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

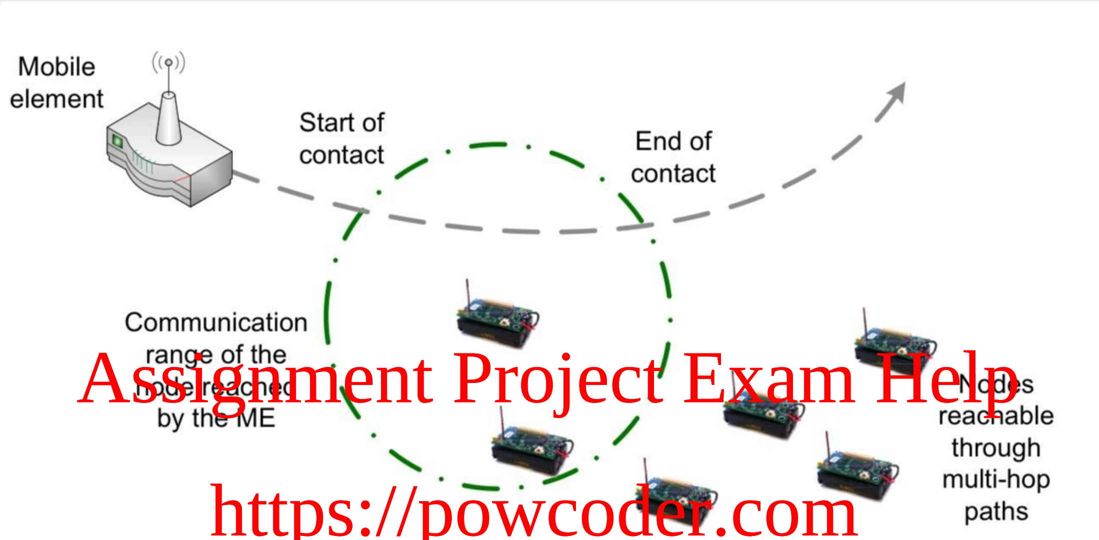
- Multi-hop networks are compromised by interference and collisions

- 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).

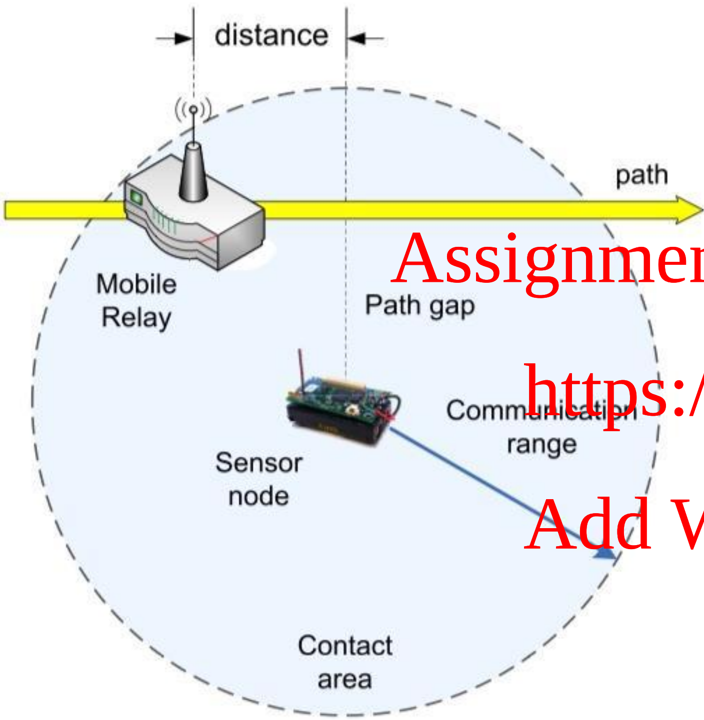
Discovery Process (2)

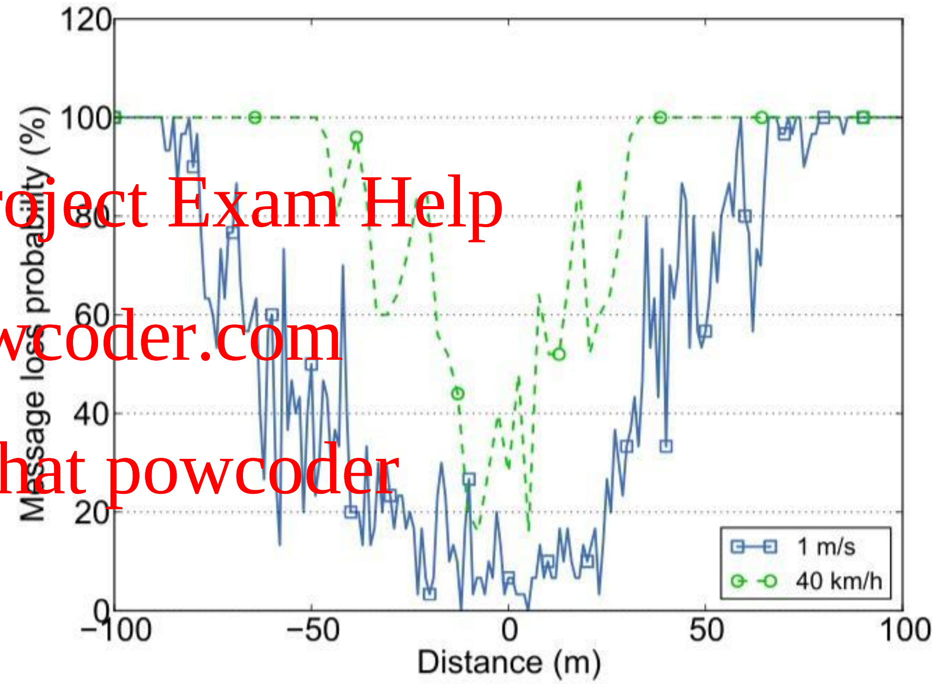
➢ *Asynchronous (used the most)*

- 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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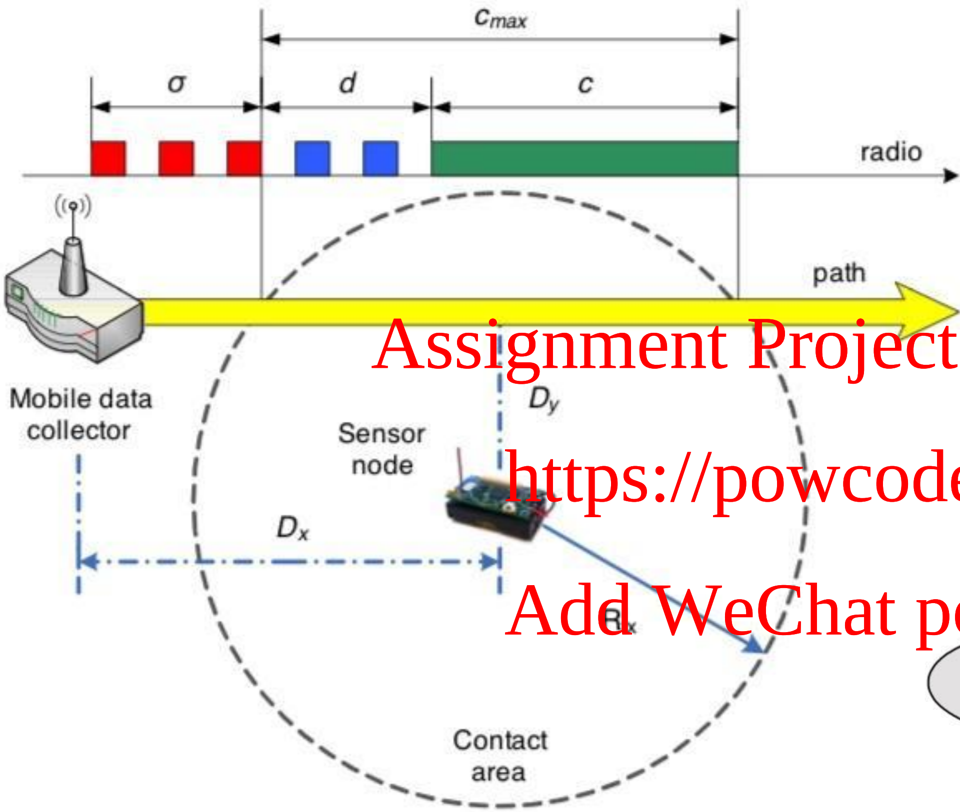
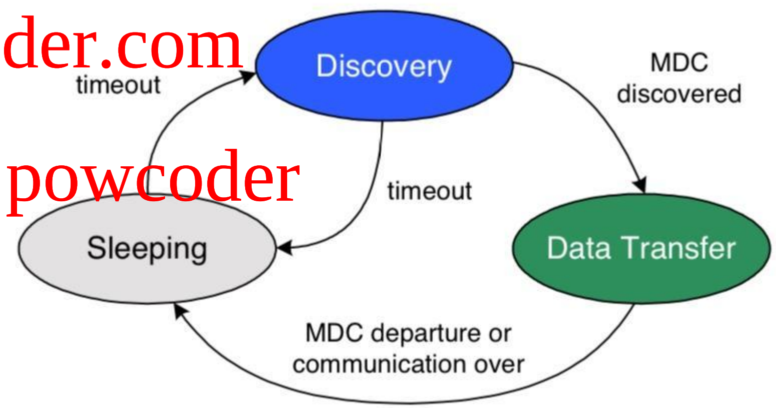
March 8, 2021

