Institute for the Wireless Internet of Things at Northeastern University

EECE 5155

Wireless Sensor Networks (and The Internet of Things)

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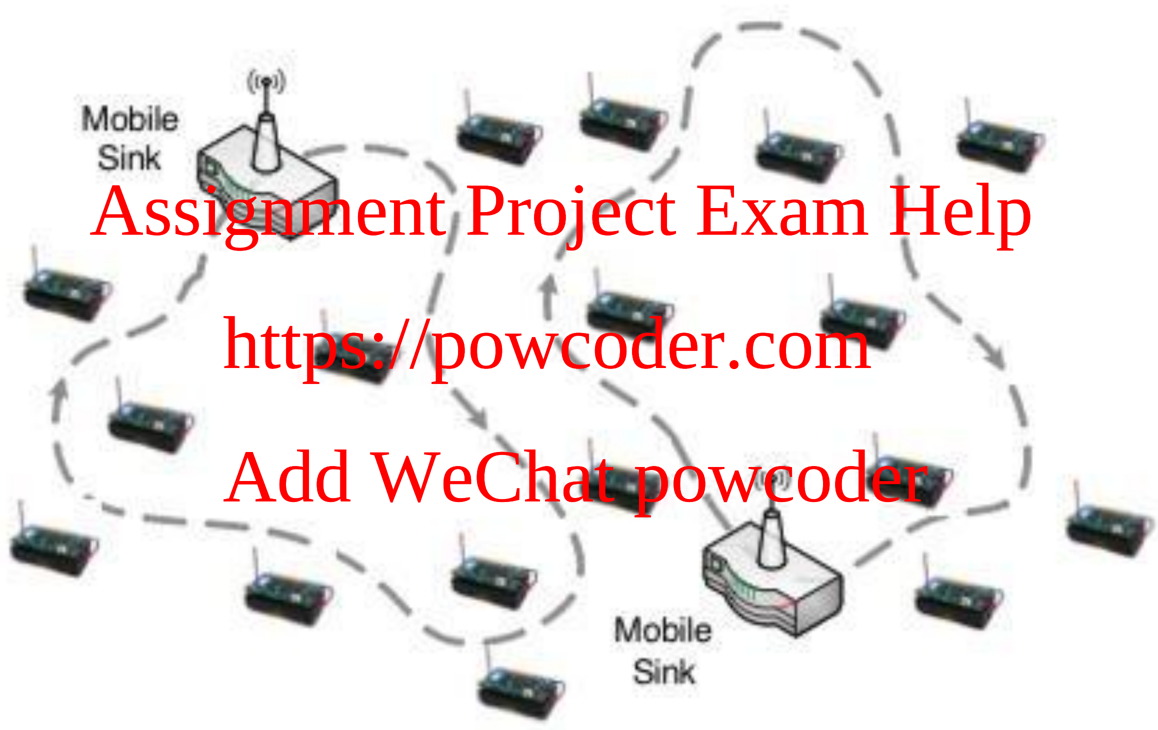
March 4, 2021

Architecture of a WSN-MSs



Why Mobile Sinks?

- Mobile sinks deal with isolated regions (**sparse WSNs**)
- Constraints on network connectivity can be **relaxed**

- Fewer nodes →→→ Reduced costs!
- Can exploit trains, buses, shuttles or cars and attach sinks to them

- Multi-hop networks are compromised by interference and collisions

- Mitigate (or eliminate) **the funnelling effect**

Challenges and Opportunities

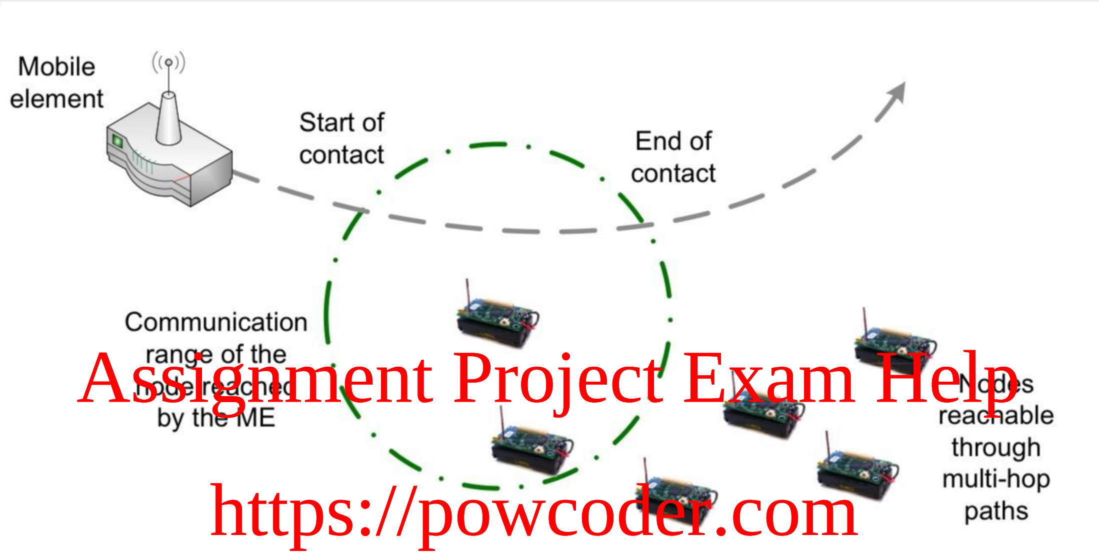
1. Detection of Mobile Sinks (*i.e.*, discovery problem)

2. Mobility-aware Power Management

3. Reliable Data Transfer

4. Mobility Control (and Optimization)

Sensors/Sink Interaction



- **Discovery & Data Transfer** phases
- Mobility can be **Deterministic or Random**
  - 1) Enters the communication range of sensor nodes at specific, and usually periodic, times (e.g., shuttles)
  - 2) Contacts may take place not regularly, but with a distribution probability

Discovery Process

- ***Scheduled rendez-vous***
  - Assume sensor nodes and MSs agree on a specific instant at which they will be in contact
  - Know exactly when the ME will enter the contact area, and can thus wake up at predefined times
  - Simple to implement but requires **tight synchronization**
- ***On-demand***
  - Sensors can wake up by the MS
  - Can use multiple radios ⟶ long-range and high-power radio for data communication, low-range low-power radio to wake up nodes
  - Exploits radio-triggered activation similar to RFID, send messages with enough energy to trigger the activation of the static sensor node (*i.e.*, an interrupt).

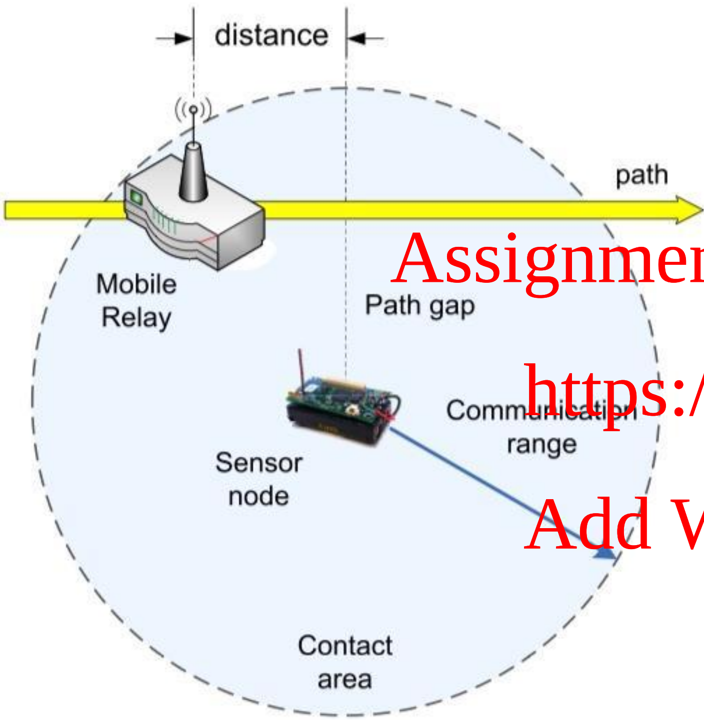
Discovery Process (2)

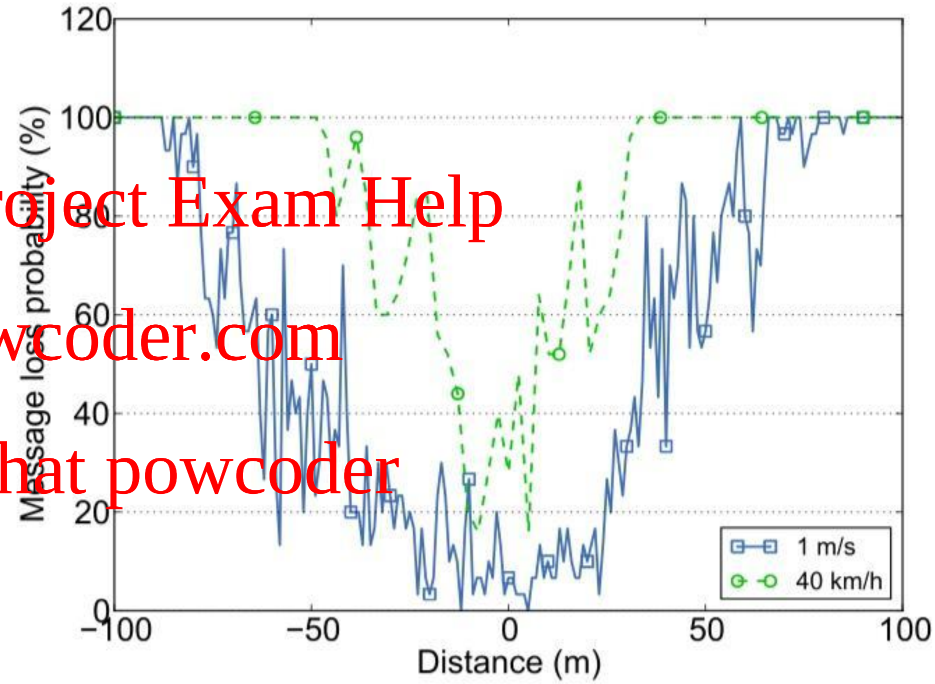
➢ ***Asynchronous (used the most)***

- Define **sleep/wake-up patterns** to communicate without explicitly agreeing on activation instants
- *Periodic Listening (PL)*: MS sends periodic discovery messages, while the static node cyclically wakes up and listens for advertisements for a short time
- If it does not detect any discovery message it can return to sleep, otherwise it can start transferring data to the MS
- Discovery parameters and the duty-cycle **have to be properly defined** to ensure that the MS will be actually discovered

Data Collection Process - What Matters

E. Borgia, G. Anastasi, M. Conti, [Energy Efficient and Reliable Data Delivery in Urban Sensing Applications: A Performance Analysis], *Computer Networks*, Vol. 57, N. 17, December 2013, pp. 3389 - 3409. Elsevier.





