# Modeling IEEE 802.15.4 based Wireless Sensor Network with Packet Retry Limits

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# Outline

- Introduction
- Objectives
- System Model
- Analytical Models
- Performance Evaluation
- Conclusions

# Introduction

- IEEE 802.15.4 MAC is designed for Wireless Personal Area Networks (WPANs)
  - **Short Range**
  - **Low Power**
  - **Low Cost**
  - **Small Networks**

# Objectives

- Design analytical models for wireless sensor networks (WSN):
  - To evaluate energy consumption
  - To evaluate throughput
  - Based on IEEE 802.15.4 MAC with retry limits.
- Consider unsaturated traffic conditions
  - All nodes of the network do not have packets to transmit at the same time.

# System Model

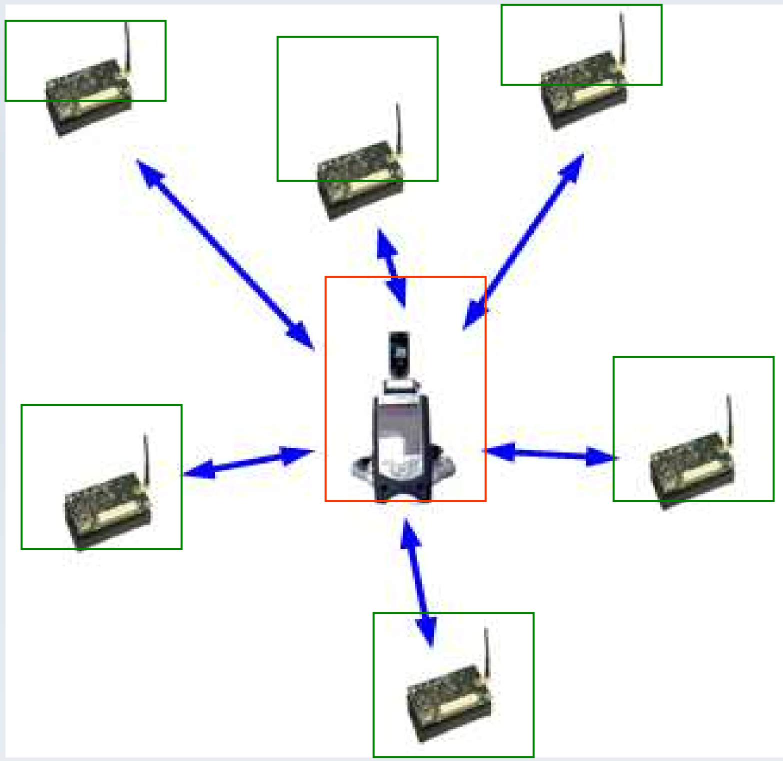
- Network Topology
- Data Transfer Methods
- Channel Access Mechanism

