# Optimal Wireless Power Transfer Scheduling for Delay Minimization

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# Outline

- Background
- Problem Modeling
- Solutions
- Simulation
- Conclusion

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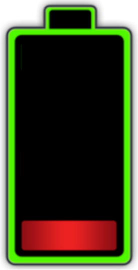
# Wireless Power Transfer (WPT)

- Current batteries:
  - Large in size
  - Heavy in weight
  - Low in capacity
  - Slow to charge

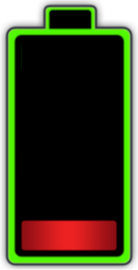


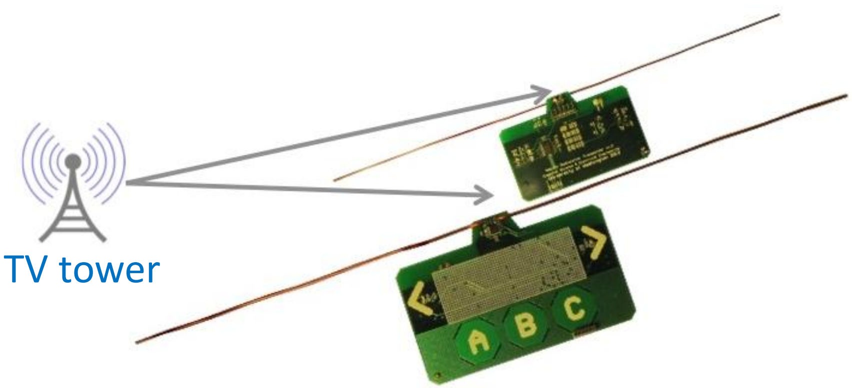
- Alternative option: wireless power transfer (industry)


There are already companies offer commercial products.

# Wireless Power Transfer (WPT)

- Current batteries:
  - Large in size
  - Heavy in weight
  - Low in capacity
  - Slow to charge
- Alternative option: wireless power transfer (academia)



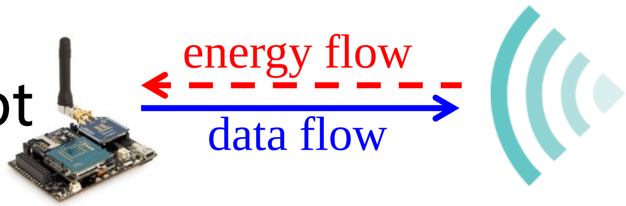



TV tower powered battery-less devices
[SIGCOMM'13] Best paper

Wi-Fi powered cameras
[CoNext'15] Best paper Nominee

# Research Work

- Because of the current hardware limitation, research works usually adopt the **Harvest-Then-Transmit** strategy




- The objectives:

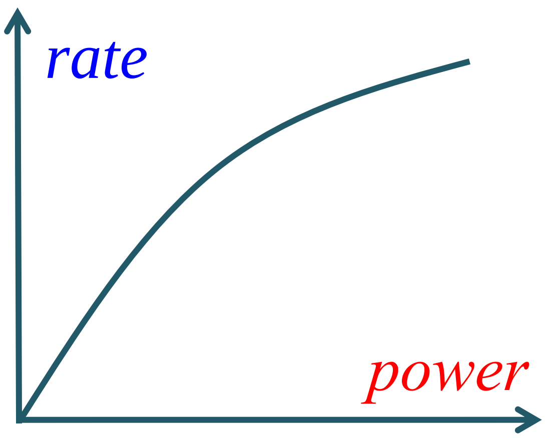
**Throughput**

**Transmission Delay**

- H. Ju, et al [TWC, 14]: Time allocation
- Y. Gu, et al [ICC'15]: Relay
- Y. L. Che, et al [JSAC, 15]: Large-scale
- S. Bi, et al [TWC, 16]: Placement

# Energy-Delay Tradeoff

Shannon-Hartley Theorem: *rate* = log ( 1 + *power* )




To deliver a block of data:

- Lower rate ➔ less energy, longer delay
- Higher rate ➔ more energy, shorter delay