- ➢ Trajectory and speed impact *significantly* MLP
- ➢ How do we evaluate how much they impact?

Can we come up with a mathematical model of the discovery and data transfer processes?

If yes, how?

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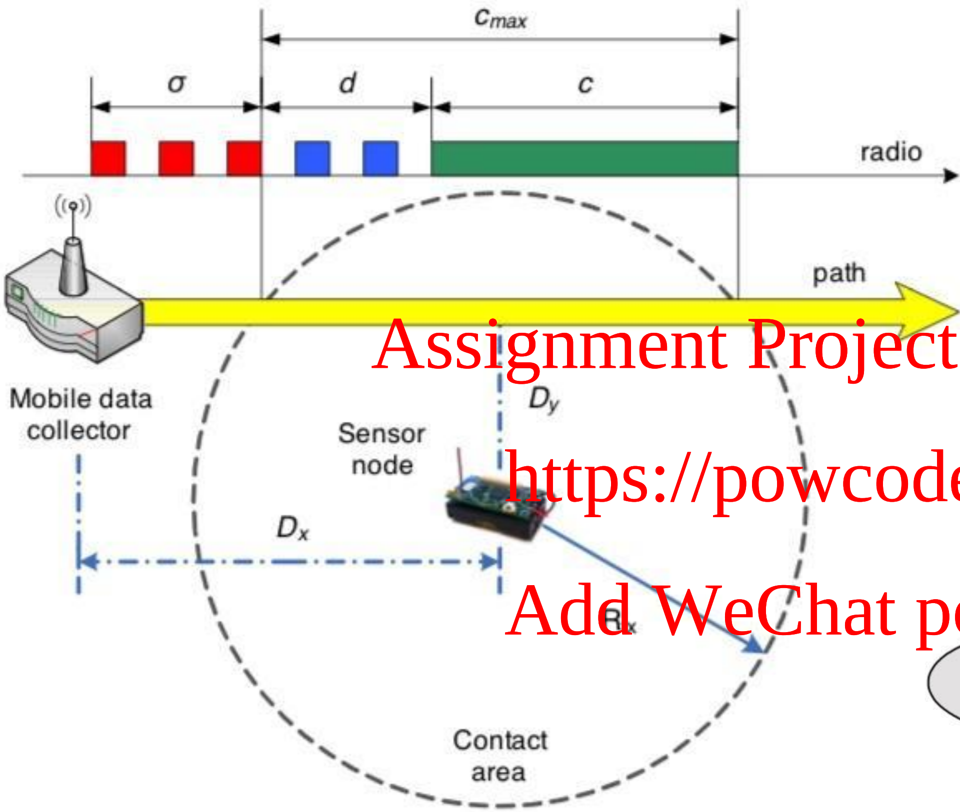
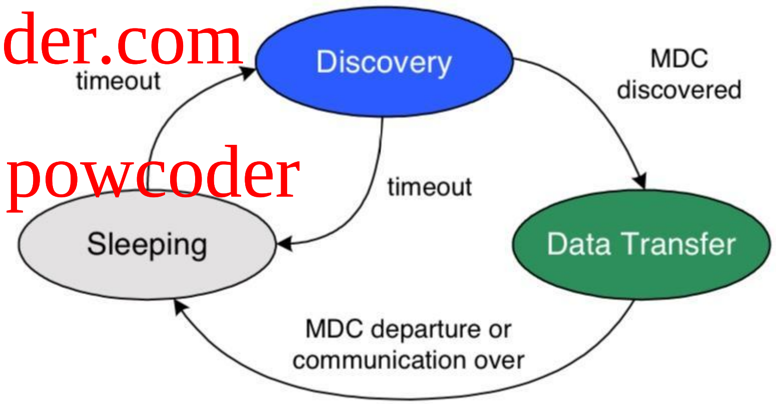
March 8, 2021

Modeling Discovery and Data Transfer

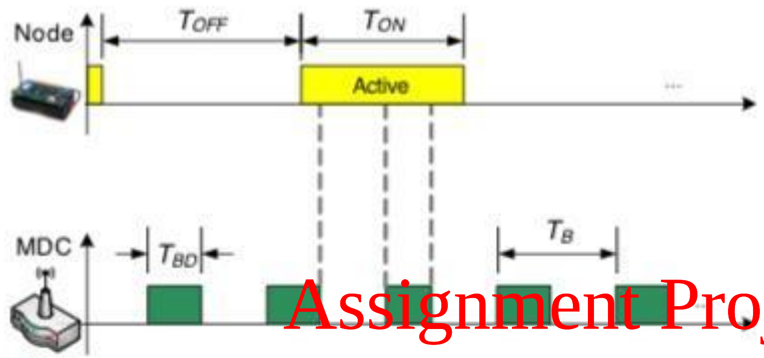


- ***p(t)*** *probability of message loss inside the contact area*



G. Anastasi, M. Conti, M. Di Francesco, **Reliable and Energy-efficient Data Collection in Sparse Sensor Networks with Mobile Elements**, *Performance Evaluation*, Special Issue on *Performance Evaluation of Ubiquitous Networks*, Vol. 66, N. 12, pp. 791-810, December 2009. Elsevier.

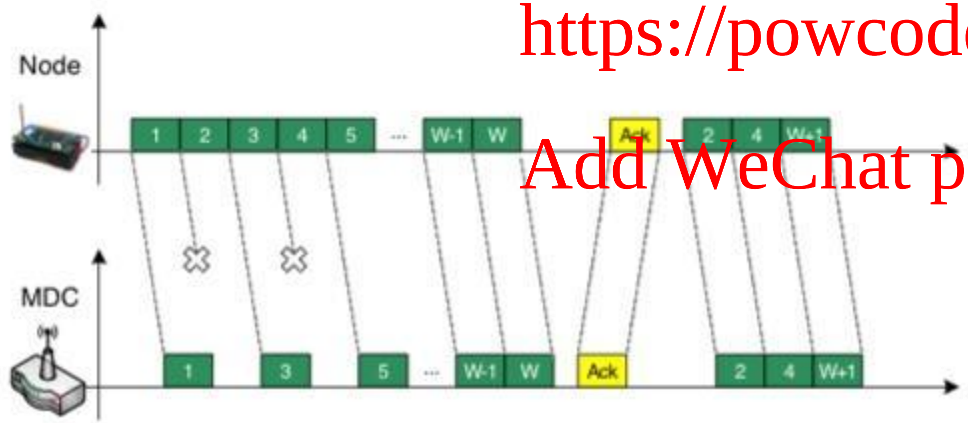
Modeling Discovery and Data Transfer (2)



(a)

$$T_{ON} = T_B + T_{BD}$$

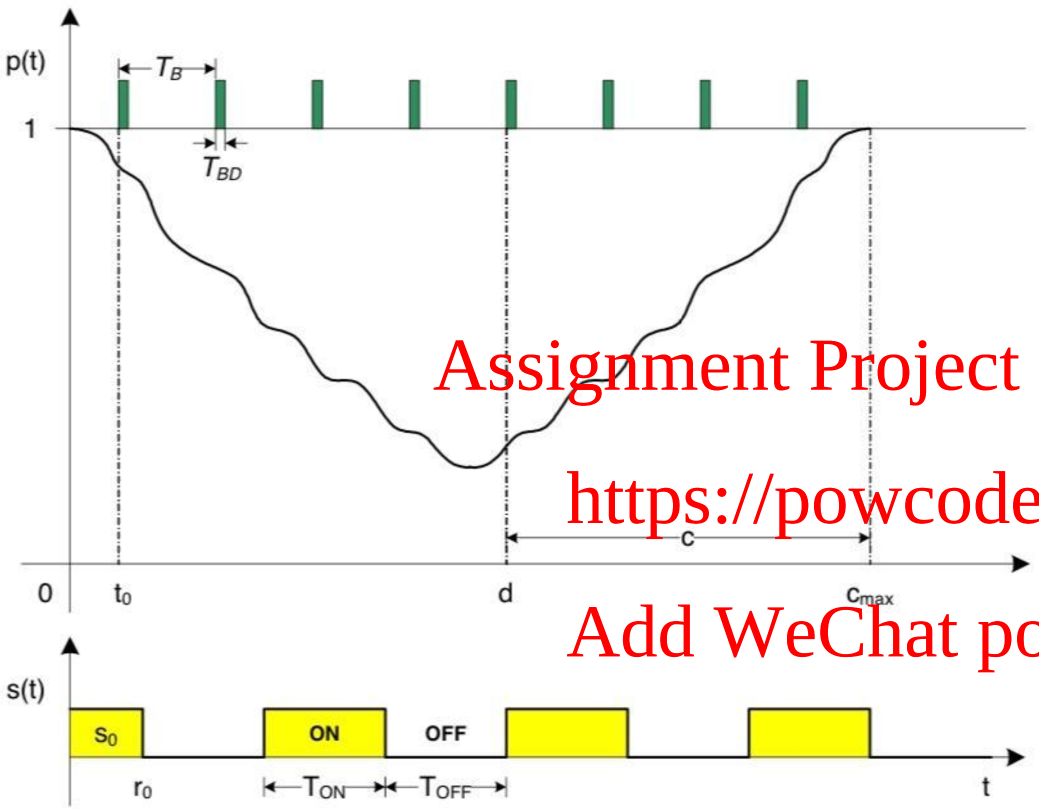
$$\delta = T_{ON}/(T_{ON} + T_{OFF})$$



(b)

- ***ARQ** scheme for data transfer inside the contact area*

Beacon Discovery Process



- *Radio state is defined by a tuple (s, r), where **s** is the state (ON/OFF) and **r** is the residual time in that state*

$$\underset{s_0=\mathrm{ON}}{s(t_n)} = \begin{cases} \mathrm{ON} & \text{if } 0 \le t'_n < r_0 \\ \mathrm{OFF} & \text{if } r_0 \le t'_n < r_0 + T_{OFF} \\ \mathrm{ON} & \text{if } r_0 + T_{OFF} \le t'_n < T_{ON} + T_{OFF} \end{cases}$$