Modeling Discovery and Data Transfer

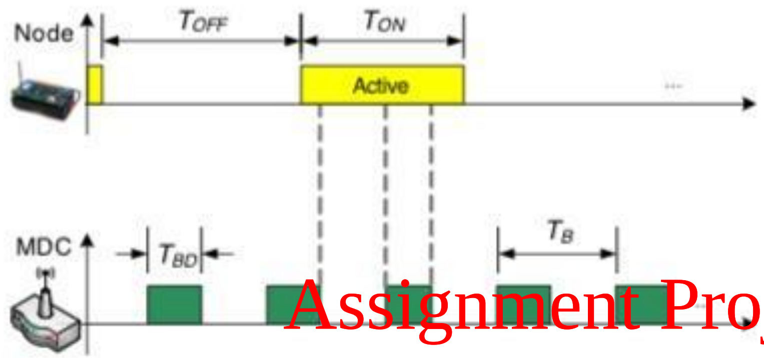


- ***p(t)*** *probability of message loss inside the contact area*

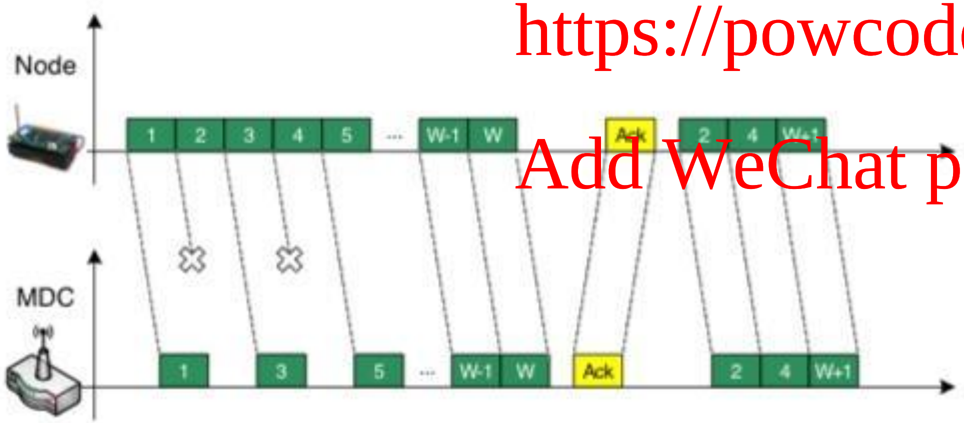


G. Anastasi, M. Conti, M. Di Francesco, **Reliable and Energy-efficient Data Collection in Sparse Sensor Networks with Mobile Elements**, *Performance Evaluation*, Special Issue on *Performance Evaluation of Ubiquitous Networks*, Vol. 66, N. 12, pp. 791-810, December 2009. Elsevier.

Modeling Discovery and Data Transfer (2)



(a)



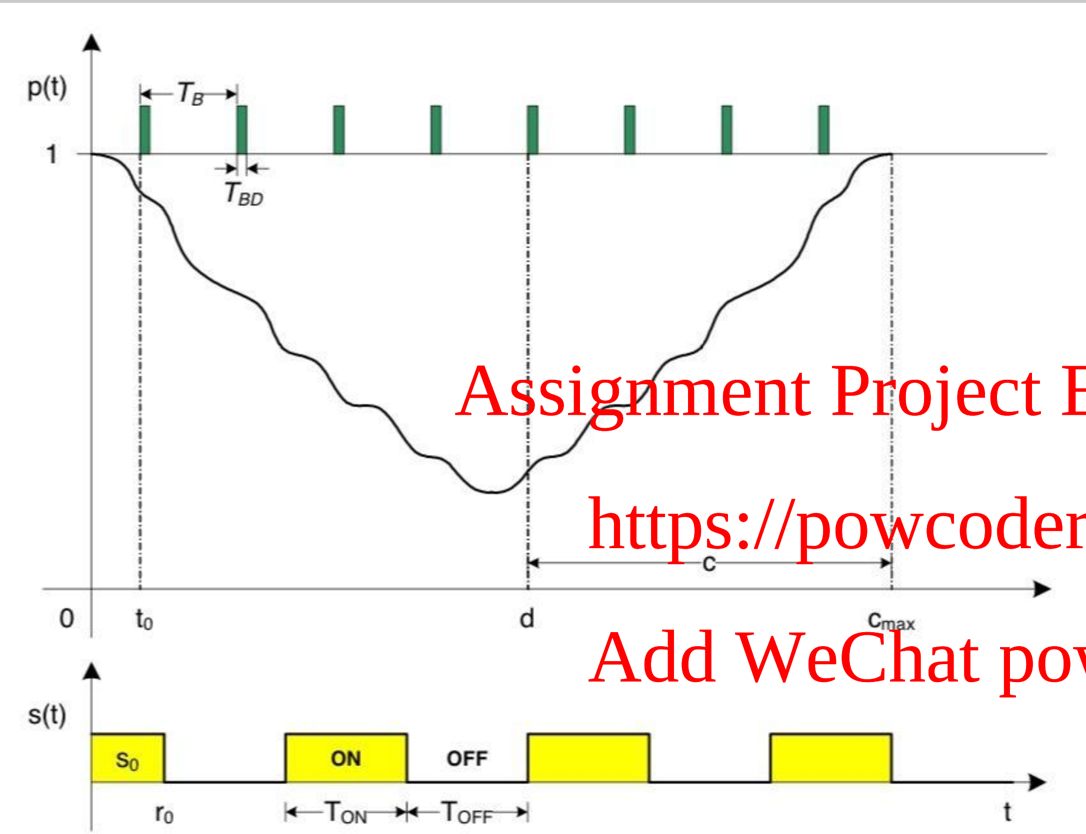
(b)

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

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

- ***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*

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

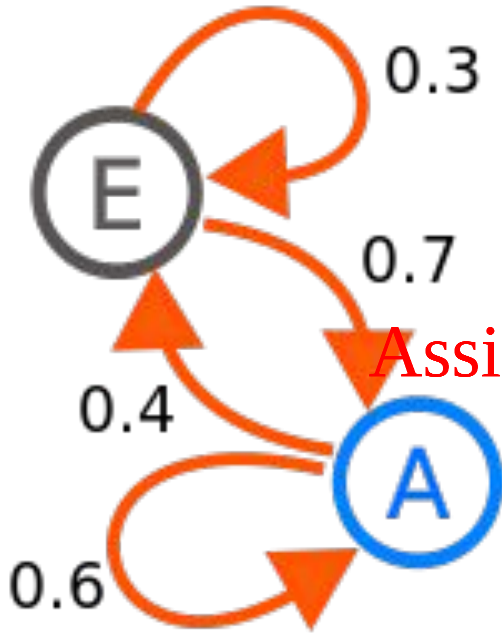
$$\underset{s_0=OFF}{s(t_n)} = \begin{cases} OFF & \text{if } 0 \le t'_n < r_0 \\ ON & \text{if } r_0 \le t'_n < r_0 + T_{ON} \\ OFF & \text{if } r_0 + T_{ON} \le t'_n < T_{ON} + T_{OFF} \end{cases}$$