❖ Trade-off between energy and delay

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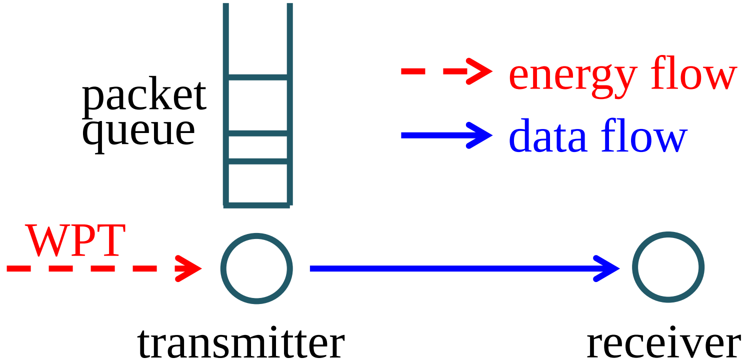
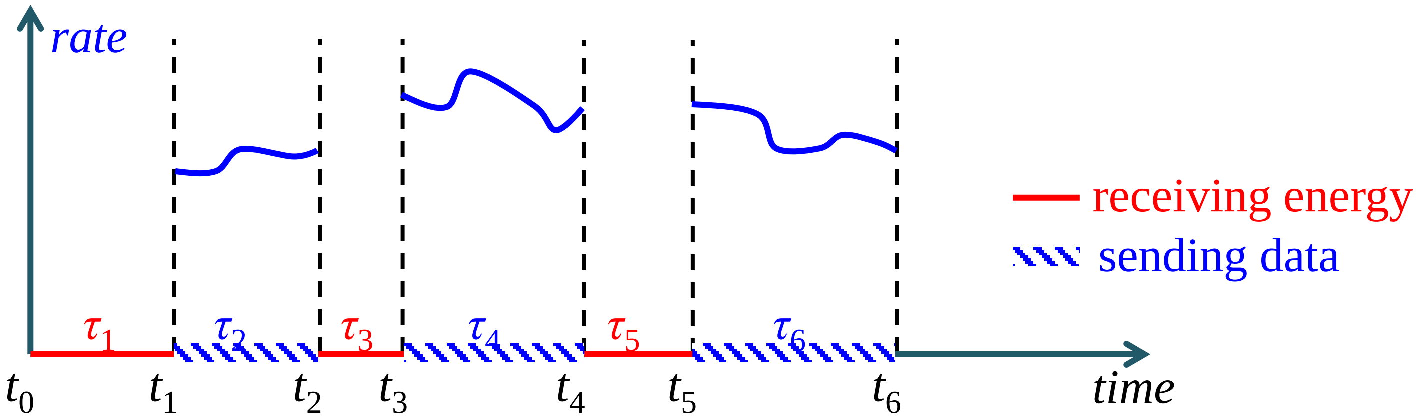
# Problem Modeling

- Input
  - Packets $\{P_1, P_2, \ldots, P_n\}$ in the queue.
  - $P_i$ has a size $B_i$ an arrival time $a_i$, e.g. $P_i(B_i, a_i)$.
- Two types of phases
  - Wireless charging in charging phases – receiving power $p$
  - Data transmission in sending phases – rate $r$ adjustable
- Objective
  - To minimize the packets transmission completion delay



# Problem Modeling (cont.)

- Define a cycle
  - Consecutive charging phase and sending phase.
- Two sub-objectives
  - Determine durations of all cycles
  - Determine rates in sending phases