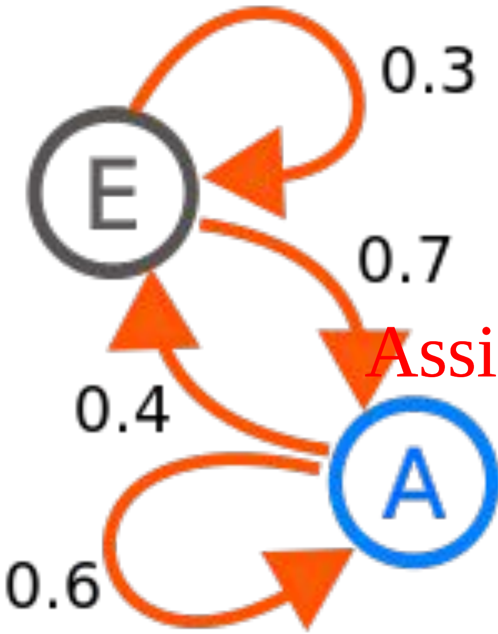
$$\underset{s_0=\mathrm{OFF}}{s(t_n)} = \begin{cases} \mathrm{OFF} & \text{if } 0 \le t'_n < r_0 \\ \mathrm{ON} & \text{if } r_0 \le t'_n < r_0 + T_{ON} \\ \mathrm{OFF} & \text{if } r_0 + T_{ON} \le t'_n < T_{ON} + T_{OFF} \end{cases}$$

$$t'_n = t_n \mod (T_{ON} + T_{OFF})$$

$$\underset{s_0=\mathrm{ON}}{r(t_n)} = \begin{cases} r_0 - t'_n & \text{if } 0 \le t'_n < r_0 \\ T_{OFF} + r_0 - t'_n & \text{if } r_0 \le t'_n < r_0 + T_{OFF} \\ T_{ON} + T_{OFF} + r_0 - t'_n & \text{if } r_0 + T_{OFF} \le t'_n < T_{ON} + T_{OFF} \end{cases} \quad (3)$$

$$\underset{s_0=\mathrm{OFF}}{r(t_n)} = \begin{cases} r_0 - t'_n & \text{if } 0 \le t'_n < r_0 \\ T_{ON} + r_0 - t'_n & \text{if } r_0 \le t'_n < r_0 + T_{ON} \\ T_{ON} + T_{OFF} + r_0 - t'_n & \text{if } r_0 + T_{ON} \le t'_n < T_{ON} + T_{OFF} \end{cases} \quad (4)$$

Markov Chains



A **Markov chain** is a

- stochastic model
- describing a sequence of possible events
- in which the probability of each event depends only on the state attained in the previous event
- If the chain moves state at discrete time steps, it is a discrete-time Markov chain (DTMC)

$$P_t^{(k)} = \begin{pmatrix} \mathbb{P}(X_{t+k} = 1 \mid X_t = 1) & \mathbb{P}(X_{t+k} = 2 \mid X_t = 1) & \dots & \mathbb{P}(X_{t+k} = n \mid X_t = 1) \\ \mathbb{P}(X_{t+k} = 1 \mid X_t = 2) & \mathbb{P}(X_{t+k} = 2 \mid X_t = 2) & \dots & \mathbb{P}(X_{t+k} = n \mid X_t = 2) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbb{P}(X_{t+k} = 1 \mid X_t = n) & \mathbb{P}(x_{t+k} = 2 \mid X_t = n) & \dots & \mathbb{P}(X_{t+k} = n \mid X_t = n) \end{pmatrix}$$

Stationary Distributions in DTMC

- A stationary distribution of a DTMC is a probability distribution that remains unchanged as time progresses.
- Represented as a row vector π whose entries are probabilities summing to 1 and satisfies the following relationship with the transition matrix P:

$$\pi = \pi P$$

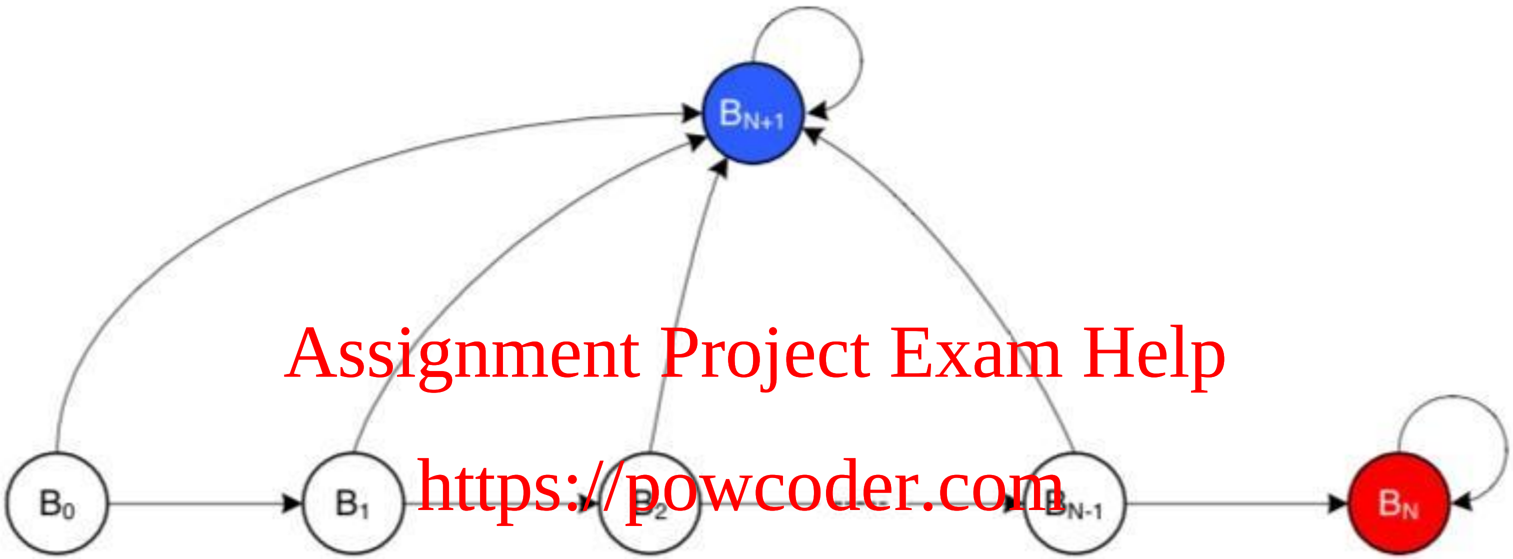
- Absorbing Markov chains have stationary distributions with nonzero elements only in absorbing states

Stationary Distribution in DTMC

$$(\pi \mathbf{P})^T = \pi^T \Rightarrow \mathbf{P}^T \pi^T = \pi^T$$

- The stationary distribution is a **left eigenvector** (as opposed to the usual right eigenvectors) of the transition matrix

Beacon Discovery Process



- B_0 is the **initial state** where the MDC has not yet transmitted the first beacon while in the contact area
- B_j is entered after **missing the first** $j \in [1, N-1]$ beacons
- B_N is entered when the static node **has not detected** the MDC
- Finally, B_{N+1} is entered when the static node has **successfully received a beacon**
- B_N and B_{N+1} are **absorbing states**

Beacon Discovery Process (2)

$$\mathbf{H} = \begin{pmatrix} 0 & H_{01} & 0 & \cdots & 0 & H_{0,N+1} \\ 0 & 0 & H_{12} & & 0 & H_{1,N+1} \\ \vdots & \vdots & & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & H_{N-1,N} & H_{N-1,N+1} \\ 0 & 0 & 0 & \cdots & H_{N,N} & 0 \\ 0 & 0 & 0 & \cdots & 0 & H_{N+1,N+1} \end{pmatrix}$$

$$h^{kl}_{(s_i,r_i),(s_j,r_j)} = \mathbb{P}\left\{B_l, (s_j, r_j) \,|\, B_k, (s_i, r_i)\right\}$$

$$h^{kl}_{(s_i,r_i),(s_j^*,r_j)} = \begin{cases} 1 & \text{if } s_j^* = \text{OFF and } B_l \neq B_{N+1} \\ 0 & \text{if } s_j^* = \text{OFF and } B_l = B_{N+1} \\ p(t_k) & \text{if } s_j^* = \text{ON and } B_l \neq B_{N+1} \\ 1 - p(t_k) & \text{if } s_j^* = \text{ON and } B_l = B_{N+1} \end{cases}$$

- *H_{kl} are sub-blocks denoting the transition probability from the state B_k to the state B_l*
- *State B_0 is evaluated at time $t = 0$, while state B_i $i \in [1, N]$ is evaluated at the i-th beacon transmission time t_i*
- *In addition to the state B related to the beacon reception, the H_{kl} blocks also keep track of the radio state of the static node*

Beacon Discovery Process (3)

$$\mathbf{X}^{(k)} = \begin{pmatrix} X_0^{(k)} & X_1^{(k)} & \cdots & X_{N-1}^{(k)} & X_N^{(k)} & X_{N+1}^{(k)} \end{pmatrix}$$

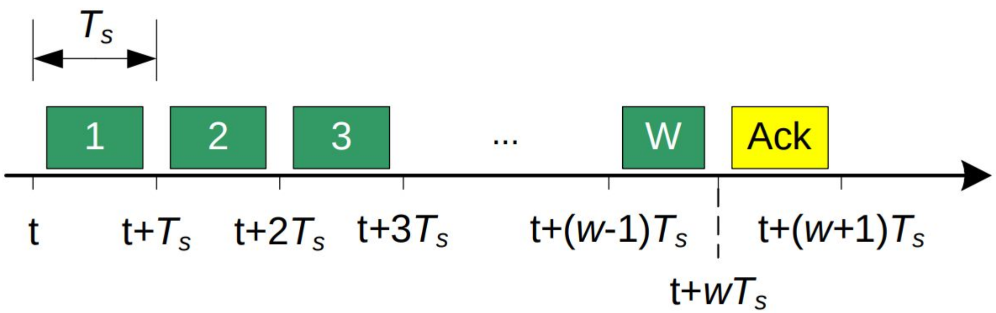
$$\mathbf{X}^{(0)} = \begin{pmatrix} X_0^{(0)} & 0 & 0 & \cdots & 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{X}^{(k+1)} = \mathbf{X}^{(k)} \cdot \mathbf{H} \quad \text{for } k = 0, 1, 2, \ldots, N-1$$

$$d(m, t_0) = \begin{cases} X_{N+1}^{(0)} & \text{if } m = t_0 \\ X_{N+1}^{(k)} - X_{N+1}^{(k-1)} & \text{if } m = t_k,\ k \in [1, N-1] \\ 0 & \text{otherwise} \end{cases}$$

$$d(m) = \sum_{\hat{t}_0 \in \mathcal{T}} d(m, \hat{t}_0) \cdot \mathbb{P}\left\{\hat{t}_0\right\} = \frac{\Delta}{T_B} \sum_{\hat{t}_0 \in \mathcal{T}} d(m, \hat{t}_0)$$