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

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

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

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:

$$\pi = \pi P$$

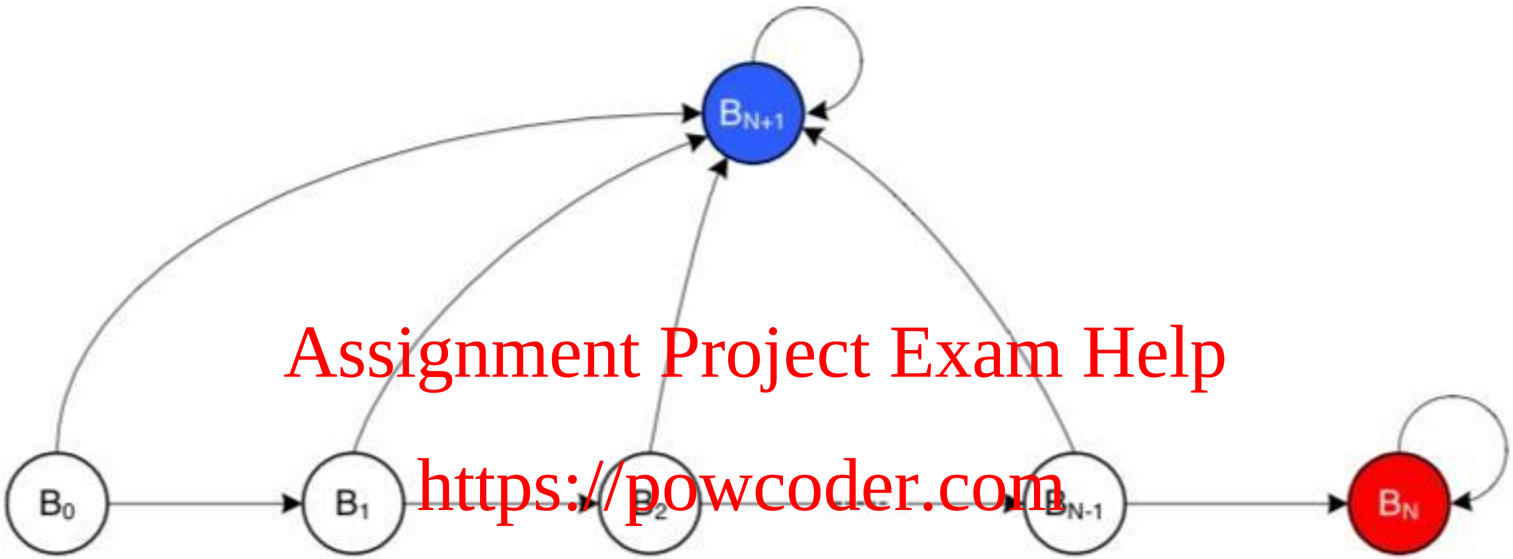
- Absorbing Markov chains have stationary distributions with nonzero elements only in absorbing states

Stationary Distribution in DTMC

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

- 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)

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

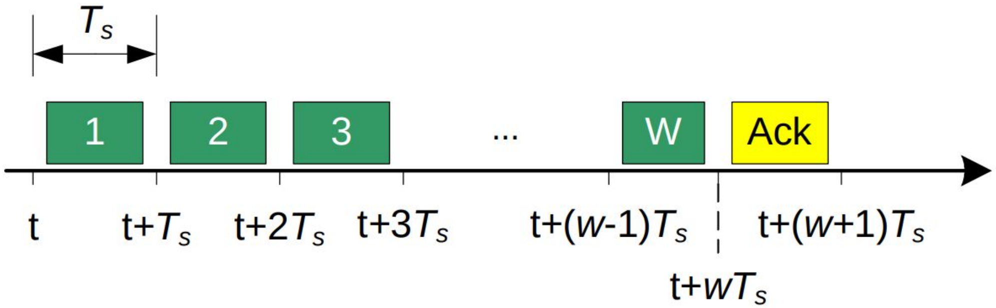
$$\mathbf{X}^{(0)} = \begin{pmatrix} X_0^{(0)} & 0 & 0 & \cdots & 0 & 0 & 0 \end{pmatrix}$$