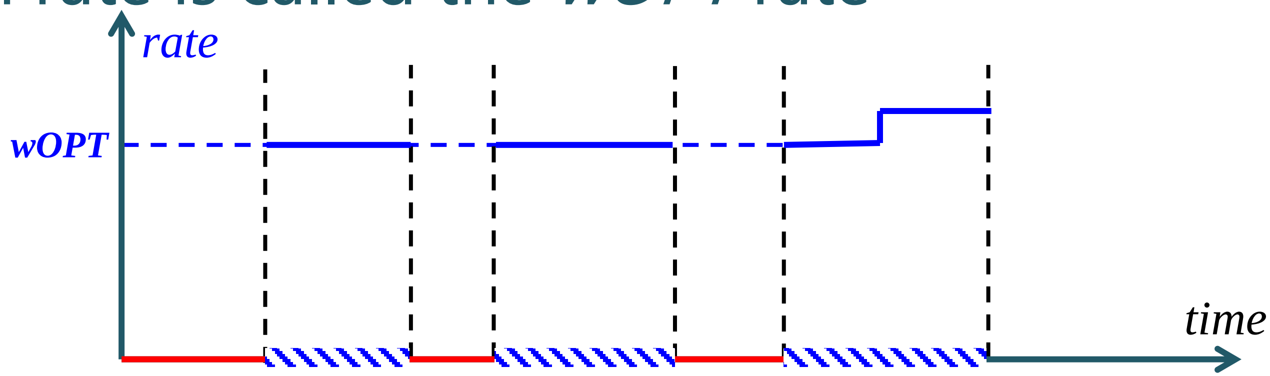
# Main Results

For the offline problem:

- Intuitively, the duration and rates depends on
  - ① initial energy of the battery
  - ② sizes of packets
- Surprisingly, our main Lemma is

> The optimal offline transmission rate for each cycle, except the last, is constant and dependents on neither ① nor ②.

- Such rate is called the *wOPT* rate



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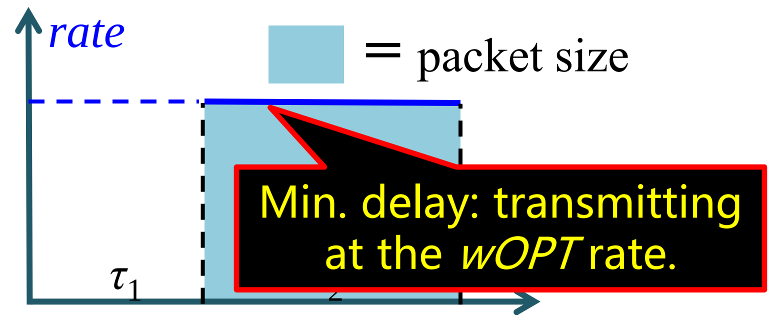
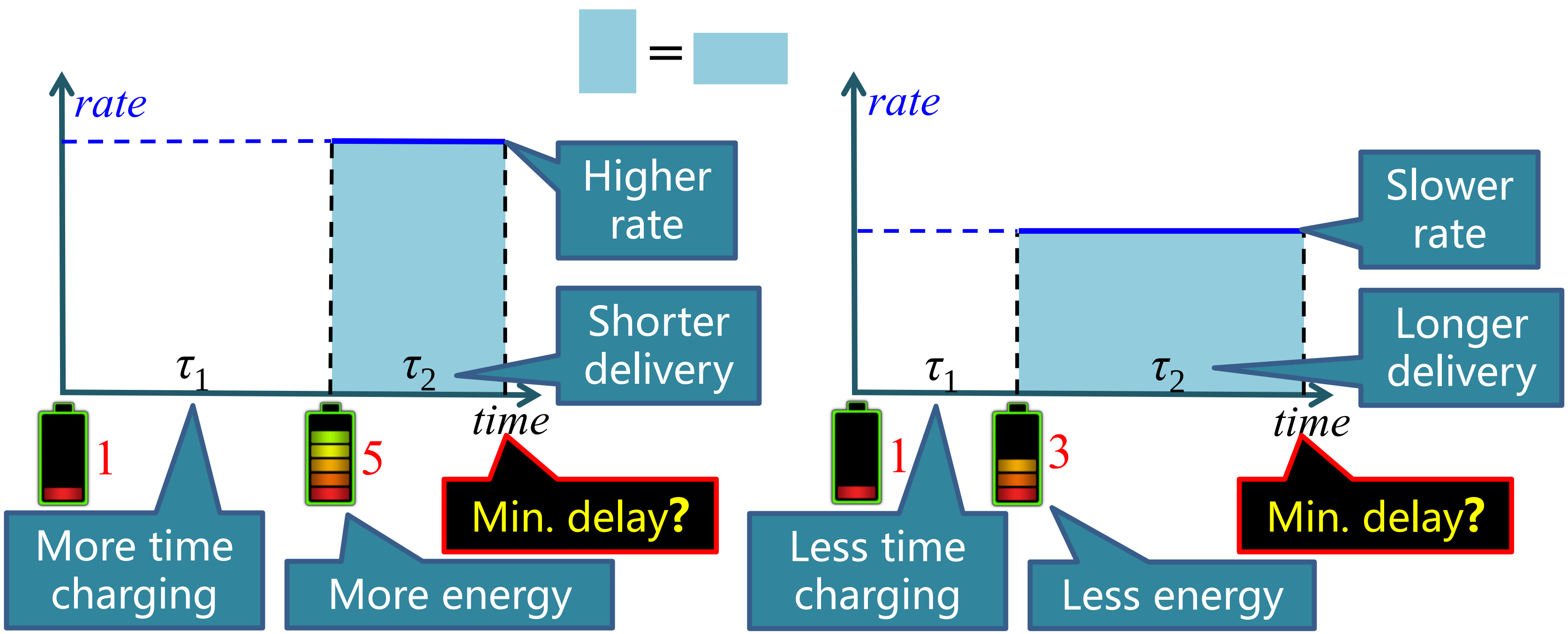
# The *wOPT* rate