Data Transfer Analysis



$$n(i,t,m) = \begin{cases} 1 - p(t + i \cdot T_s) & \text{if } m = 1 \\ p(t + i \cdot T_s) & \text{if } m = 0 \\ 0 & \text{otherwise} \end{cases}$$

$$N(t) = \sum_{i=0}^{w-1} N(i,t) \qquad n(t,m) = \otimes_{i=0}^{w-1} n(i,t,m)$$

$$\mathbb{E}\left[R(t)\right] = \mathbb{E}\left[N(t)\right] \cdot \mathbb{E}\left[A(t)\right] = \sum_{i=0}^{w-1} [1 - p(t + i \cdot T_s)] \cdot [1 - p(t + w \cdot T_s)]$$

- Focus now on a **single window** starting at the generic time t
- Message loss **changes with the distance** and changes over time
- Assume that the message loss is **constant** during the message, i.e. that the i-th message in the window starting at time t will experience a message loss probability p(t + i · Ts).
- **Is it reasonable?**

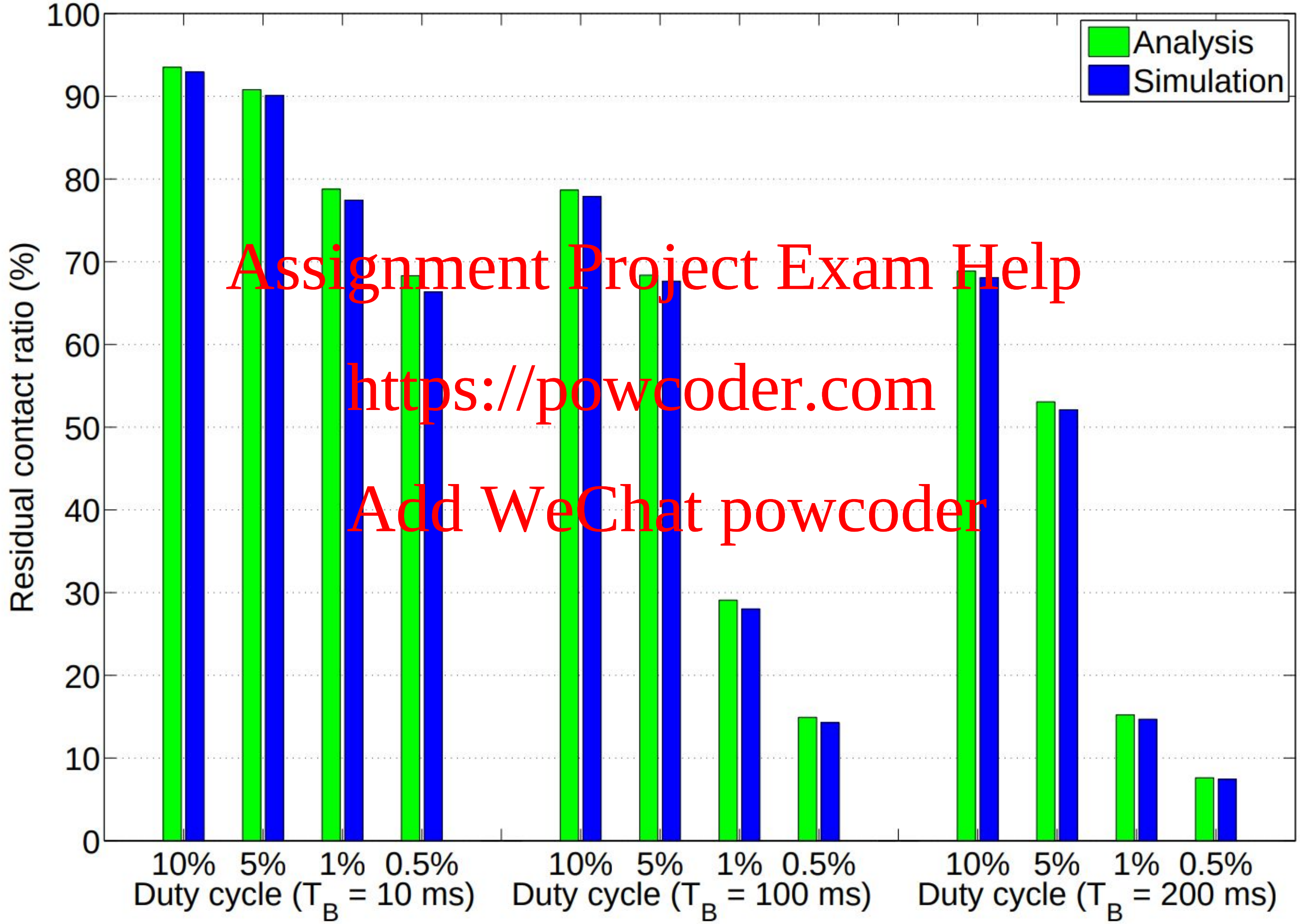
Energy Model

$$\overline{E}_{disc} = P_{sl} \cdot (\sigma + \mathbb{E}[D]) \cdot (1 - \delta) + P_{rx} \cdot (\sigma + \mathbb{E}[D]) \cdot \delta$$

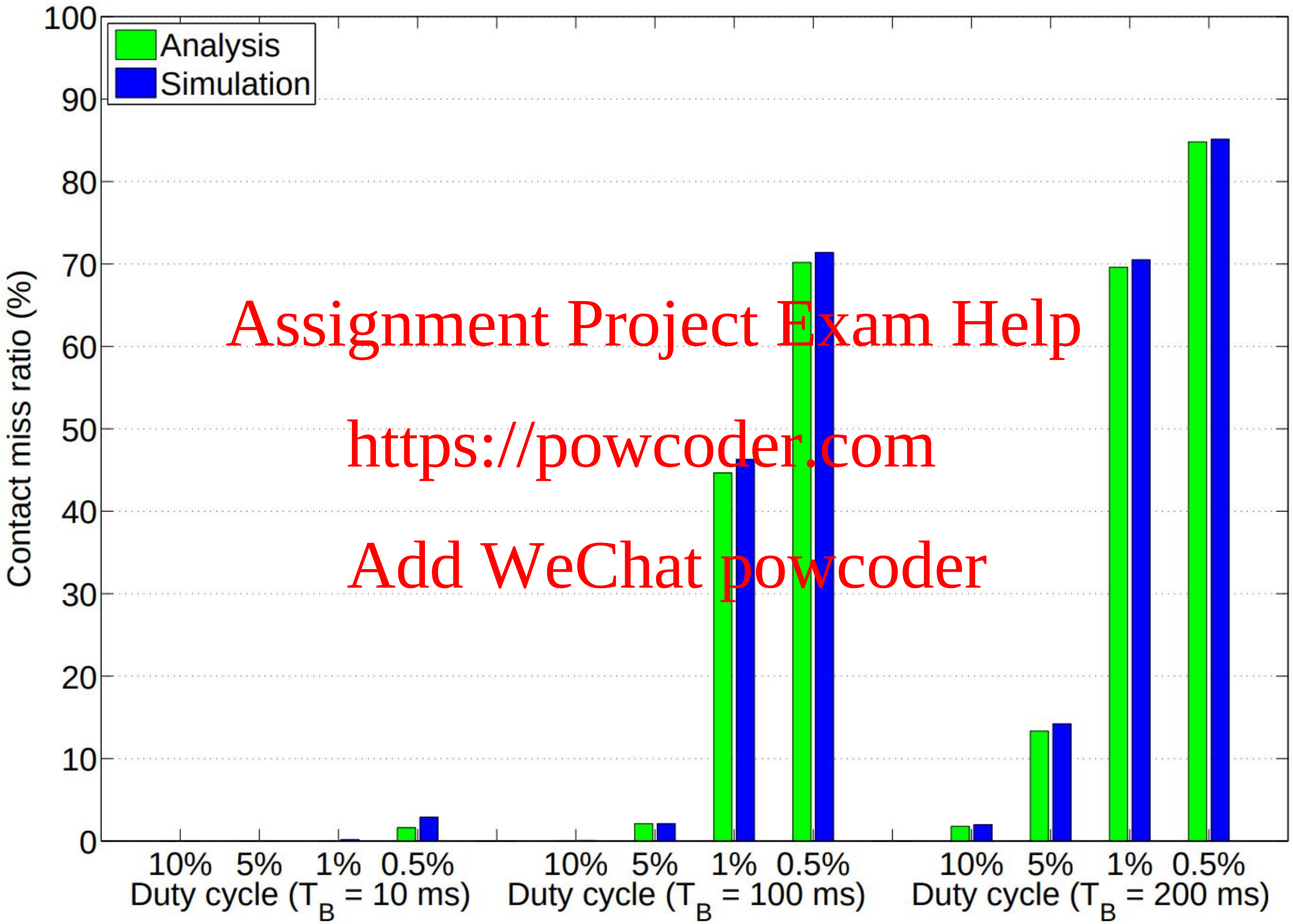
$$\overline{E}_{dt,r} = \left(\frac{\mathbb{E}[c_{max} - D]}{w+1} + \mathbb{P}\{D\} \cdot \frac{N_{ack}}{2} \cdot T_s \right) \cdot (w \cdot P_{tx} + P_{rx})$$

- *First part of the equation is avg # of windows in the residual contact time plus the average number of windows wasted after the end of the contact*
- *Assume that application **has always data to transfer***
- *Using $N_{ack}/2$ in under the assumption that the static node remains awake for a number of windows uniformly distributed in [0, N_{ack}]*
- *The second term is the amount of power spent during each window*