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

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

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

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?**

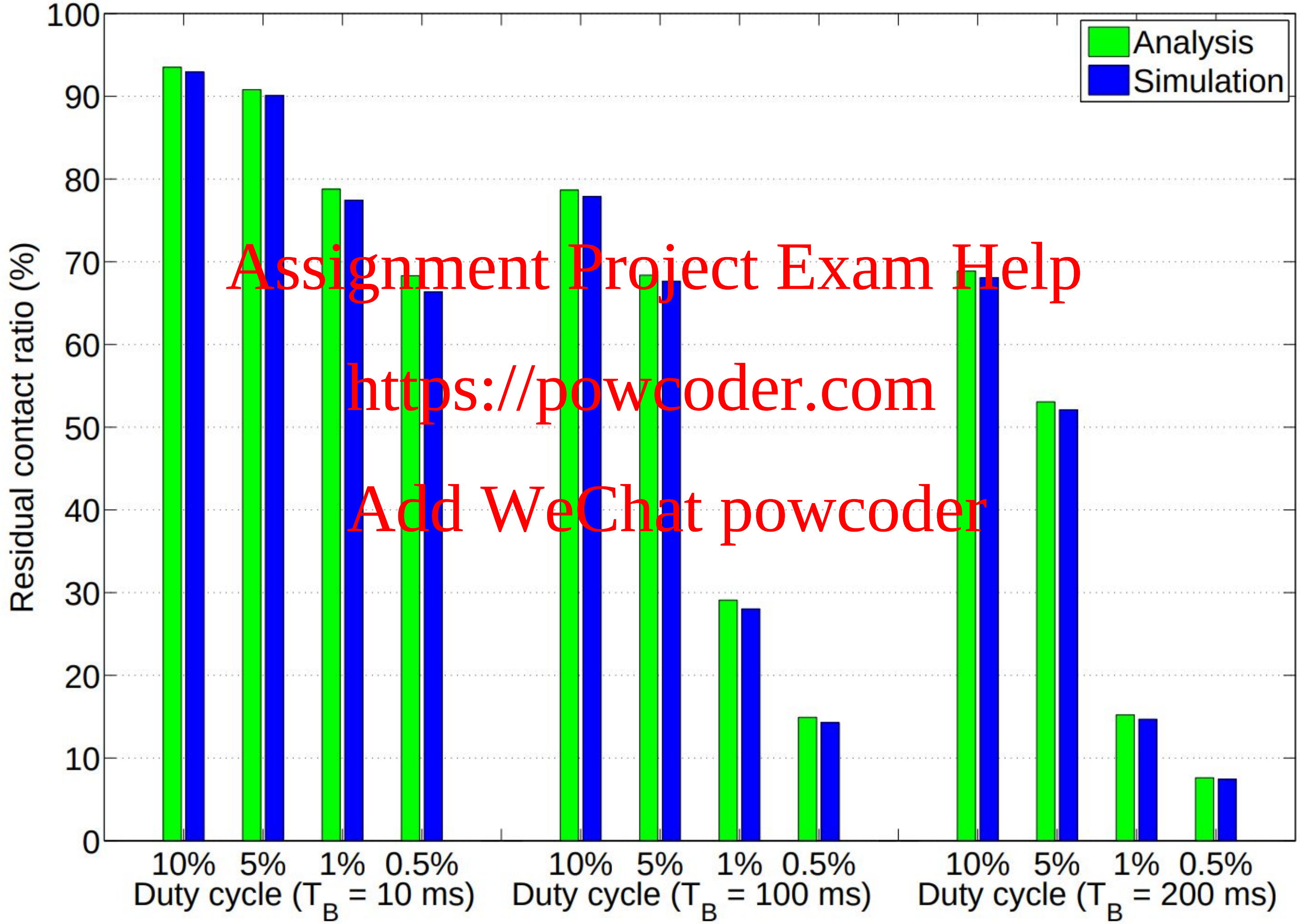
Energy Model

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

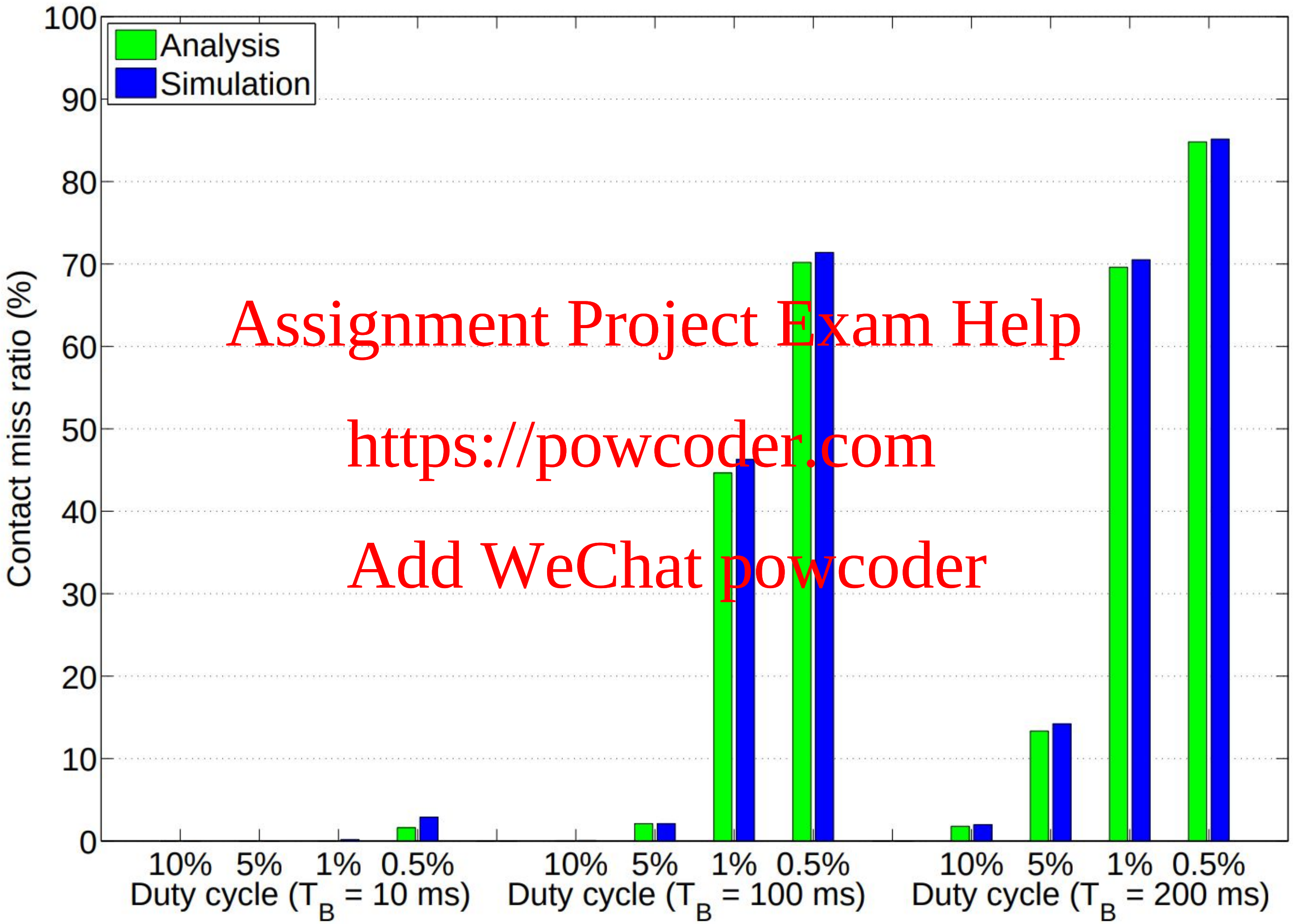
$$\overline{E}_{dt,r} = \left(\frac{\mathbb{E}[c_{max} - D]}{w+1} + \mathbb{P}\{D\} \cdot \frac{N_{ack}}{2} \cdot T_s \right) \cdot (w \cdot P_{tx} + P_{rx})$$