- A simplified problem
  1. One packet
  2. Large battery capacity




- Trade-off between two strategies



# The *wOPT* rate (cont.)

- Theorem

> The optimal offline solution transmits at *wOPT* rate $r_s$, which is independent of the initial energy $E_0$ and packet size *B*.

- Proof
  1. Energy in battery equals energy consumed
  $$E_0 + p\tau_1 = \tau_2(2^r - 1)$$
  2. All data must be delivered $\tau_2 = \frac{B}{r}$
  3. Combine the two
  4. Let $T(r) = \tau_1 + \tau_2 = \frac{B(2^r - 1 + p)}{rp} - \frac{E_0}{p}$
  5. To minimize $T(r)$, we have
  $$T(r)' = \left(\frac{2^r - 1 + p}{r}\right)' = 0$$
  6. Therefore
  $$r_s = \frac{w+1}{\ln 2}$$ where $w = \mathcal{W}(\frac{p-1}{e})$ and $\mathcal{W}(z)e^{\mathcal{W}(z)} = z$

# Importance of *wOPT* rate

- Although derived from a simple scenario, it plays an important role in the general scenario.
- Conclude

> The discovery of the *wOPT* rate reveals an essential property of Wireless Power Transfers.

# General problem

- The general problem
  1. Multiple packets
  2. Battery capacity limited

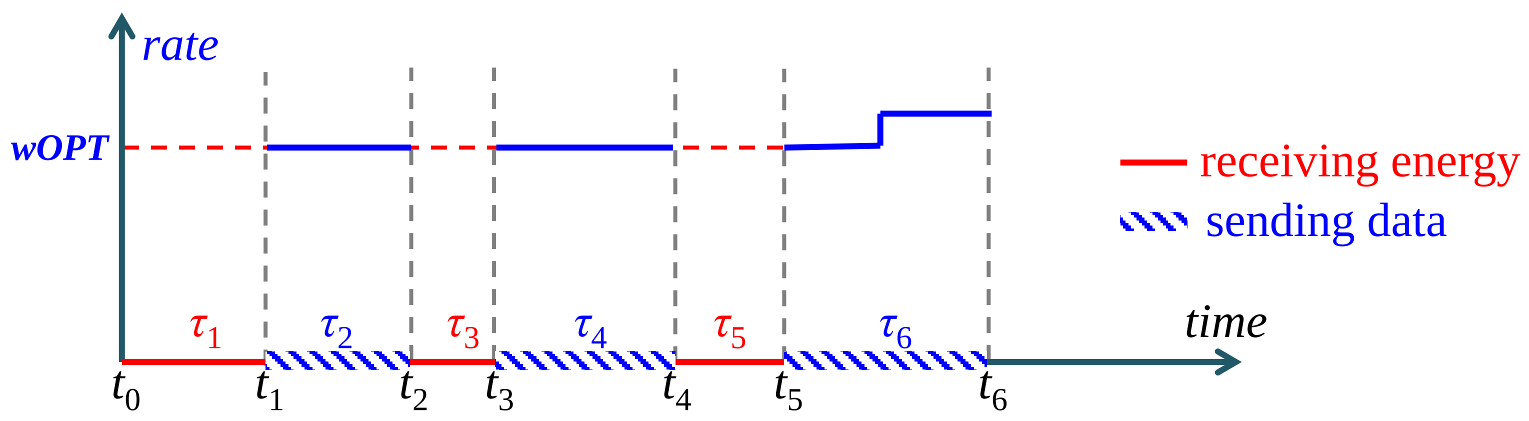
- Lemma

The optimal offline solution transmits at the *wOPT* rate in every cycle, except the last cycle.

- In the last cycle, transmission rate
  1. Increase only
  2. Increase only at packet arrivals
  3. Increase when arrived data all transmitted

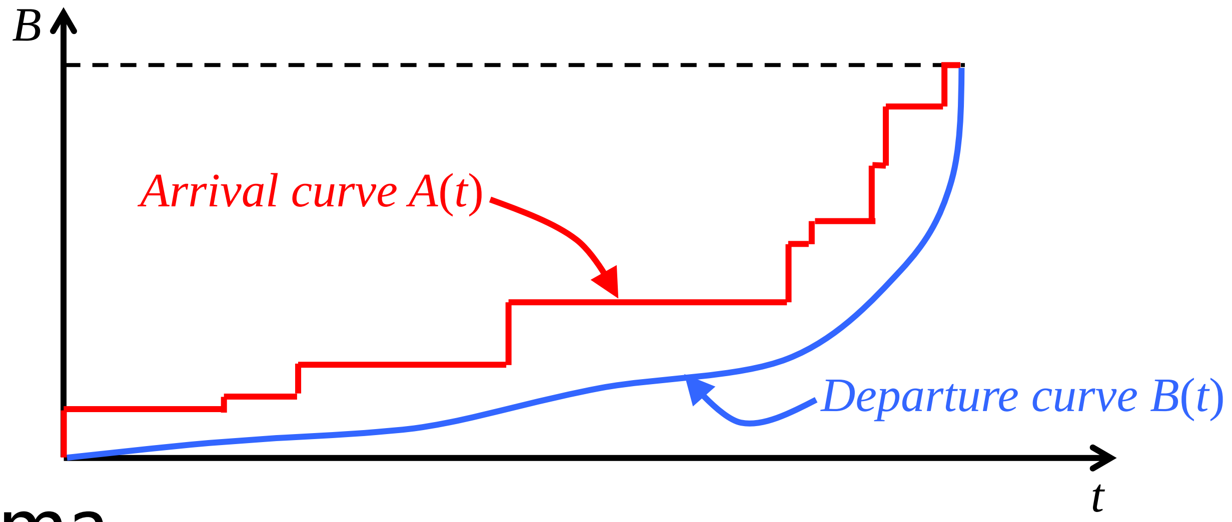
# Solution keys

- Although know the transmission rate in most cycles
- Still need to
  1. Determine the beginning and ending of each cycles
  2. Determine the rates in the last cycle



# Cumulative Data-time diagram

- The *Cumulative data-time* diagram
  - $A(t)$: total amount of bits arrived before $t$
  - $B(t)$: actual amount of data transmitted before $t$
  - slope of $B(t)$ is actually the transmission rates