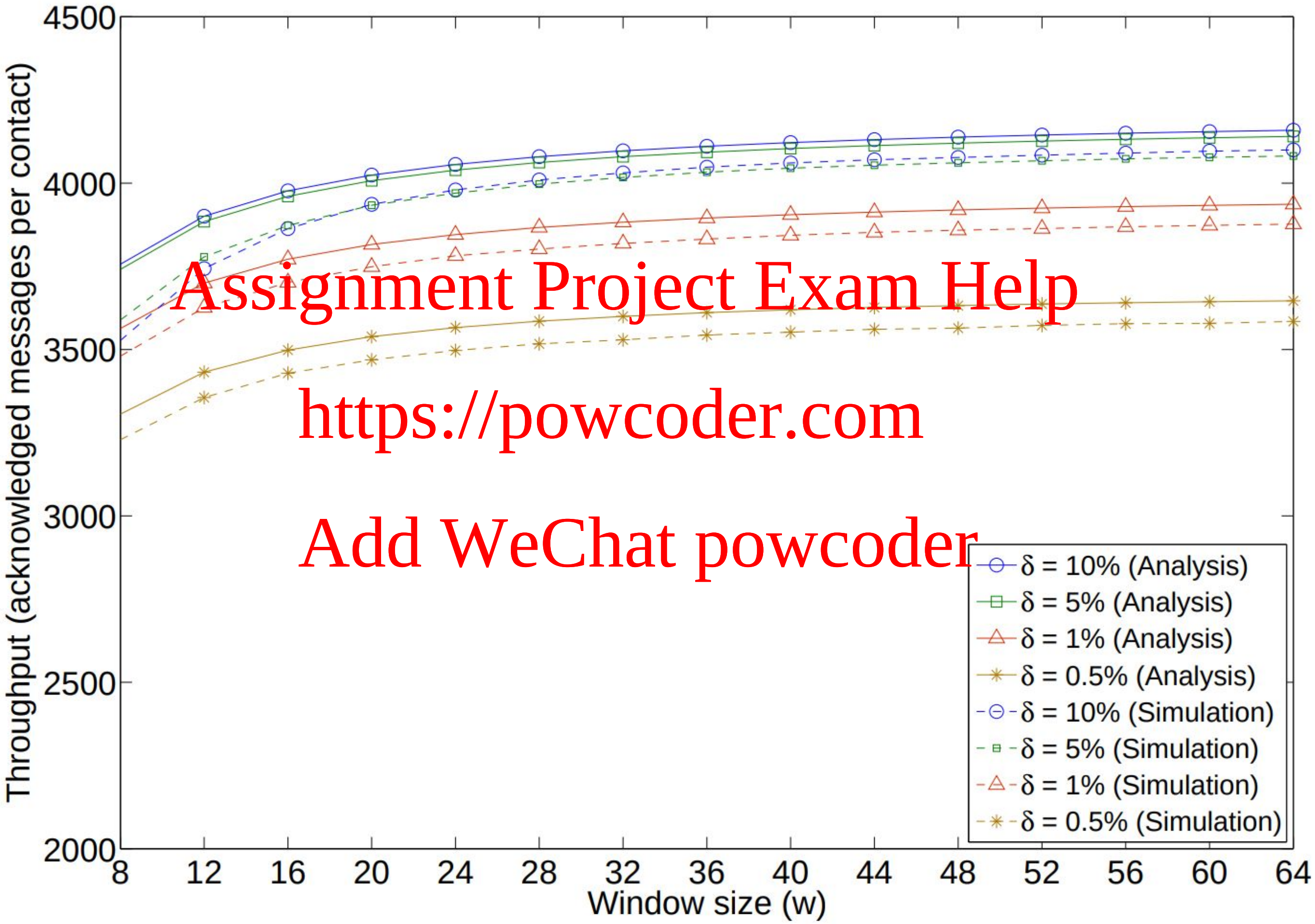
Performance Evaluation



Performance Evaluation

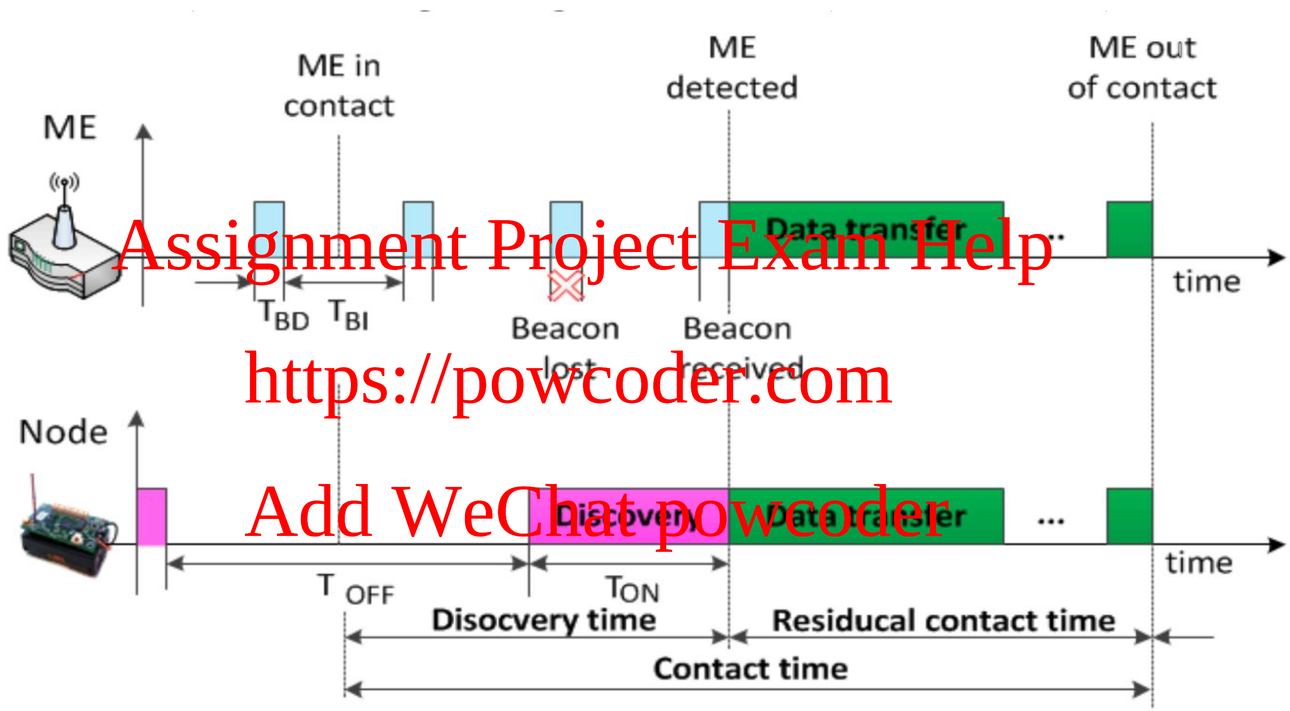


Performance Evaluation

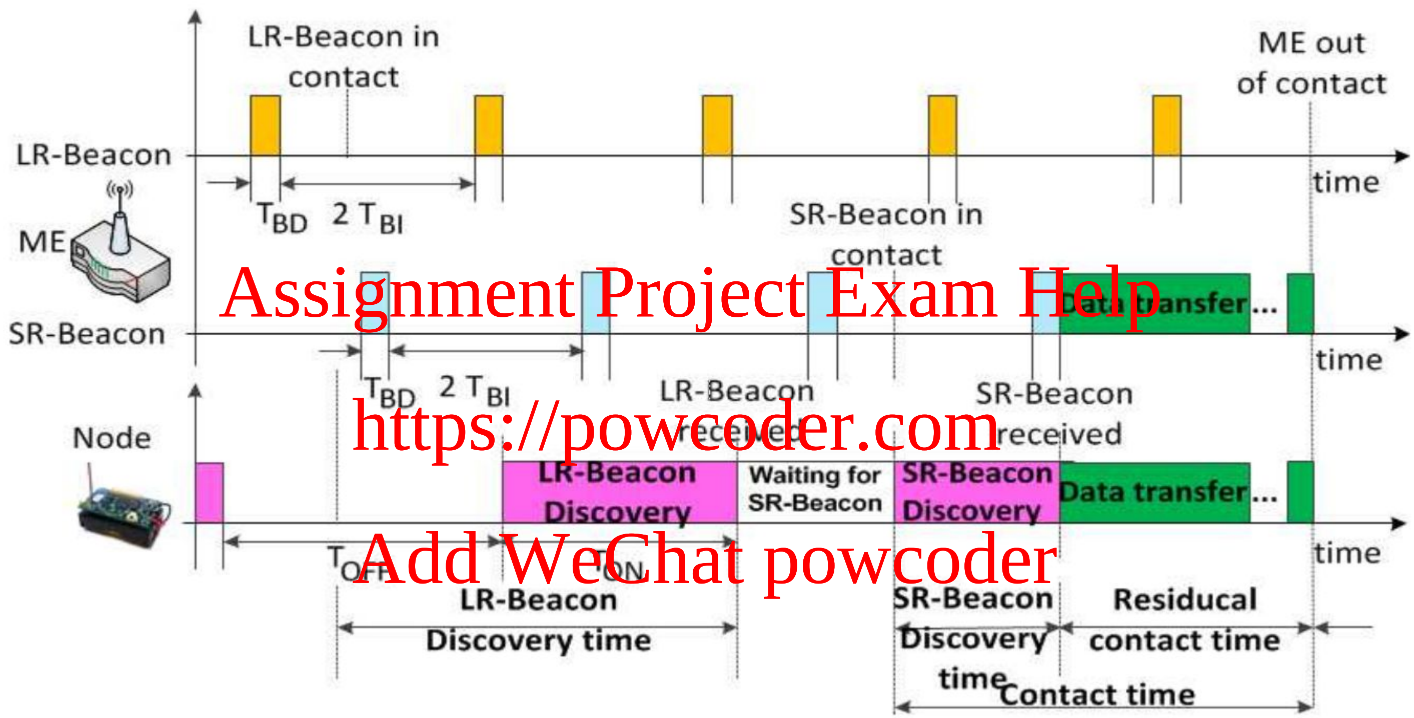


We can do better than PL…

Periodic Listening

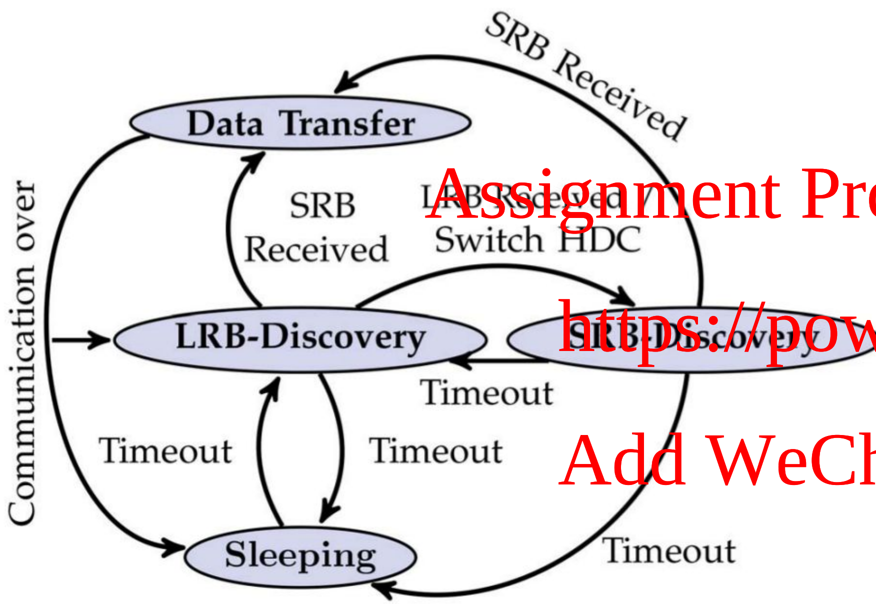


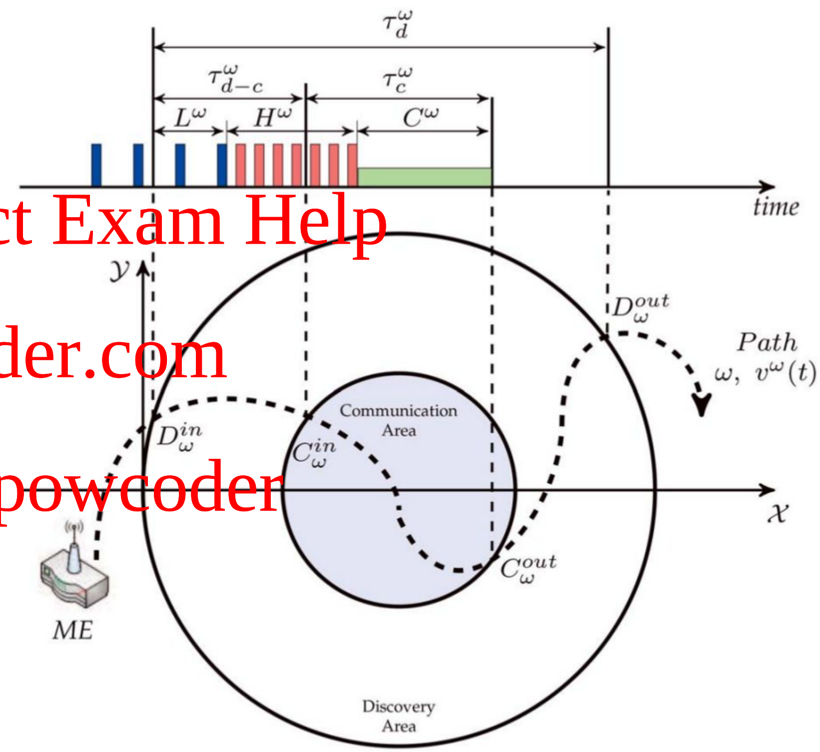
Dual-beacon Discovery (2BD)