- *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*

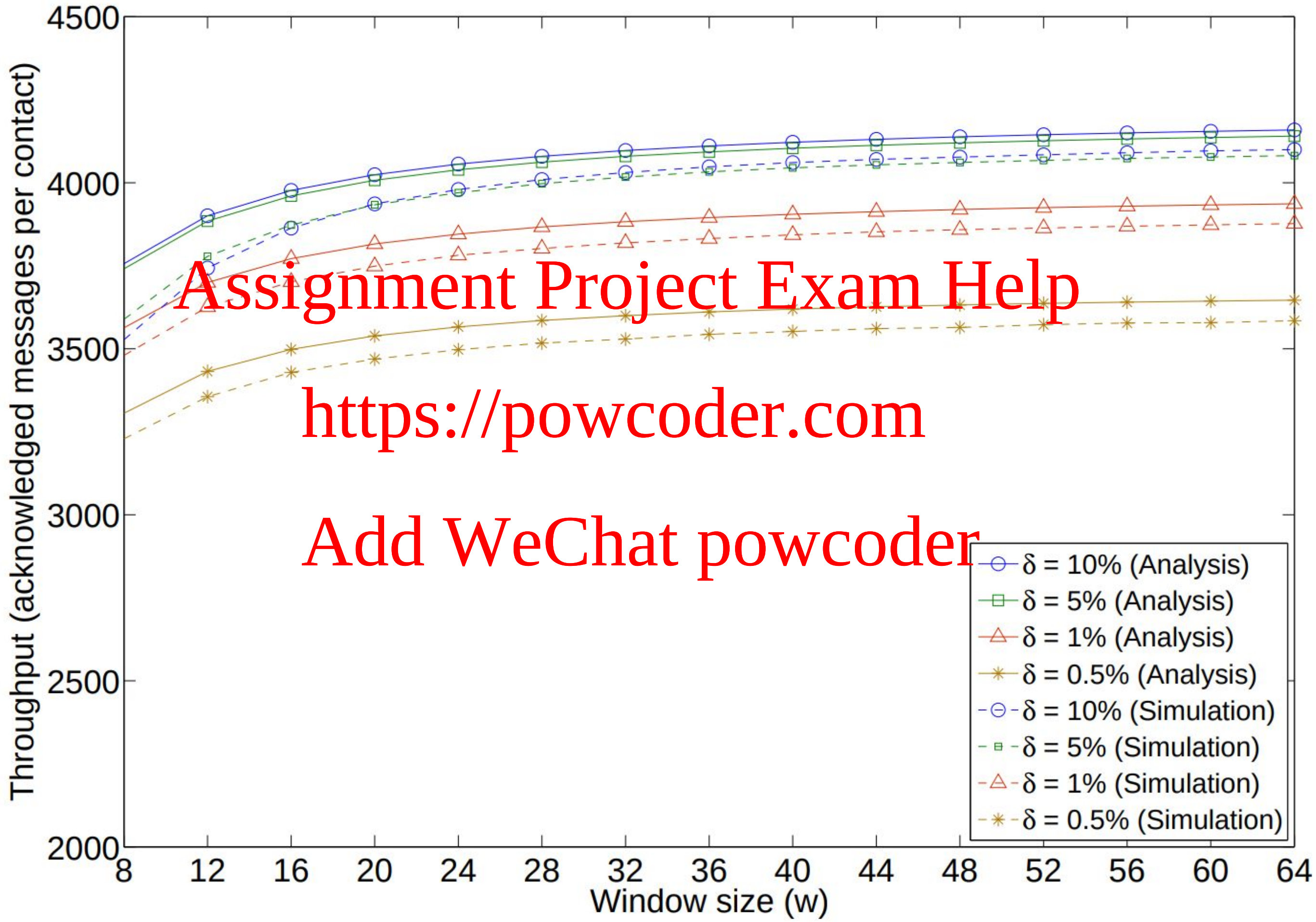
Performance Evaluation



Performance Evaluation

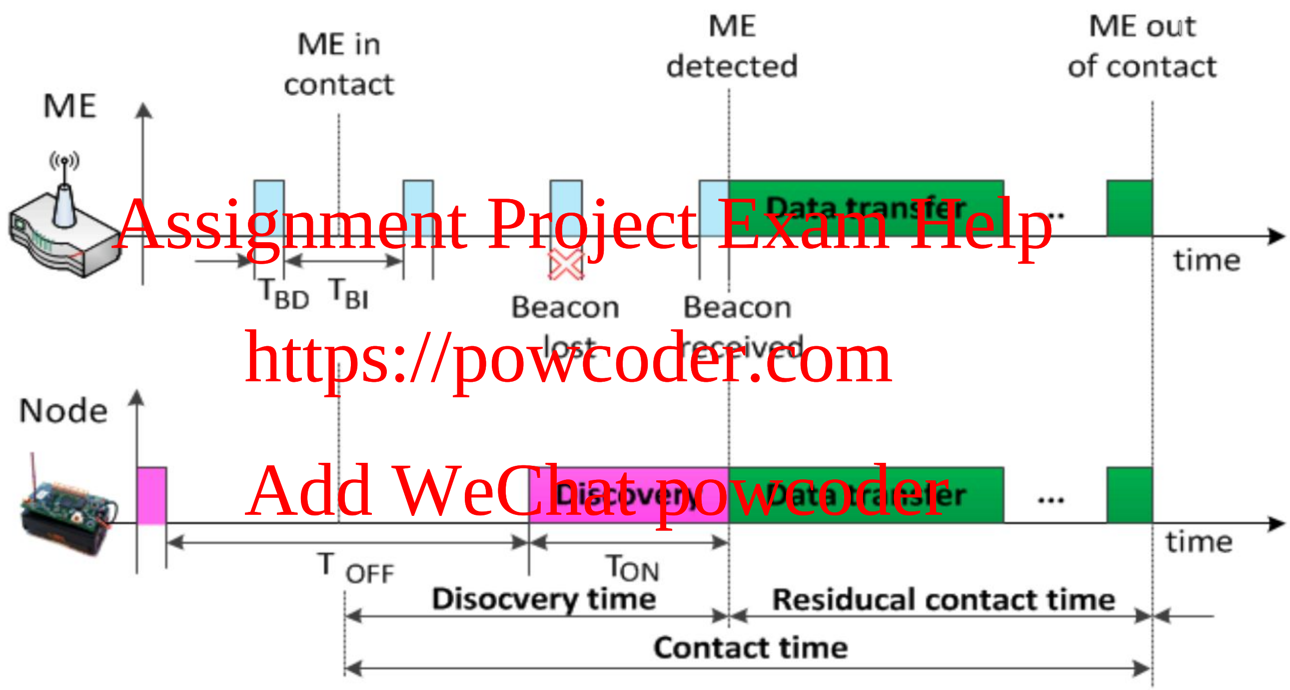


Performance Evaluation

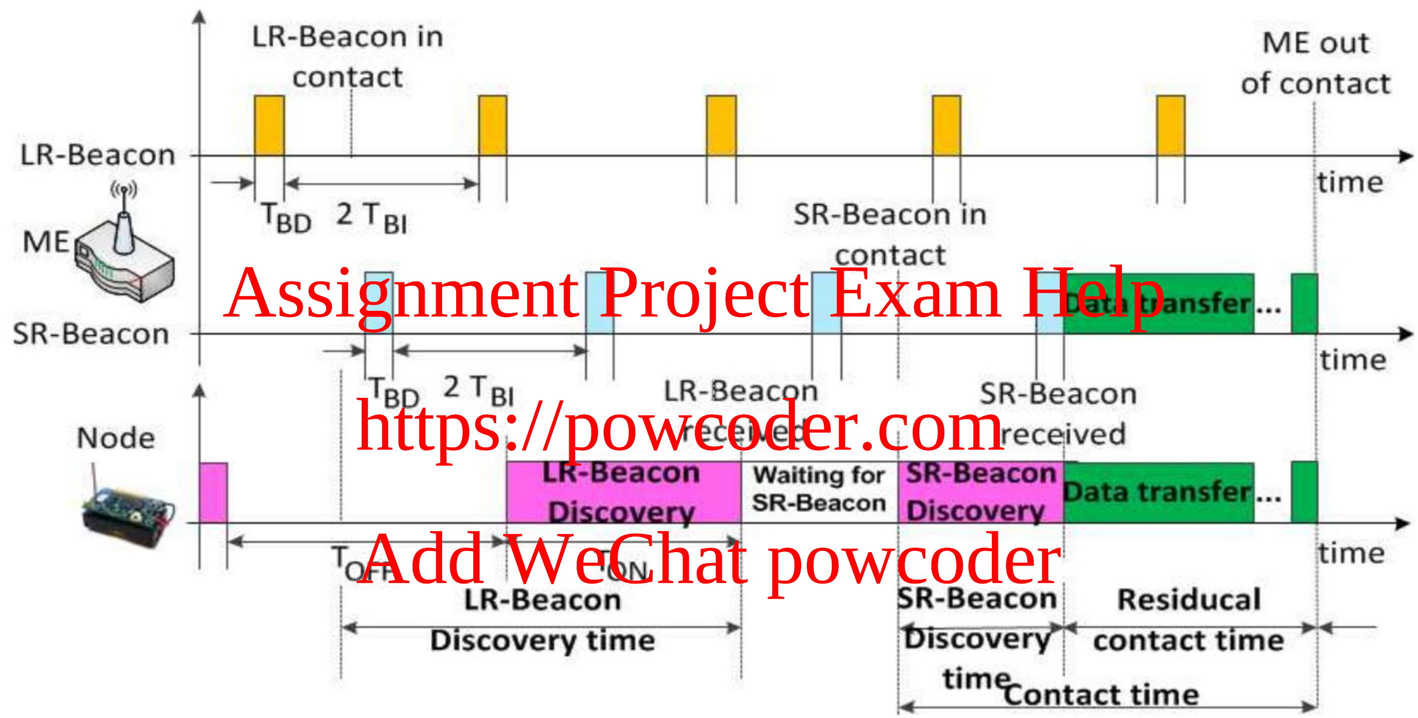


We can do better than PL...