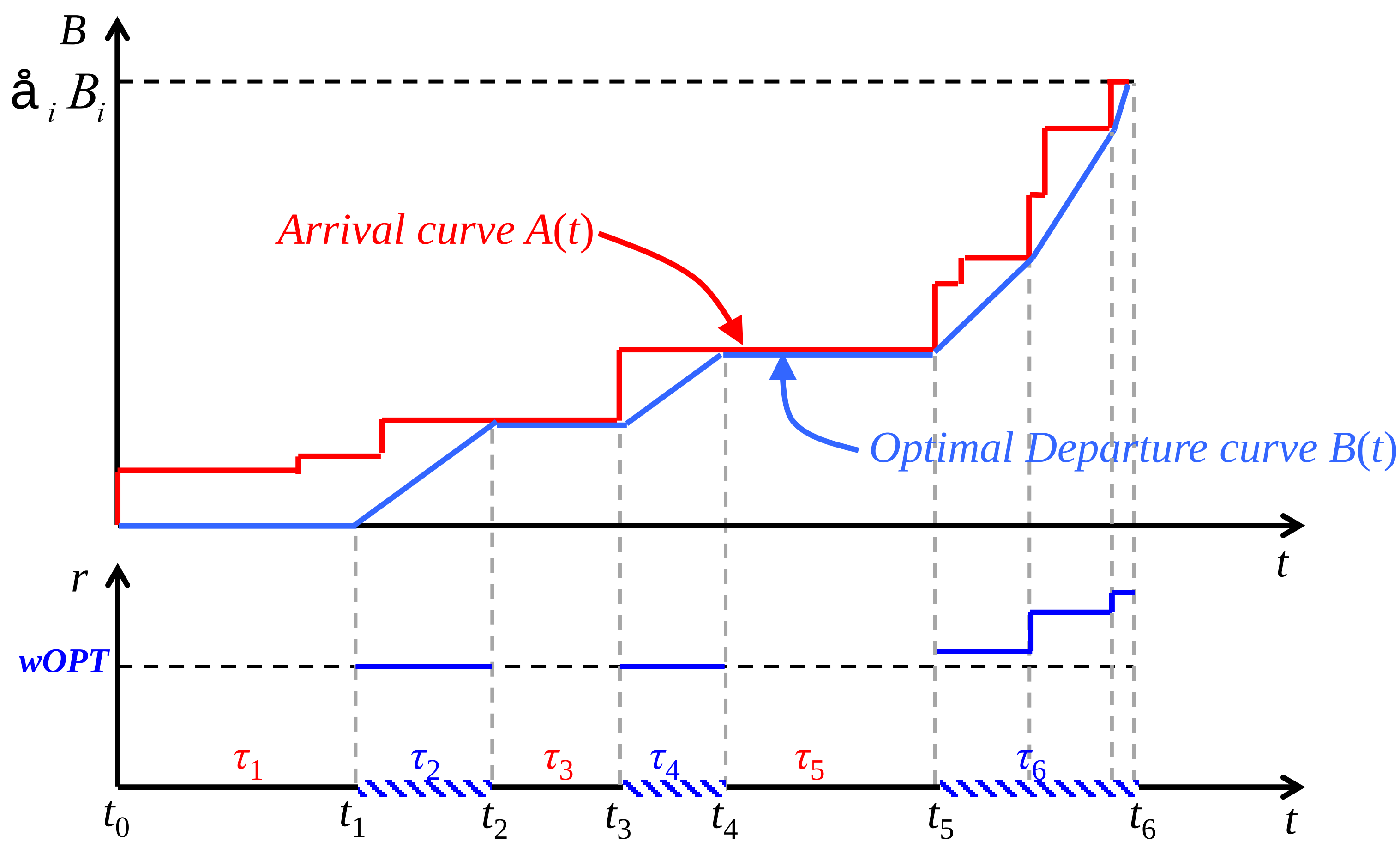



- Lemma

Any departure curve must be on the right of the arrival curve.