Restuccia, F., Anastasi, G., Conti, M., & Das, S. K. (2014). Analysis and optimization of a protocol for mobile element discovery in sensor networks. ***IEEE Transactions on Mobile Computing***, *13*(9), 1942-1954.

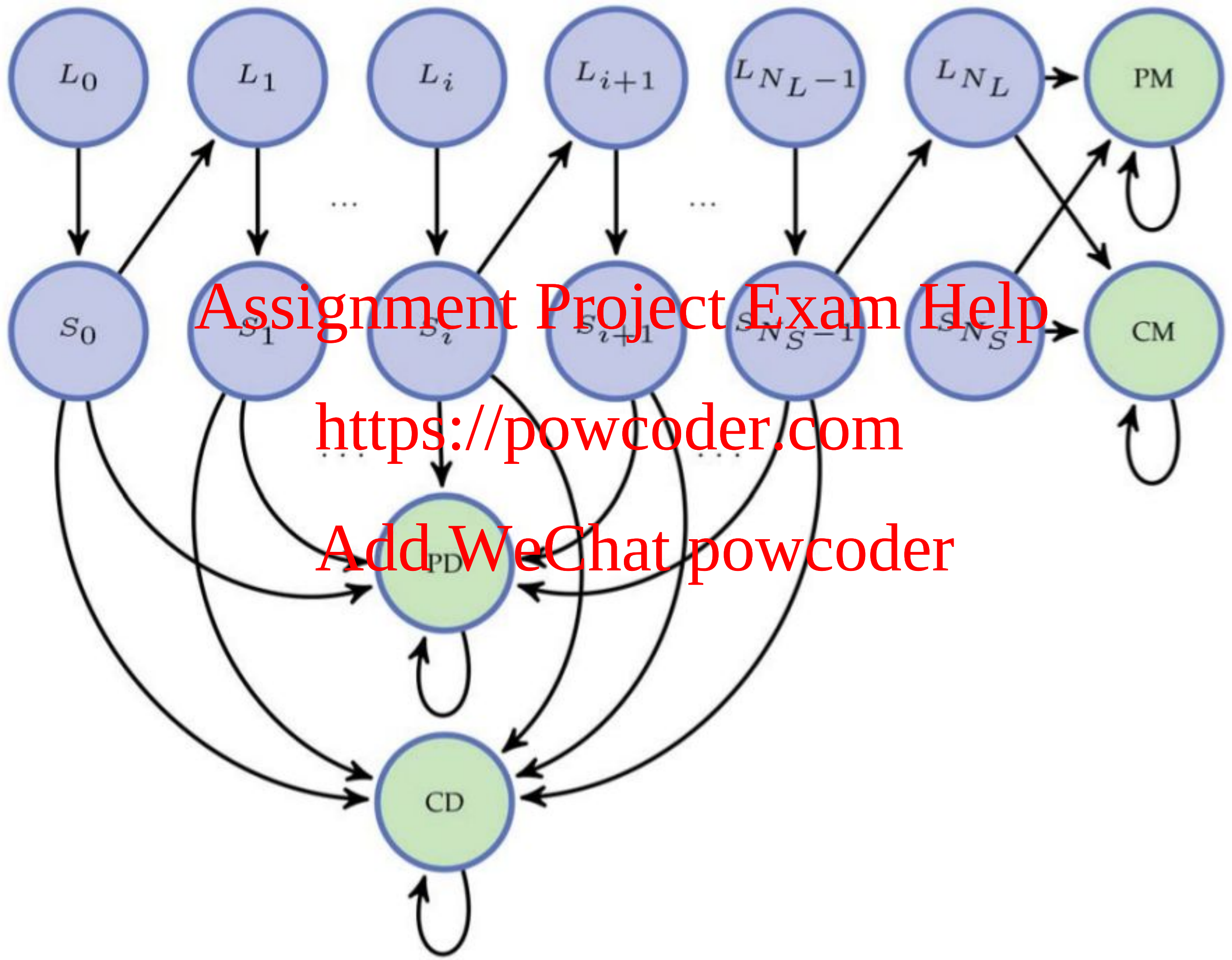
Modeling 2BD



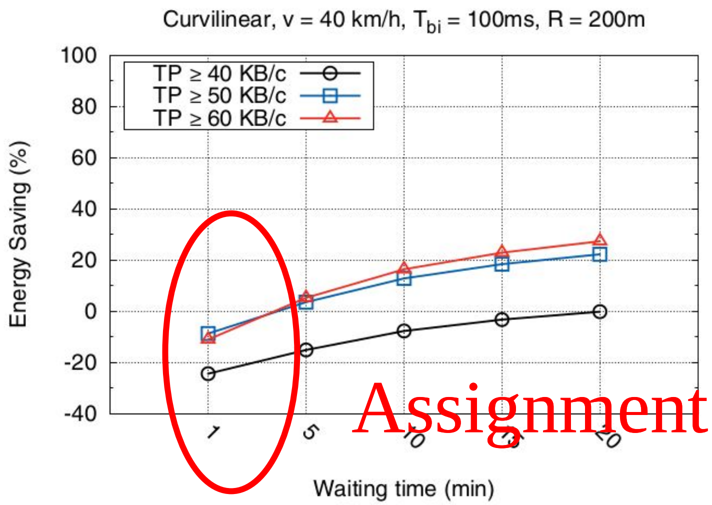


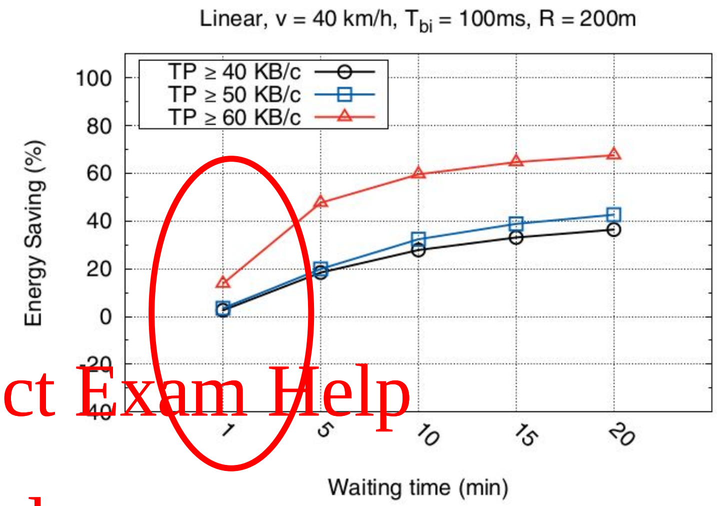
How do we model 2BD?
Think about the PL model

Modeling 2BD (2)