Periodic Listening

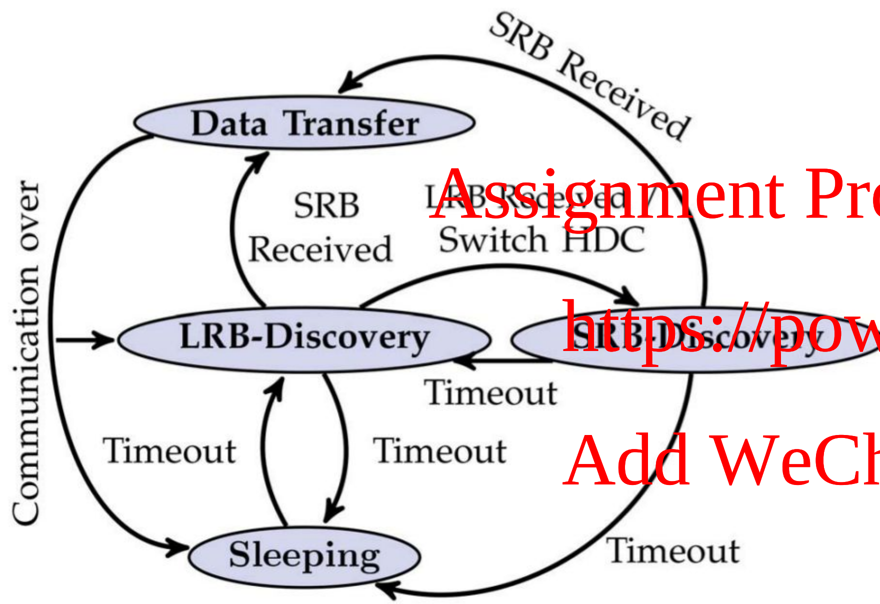


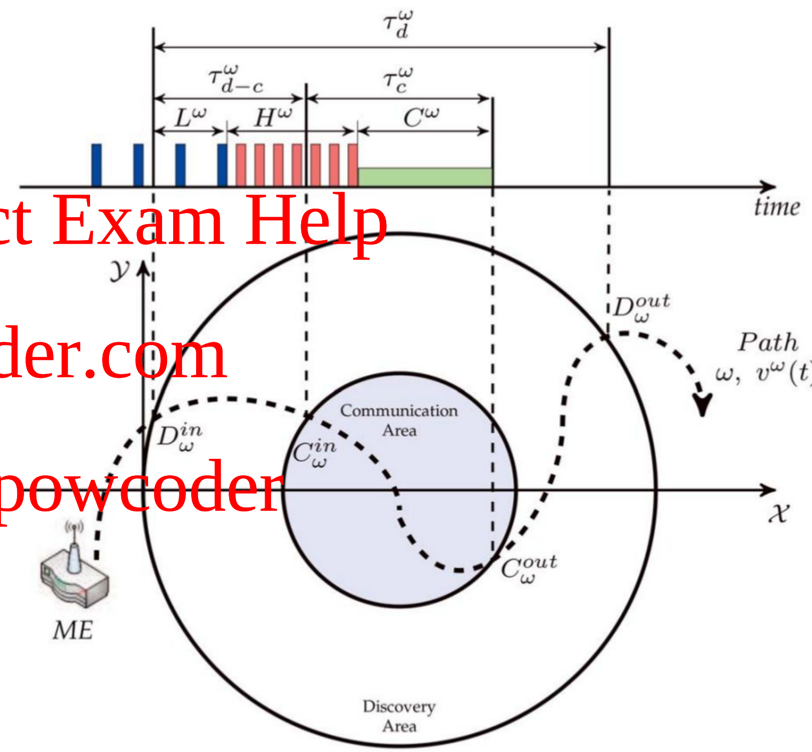
Dual-beacon Discovery (2BD)



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.

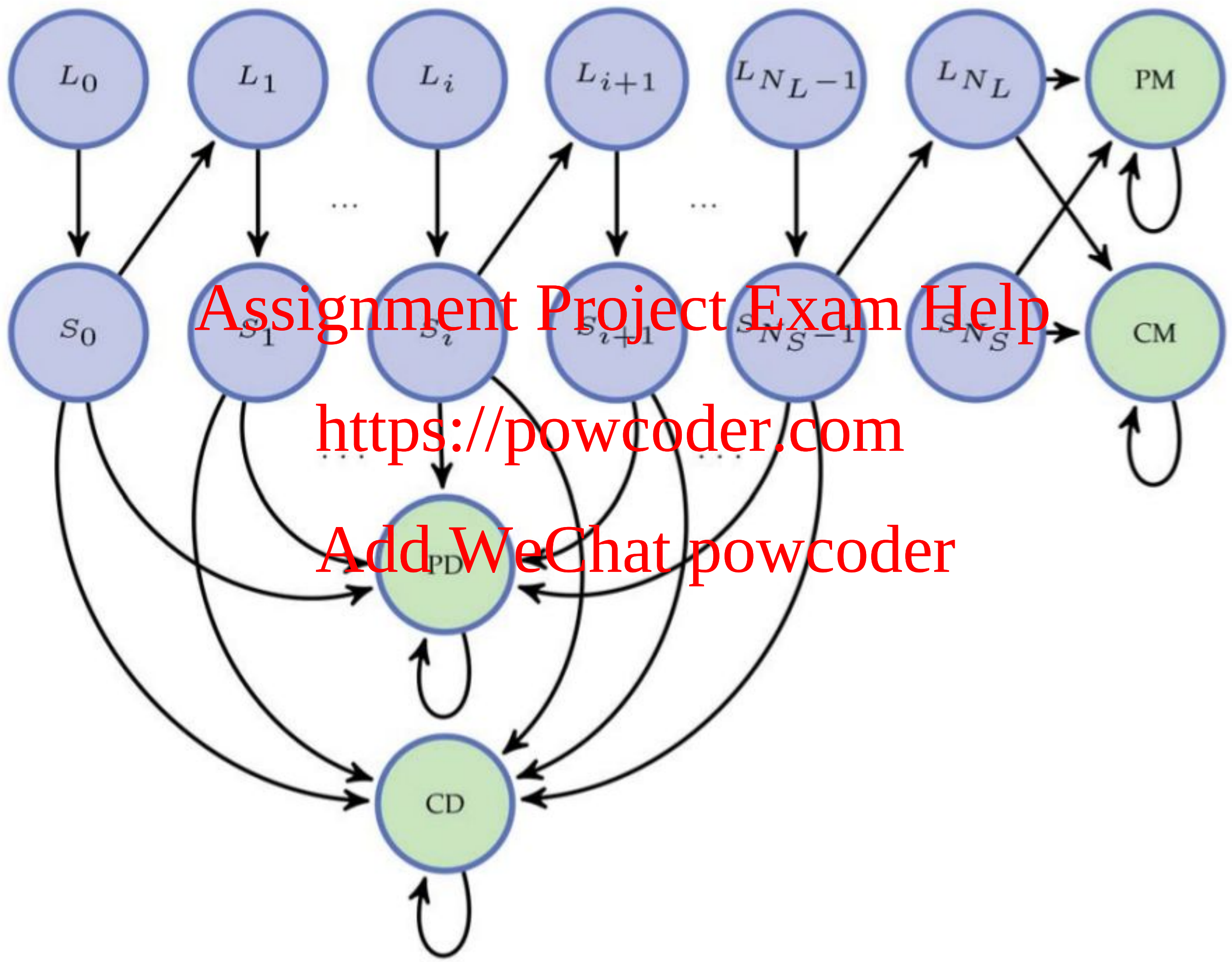
Modeling 2BD



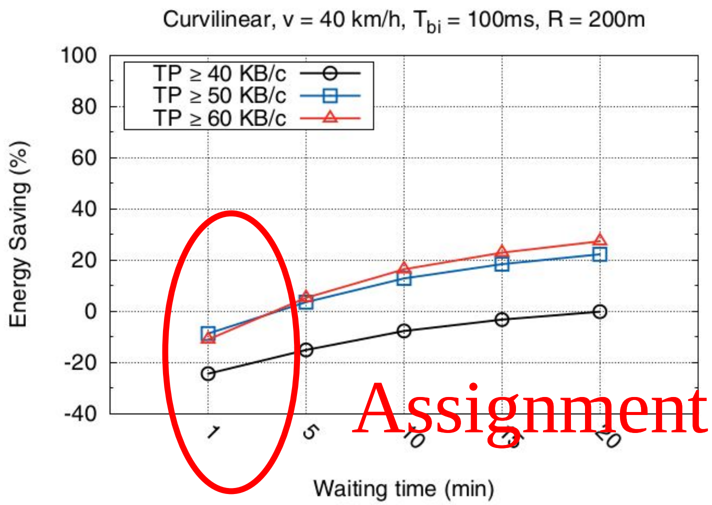


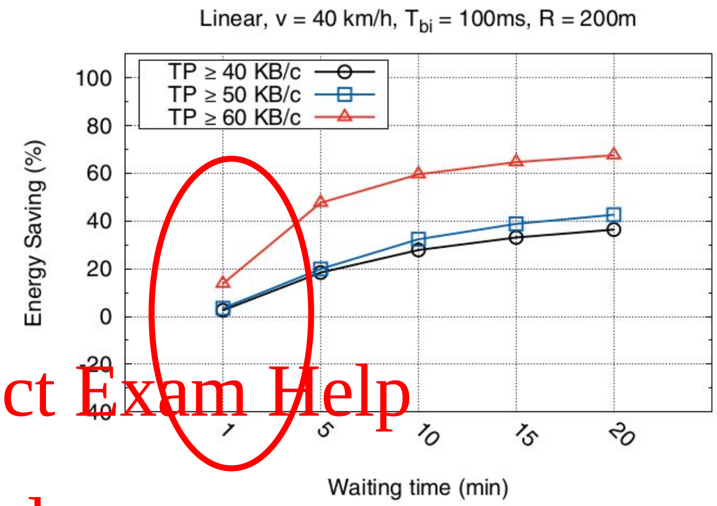
How do we model 2BD?
Think about the PL model