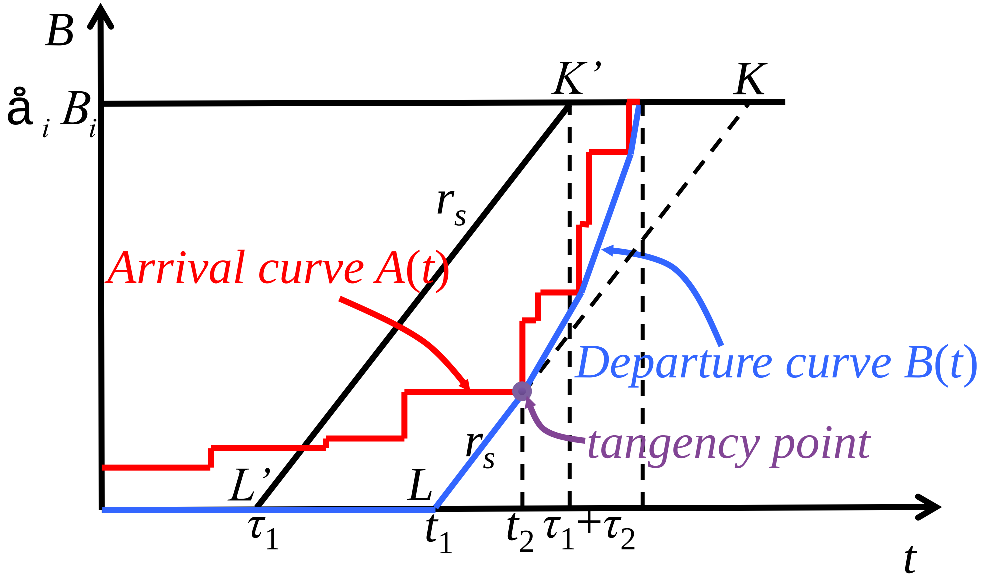
# Algorithm Outline

1. Transmit at *wOPT* rate whenever possible
2. In the last cycle, set increasing rates



# Algorithm Details

In Step 2: Detailed method to determine the rates in the last cycle.



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# Online algorithm

- The online algorithm is quite simple
  - Transmit at *wOPT* rate whenever possible
- In the simulation, we compare it with the offline optimal algorithm

# Simulation Settings

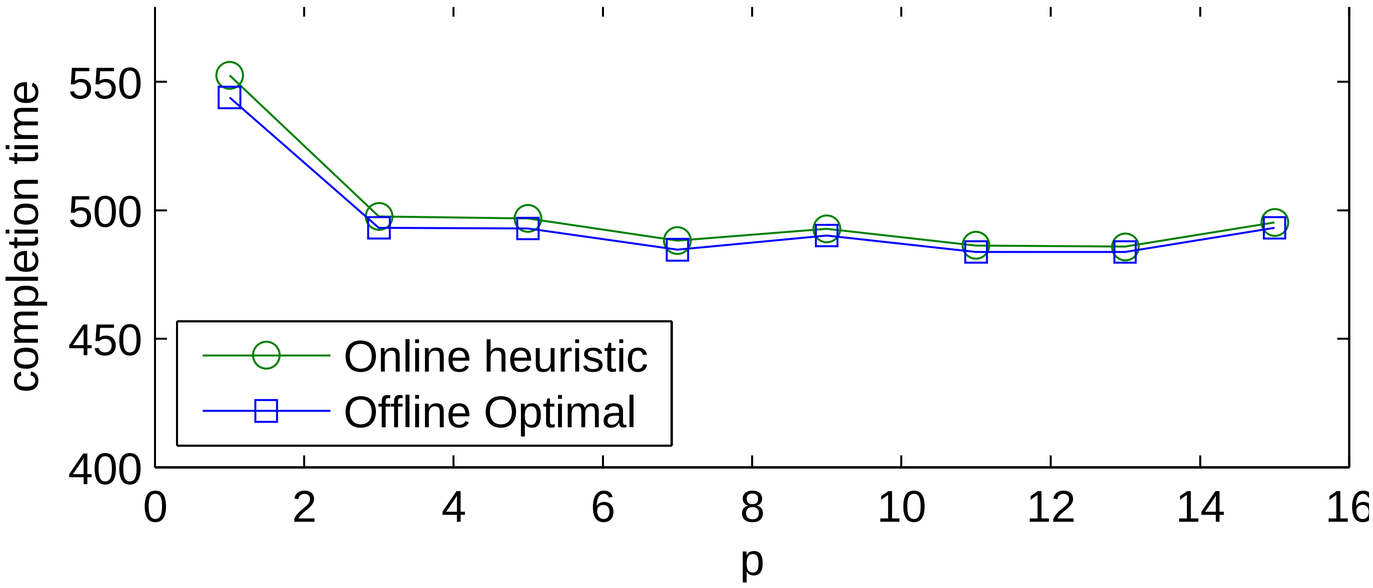
- Parameter Settings

| Parameter | Packet arrival | Packet size | Battery capacity | Initial energy |
|---|---|---|---|---|
| Distribution | Poisson | Uniform | - | - |
| Value | 1/10 | [7, 10] | [800,1500] | [0, full] |