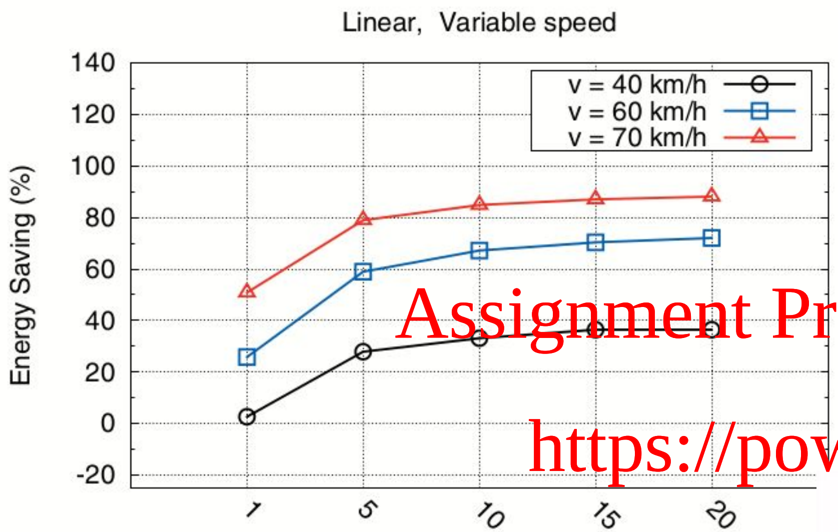
Results





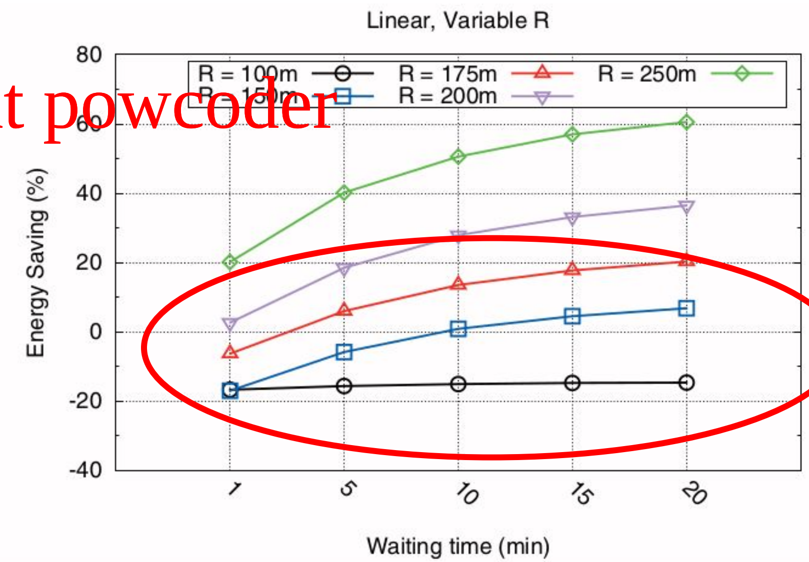
θ	δ^{opt}	δ_L^{opt}	δ_H^{opt}	L	H	CR_{2bd}	CR_{pl}
≥ 40	1.5	0.8	6.4	12.54	15.78	65.50%	66.48%
≥ 50	2.4	1.0	7.8	10.04	14.93	77.57%	77.86%
≥ 60	6.5	1.4	9.2	5.01	13.68	89.31%	90.53%
θ	δ^{opt}	δ_L^{opt}	δ_H^{opt}	L	H	CR_{2bd}	CR_{pl}
≥ 40	0.8	0.6	5.5	16.72	22.15	59.75%	59.21%
≥ 50	1.0	0.6	5.7	16.72	20.42	61.65%	60.22%
≥ 60	1.3	0.7	6.8	14.33	19.58	68.33%	69.44%

Results (2)



v	δ^{opt}	δ_L^{opt}	δ_H^{opt}	L	H	CR_{2bd}	CR_{pl}
40	1.5	0.8	6.4	12.54	15.78	65.50%	66.48%
60	9.3	2.1	17.0	4.77	9.08	89.90%	90.26%
70	13.33	1.1	20.4	4.58	7.60	92.95%	92.11%
v	δ^{opt}	δ_L^{opt}	δ_H^{opt}	L	H	CR_{2bd}	CR_{pl}
40	0.8	0.6	5.5	16.72	22.15	59.75%	59.21%
60	2.2	1.1	6.0	9.12	14.41	65.29%	63.69%
70	3.8	1.5	6.7	6.69	12.66	69.38%	74.95%

R (m)	δ^{opt}	δ_L^{opt}	δ_H^{opt}	L	H	CR_{2bd}	CR_{pl}
100	1.5	1.7	5.8	5.89	6.88	64.37%	66.48%
150	1.5	1.2	4.2	8.35	11.65	64.59%	66.48%
175	1.5	1.0	5.6	10.26	13.23	64.85%	66.48%
200	1.5	0.8	6.4	12.54	15.78	65.50%	66.48%
250	1.5	0.6	7.6	14.82	18.04	64.59%	66.48%
R (m)	δ^{opt}	δ_L^{opt}	δ_H^{opt}	L	H	CR_{2bd}	CR_{pl}
100	0.8	1.2	4.0	8.35	10.32	55.43%	59.21%
150	0.8	0.8	4.6	12.54	15.90	55.26%	59.21%
175	0.8	0.7	5.1	12.54	15.90	55.26%	59.21%
200	0.8	0.6	5.5	16.72	22.15	59.75%	59.21%
250	0.8	0.5	6.2	20.12	28.02	59.43%	59.21%



What are the Pros and Cons of PL and 2BD?

Think-Pair-Share!

Wait a moment…

Aren't we missing something?

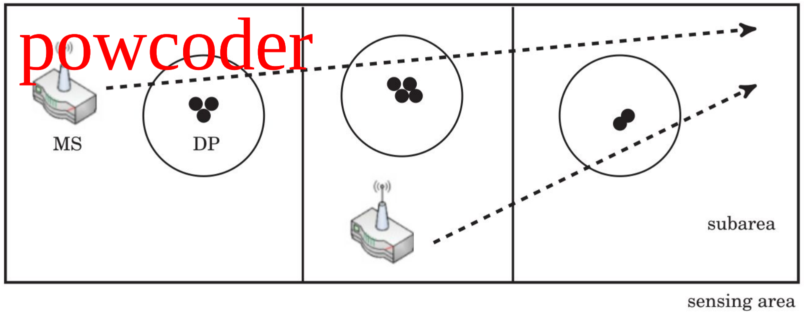
Can we increase reliability without compromising energy efficiency?

The SISSA Algorithm

- *What about deploying MORE nodes in a specific area?*
- *Can extend lifetime significantly, but need to take care of MAC!*
- *Need to **self-organize** in a reliable, distributed, energy-efficient way*
- ***Swarm-intelligence Based Sensor Selection Algorithm (SISSA)***
- *We want to optimize QoS (lifetime vs. throughput & and reliability)*

For every sensor s_i, and for every MS tour j,

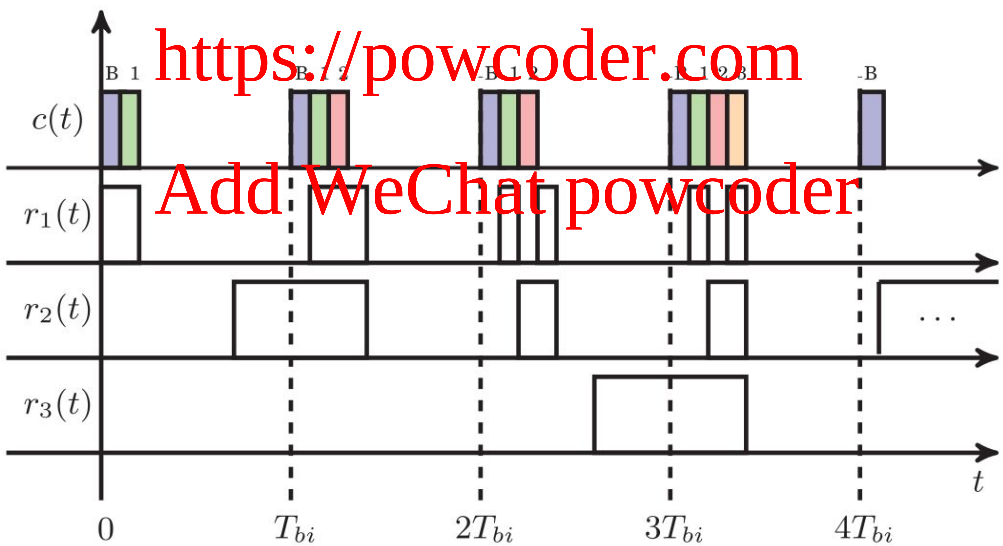
$$\begin{cases} \text{Minimize } E_{tot}^{i,j} \\ \text{subject to} \\ \theta \geq \theta_{des,p} \\ k \geq k_{des,p} \geq 1 \end{cases}$$



Francesco Restuccia and Sajal K. Das. 2016. Optimizing the Lifetime of Sensor Networks with Uncontrollable Mobile Sinks and QoS Constraints. ACM Trans. Sen. Netw. 12, 1, Article 2 (March 2016), 31 pages

The Swarm and Communication Phases

- *Every node has a node ID, defines a* ***TDMA scheme***
- ***Swarm agents*** *are broadcast as soon as a beacon is received*
- *They contain the residual energy level of each sensor*
- *Every swarm agent is transmitted* ***reliably*** *since TDMA is used*
- *When each node receives every swarm agent, the k nodes having the most residual energy level transmit their data*



Comments on Swarm Phase

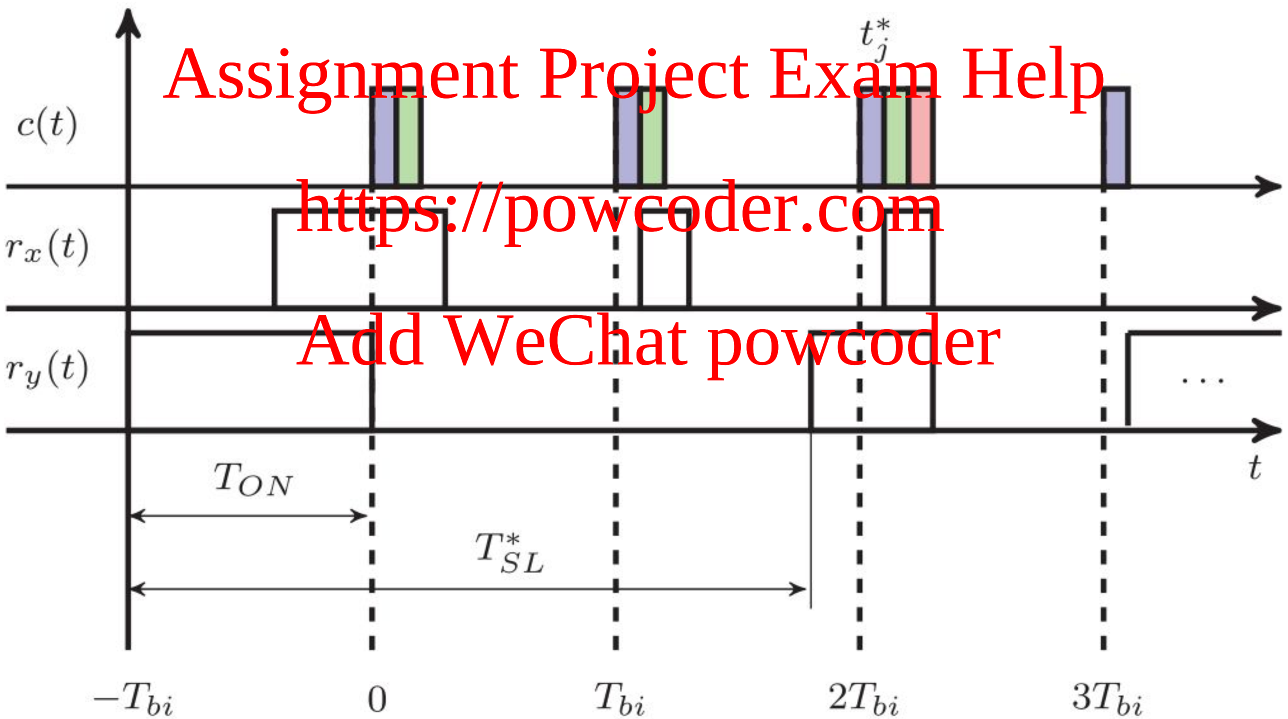
- (1) Cannot converge until **every sensor receives a swarm agent from all other sensors**
- Each sensor node will terminate the swarm phase **at the same time**
- Without any global information, intelligence, or synchronization, each sensor **knows the swarm phase is completed**
- (2) The sensor radio remains active **only during the instants** of swarm transmission / receptions
- We assume no homogeneous initial energy budget nor a homogeneous sensor platform

