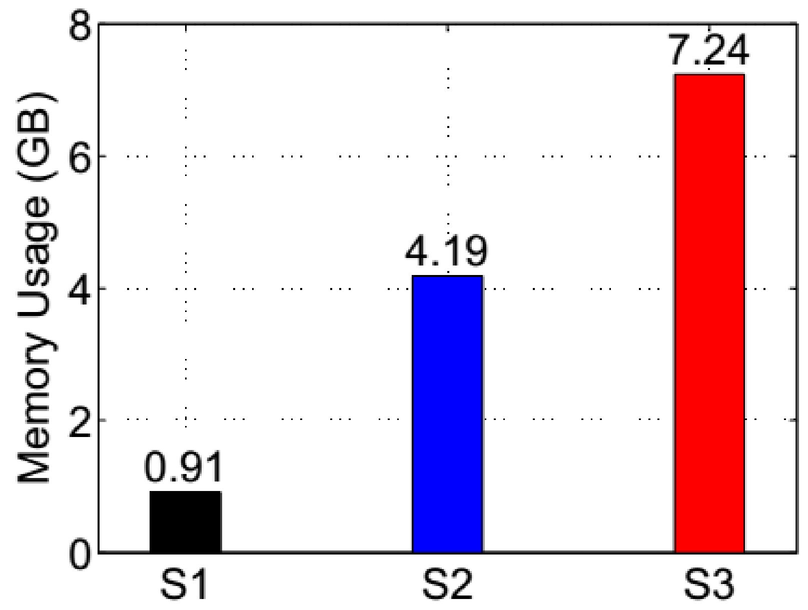
Cost: 45%

Effects of Traffic Delay and Commu. Range



Computational Cost of Large-Scale LP





Instance	$\lvert\mathcal{B}\rvert$	$\lvert\mathcal{U}\rvert$	$\lvert\mathcal{E}\rvert$	# of demands	T
S1 (Light)	3	15	139	4035	43200
S2 (Medium)	6	30	344	6945	43200
S3 (Heavy)	9	45	1083	10095	43200

Conclusion

- Advocate the concept of D2D load balancing
- Define the performance metrics for both benefit and cost
- Theoretical upper bound for arbitrary settings
- Real-world trace-driven simulations

Future Work

- Design efficient algorithms for sum peak traffic minimization with D2D LB
- Design incentive mechanisms for D2D users
- Distributed/Online scheduling algorithms
- Refine the physical-layer channel model and relax some assumptions

Q&A

Thank you!

Backup Slides

Minimize Sum Peak Traffic: No D2D

$$
\begin{aligned}
\min \quad & P_b \\
\text{s.t.} \quad & \sum_{t=\tau}^{d^{s\tau}} y_{sb}^{s\tau}(t) R_{sb} = x^{s\tau}, \forall s \in \mathcal{U}_b, \tau \in [1, T] \\
& \sum_{s \in \mathcal{U}_b} \sum_{\tau : \tau \le t \le d^{s\tau}} y_{sb}^{s\tau}(t) = \alpha_b(t), \forall t \in [1, T] \\
& \alpha_b(t) \le P_b, \forall t \in [1, T] \\
& y_{sb}^{s\tau}(t) \ge 0, \forall s \in \mathcal{U}_b, \tau \in [1, T], t \in [\tau, d^{s\tau}] \\
\text{var} \quad & y_{sb}^{s\tau}(t), \alpha_b(t), P_b
\end{aligned}
$$