Modeling 2BD (2)



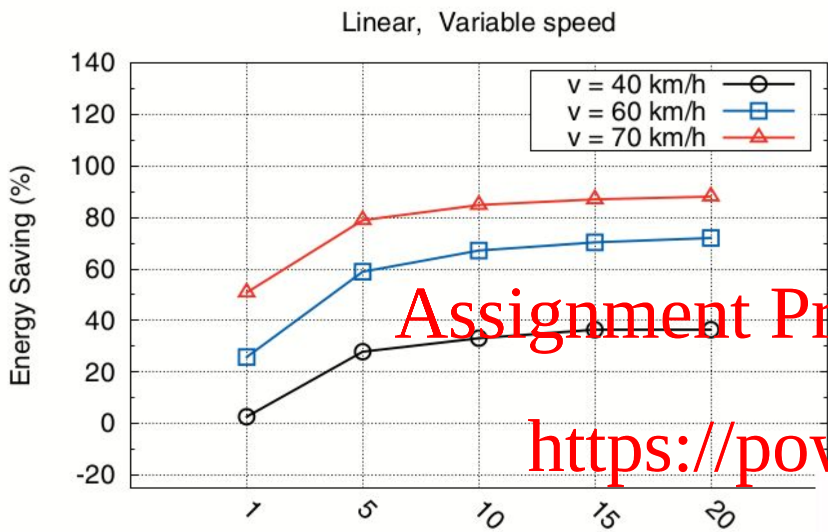
Results





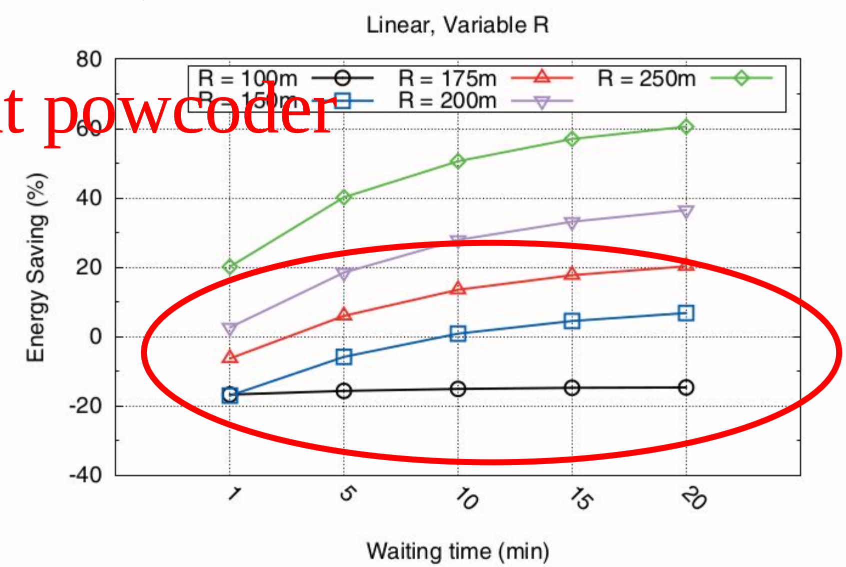
θ	δ^{opt}	δ^{opt}_L	δ^{opt}_H	L	H	CR_{2bd}	CR_{pl}
≥ 40	1.5	0.8	6.4	12.54	15.78	65.50%	66.48%
≥ 50	2.4	1.0	7.8	10.04	14.93	77.57%	77.86%
≥ 60	6.5	1.4	9.2	5.01	13.68	89.31%	90.53%
θ	δ^{opt}	δ^{opt}_L	δ^{opt}_H	L	H	CR_{2bd}	CR_{pl}
≥ 40	0.8	0.6	5.5	16.72	22.15	59.75%	59.21%
≥ 50	1.0	0.6	5.7	16.72	20.42	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?

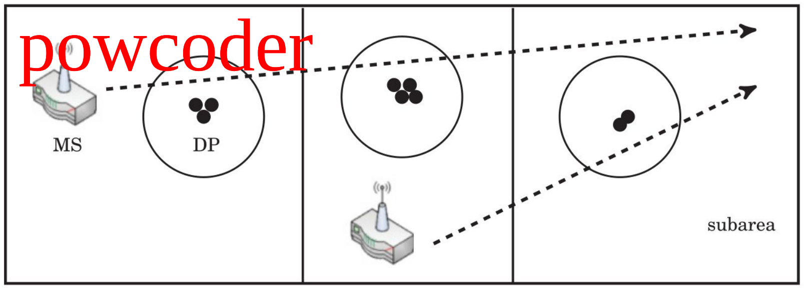
Can we increase reliability without compromising energy efficiency?

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,

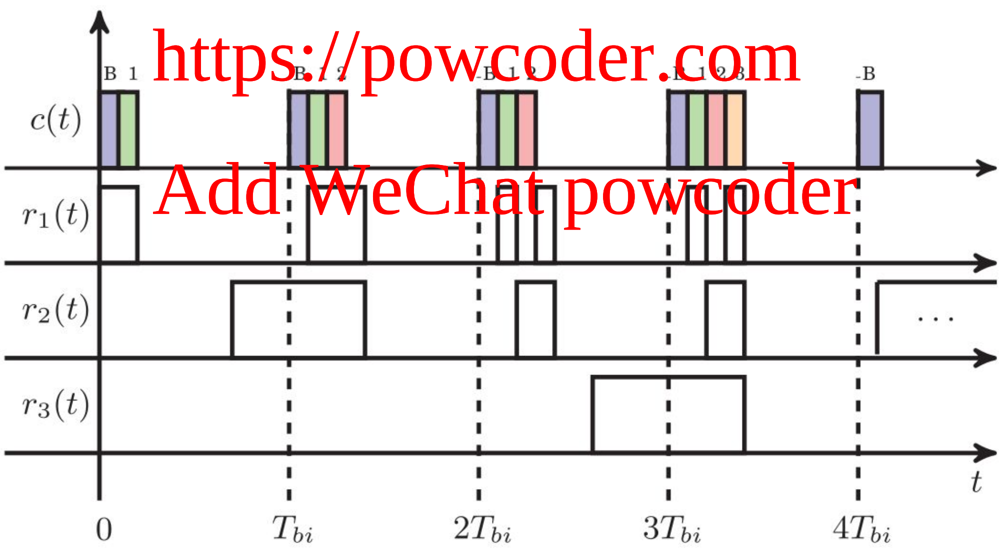
$$\begin{cases} \text{Minimize } E_{tot}^{i,j} \\ \text{subject to} \\ \theta \geq \theta_{des,p} \\ k \geq k_{des,p} \geq 1 \end{cases}$$