Worst-case Convergence of SISSA

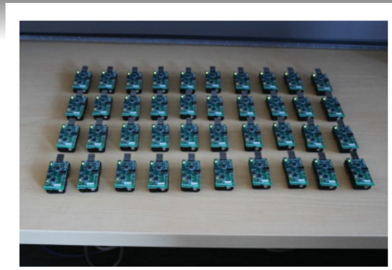
1. *Worst-case convergence is bound*
2. *Number of messages is constant $O(t^*_j/T_{bi})$*
3. *Min Channel Time, max Energy Consumption*

$$E^{sp}_{max} = P^{sa}_{TX} \cdot \frac{t^*_j}{T_{bi}} \cdot T_{sa} + P_{RX} \cdot T_{sa} \cdot (S-1).$$

$$\theta_{min} = T_k \cdot \left\lfloor \frac{C_{min} - t^*_j}{T_{bi}} \right\rfloor$$



Experimental Evaluation



- 40 TelosB nodes, both indoor and outdoor scenarios
- Wanted to test accuracy of mathematical model
- What is the major problem with the swarm phase?

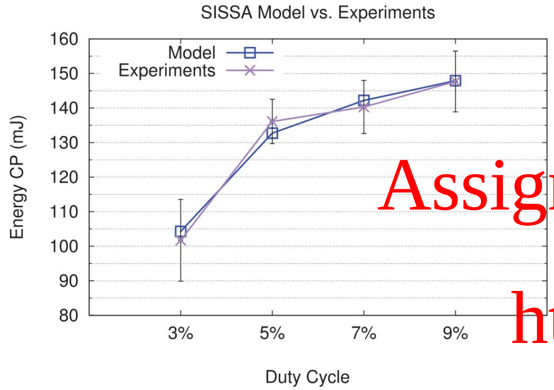


Fig. 10. Energy spent (mJ) during communication phase.

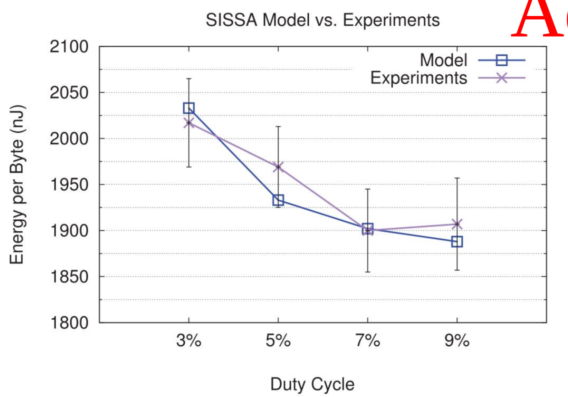


Fig. 11. Energy (nJ) per byte.

Table V. Experimental Convergence Ratio in Function of TPL (Transmission Power Level) and R

R	Transmission Powel Level											
	6	CI	9	CI	12	CI	15	CI	18	CI	21	CI
7m	0.444	±0.091	0.974	±0.048	0.996	±0.045	0.996	±0.021	0.994	±0.032	0.996	±0.012
10m	0.190	±0.082	0.928	±0.056	0.906	±0.037	0.956	±0.012	0.984	±0.016	0.994	±0.015
13m	0.218	±0.079	0.894	±0.026	0.956	±0.089	0.960	±0.018	0.966	±0.043	0.990	±0.021
15m	0.150	±0.086	0.894	±0.075	0.982	±0.032	0.990	±0.009	0.990	±0.024	0.986	±0.040

Table III. Swarm Phase Energy Consumption (S = Number of Sensors, δ = Duty-Cycle Ratio, CI = Confidence Interval)

S	$\delta = 3\%$			$\delta = 5\%$			$\delta = 7\%$			$\delta = 9\%$		
	Mod.	Exp.	CI	Mod.	Exp.	CI	Mod.	Exp.	CI	Mod.	Exp.	CI
5	2.26	2.36	±0.52	1.45	1.74	±0.18	1.07	1.17	±0.23	0.89	0.98	±0.44
10	3.58	3.77	±1.06	2.29	2.94	±0.32	1.71	1.95	±0.30	1.42	1.76	±0.60
20	6.21	5.47	±1.62	3.98	4.67	±0.60	2.97	3.29	±0.41	2.46	2.86	±0.95
30	8.85	9.28	±2.56	5.66	5.87	±0.68	4.23	4.43	±0.50	3.50	3.50	±1.15
40	11.50	11.00	±2.47	7.34	7.70	±0.90	5.49	5.81	±0.60	4.54	4.94	±1.84

Table IV. Swarm Phase Convergence Time (S = Number of Sensors, δ = Duty-Cycle Ratio, CI = Confidence Interval)

S	$\delta = 3\%$			$\delta = 5\%$			$\delta = 7\%$			$\delta = 9\%$		
	Mod.	Exp.	CI	Mod.	Exp.	CI	Mod.	Exp.	CI	Mod.	Exp.	CI
5	5.80	5.67	±0.20	3.60	3.78	±0.17	2.60	2.56	±0.34	2.2	2.60	±0.51
10	6.20	6.06	±0.30	3.60	3.64	±0.21	2.80	2.88	±0.40	2.2	2.40	±0.36
20	6.20	6.53	±0.35	4.00	4.12	±0.24	3.00	3.14	±0.55	2.4	2.46	±0.25
30	6.60	6.61	±0.15	4.00	3.95	±0.20	3.00	2.75	±0.50	2.4	2.57	±0.42
40	6.80	6.54	±0.28	4.00	4.06	±0.30	3.00	3.44	±0.50	2.4	2.85	±0.58

Simulations

➢ *Pure TDMA, SISSA, Unslotted 802.15.4*

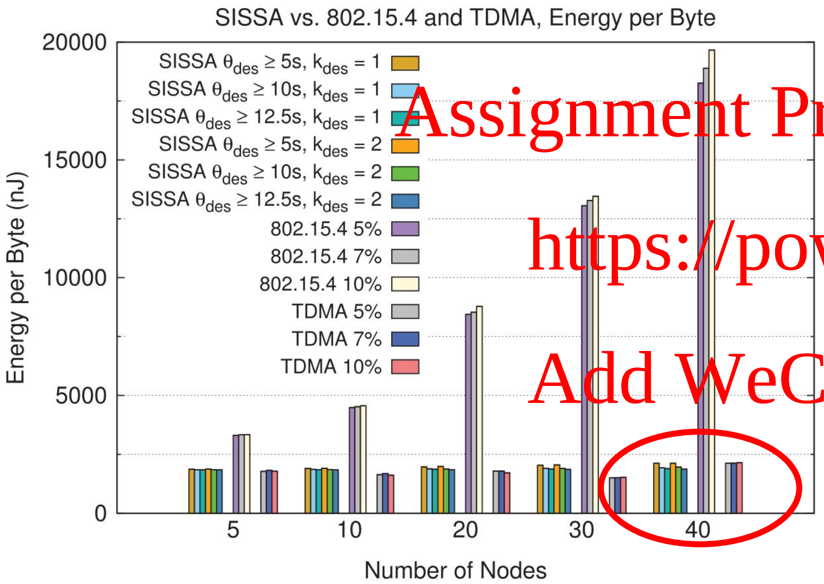
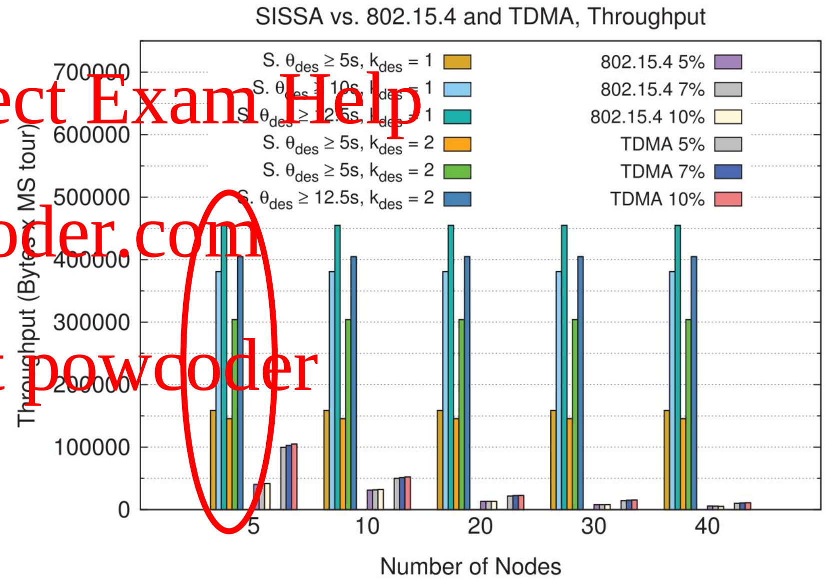


Fig. 14. Energy per byte, SISSA vs. 802.15.4 and TDMA.



What are the Pros and Cons of SISSA?

Think-Pair-Share!

Q&A