Minimize Sum Peak Traffic: D2D

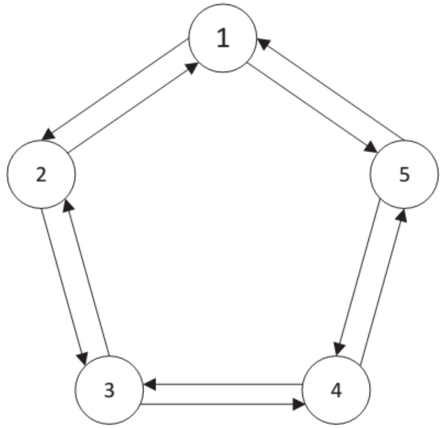
$$
\begin{aligned}
\min \quad & \sum_{b \in \mathcal{B}} P_b \\
\text{s.t.} \quad & \text{feasible traffic scheduling policy}, \\
& \sum_{v \in \mathcal{U}_b} \sum_{s \in \mathcal{U}} \sum_{\tau : \tau \le t \le d^{s\tau}} y_{vb}^{s\tau}(t) = \alpha_b(t), \\
& \qquad \qquad \forall b \in \mathcal{B}, t \in [1, T] \\
& \sum_{u \in \mathcal{U}_b} \sum_{v \in \mathrm{in}(u) \backslash \{u\}} \sum_{s \in \mathcal{U}} \sum_{\tau : \tau \le t \le d^{s\tau}} y_{vu}^{s\tau}(t) = \beta_b(t), \\
& \qquad \qquad \forall b \in \mathcal{B}, t \in [1, T] \\
& \alpha_b(t) + \beta_b(t) \le P_b, \forall b \in \mathcal{B}, t \in [1, T] \\
\text{var} \quad & y_{uv}^{s\tau}(t), \alpha_b(t), \beta_b(t), P_b
\end{aligned}
$$

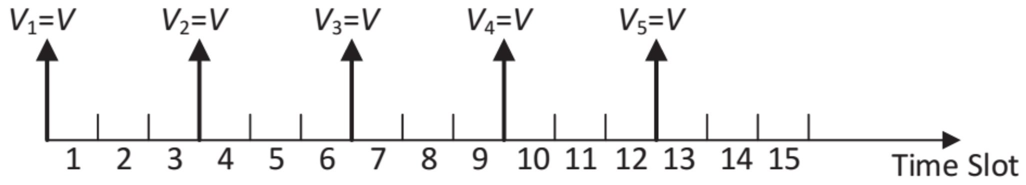
Ring Topology

- For any $D \geq 1$, there exists a ring topology and a traffic demand pattern such that

$$\rho = \frac{2(D-1)}{3D-2}$$

  - $\lim_{D\to\infty} \rho = \frac{2}{3} = \frac{\Delta^-}{\Delta^-+1}$
  - The bound is **asymptotically tight**





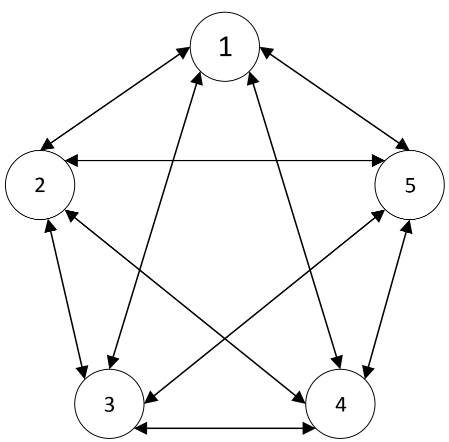
$(D = 3)$

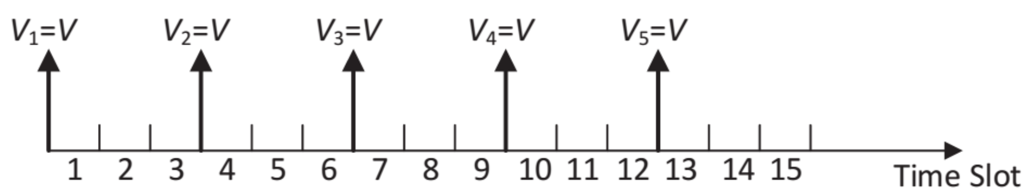
Complete Topology

- In a *N*-BS complete topology, there exists a traffic demand pattern such that

$$\rho = \frac{N-1}{N+1}$$

  - $\lim_{N\to\infty} \rho = 1$
  - In ***the best case***, we can achieve **100%** sum peak traffic reduction!





$$(N = 5)$$

Tradeoff between Benefit and Cost

- Tradeoff between sum peak traffic reduction ρ and overhead ratio η