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

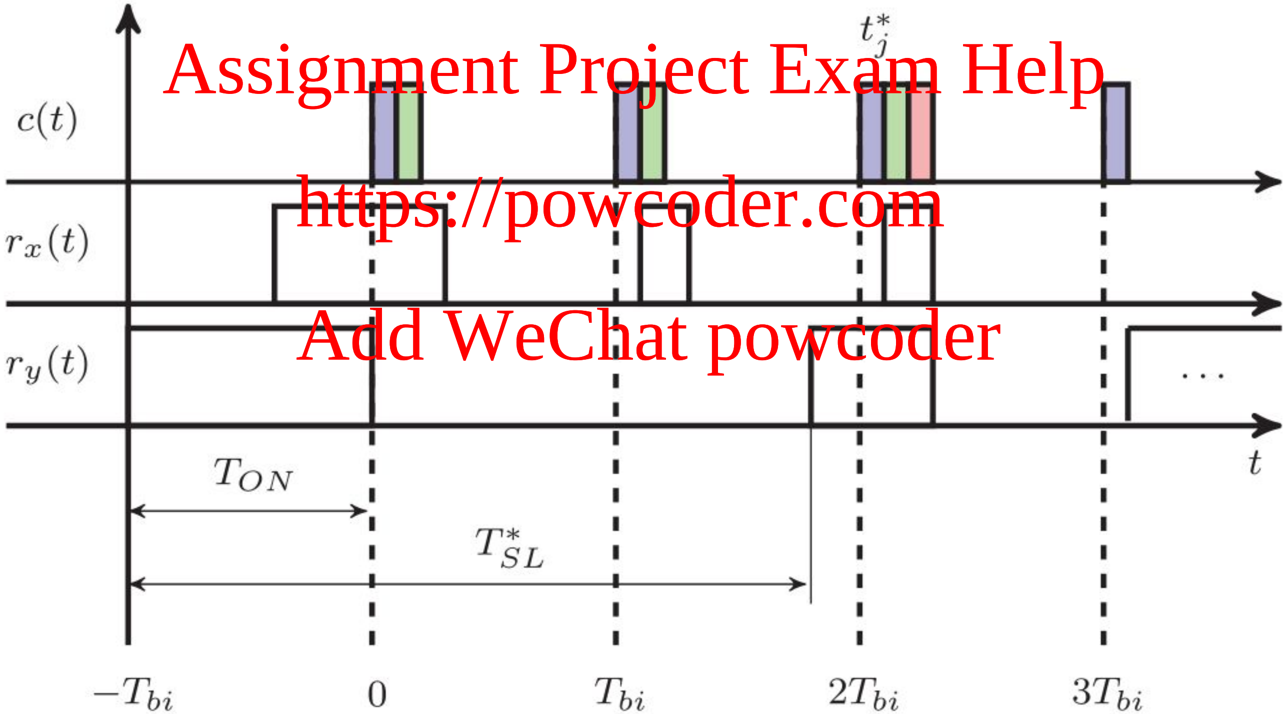
- *(1) Cannot converge until **every sensor receives a swarm agent from all other sensors***
- *Each sensor node will terminate the swarm phase **at the same time***
- *Without any global information, intelligence, or synchronization, each sensor **knows the swarm phase is completed***
- *(2) The sensor 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?*

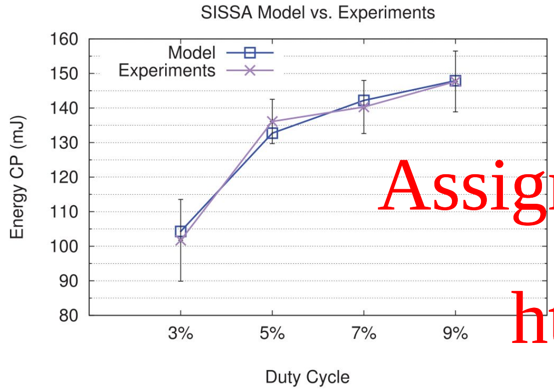


Fig. 10. Energy spent (mJ) during communication phase.

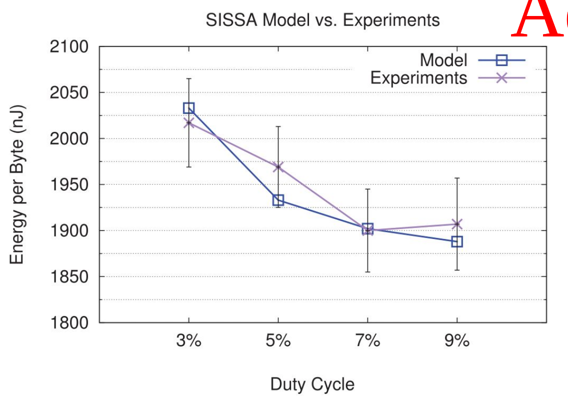


Fig. 11. Energy (nJ) per byte.

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)

	$\delta = 3\%$			$\delta = 5\%$			$\delta = 7\%$			$\delta = 9\%$		
S	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)

	$\delta = 3\%$			$\delta = 5\%$			$\delta = 7\%$			$\delta = 9\%$		
S	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*

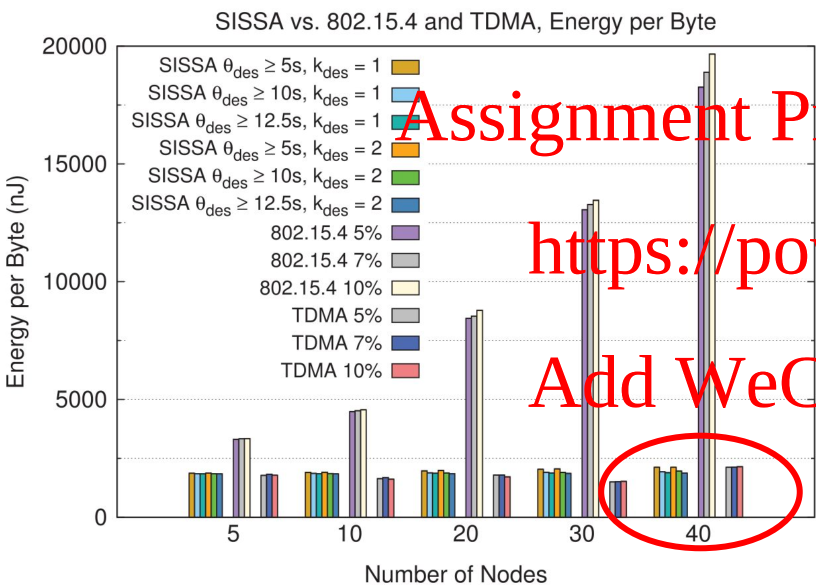
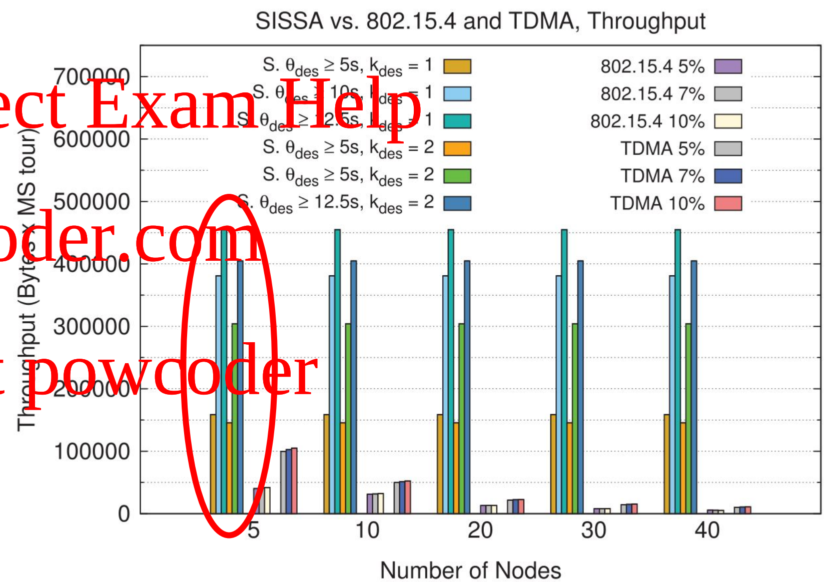


Fig. 14. Energy per byte, SISSA vs. 802.15.4 and TDMA.



What are the Pros and Cons of SISSA?

Think-Pair-Share!

Q&A