- Data Generation
  – Mean of 100 instances
  – Each instance generates random 50 packets
- Objective
  – The completion time for all packets transmission

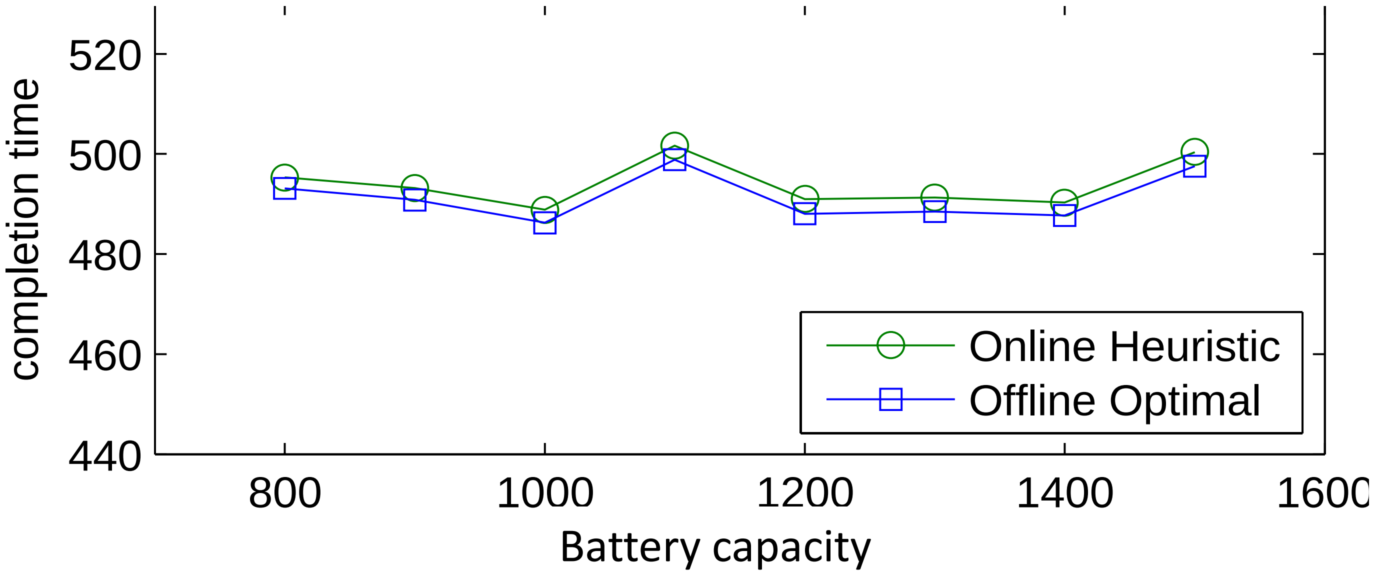
# Simulation Results

- The higher energy transfer speed *p*, the shorter the completion time
  - When *p* is large, less time to charge the battery, therefore the total time decreases
  - While *p* is small, more careful effect to schedule the transmission. Thus the simple online heuristic fails to produce a solution close to the optimal.



# Evaluation Results

- Battery capacity does not have much impact on the algorithm performance
- Overall, the online heuristic has a similar performance to the offline optimal
  - Because it is designed based on the optimality property and transmits at the *wOPT* rate.



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# Conclusion

1. Study the delay minimization problem in Wireless Power Transfer
2. Discovery the *wOPT* rate
3. Based on it, design optimal offline algorithm and online heuristic algorithm.
4. The discovery of the *wOPT* rate reveals an essential property of Wireless Power Transfer

# Thank You!

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