# Network Topology

- **We design analytical models for the star topology based WSN.**

Network Devices

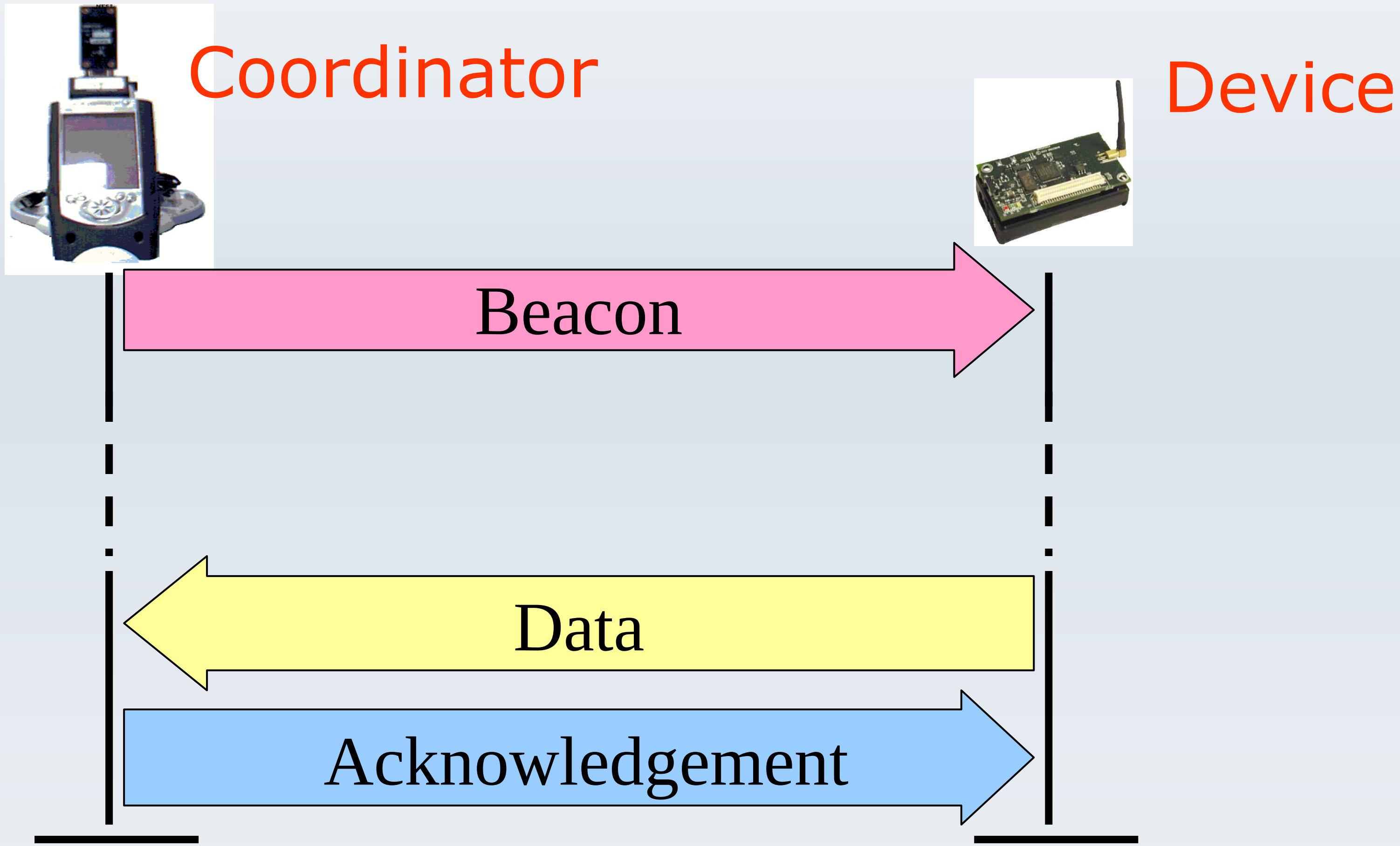
Coordinator



# Data Transfer Method

- In star topology, only two types of data transfer methods are used.
  - **Uplink:** Network Devices → Coordinator
  - **Downlink:** Coordinator → Network Devices
- **Take accounts of the acknowledgements**
- **Only concentrate on the uplink data transfer**
  - Sensed data are generally flown from devices to the coordinator.

# Data Transfer Model



# Channel Access Mechanism

- **Two types of CSMA-CA in IEEE 802.15.4**
- Slotted (in beacon enabled network)
- Un-slotted (in non-beacon enabled network)
- **Consider slotted CSMA-CA with ACK**

# Channel Access Mechanism

- **Each device shall maintain three variables for each transmission attempts.**
  - Number of Backoffs (*NB*)
  - Contention Window Length (*CW*):
  - Number of backoff periods that need to be cleared of channel activity before the transmission can commence
  - Backoff Exponent (*BE*): backoff period=R(0, $2^{BE}$-1)

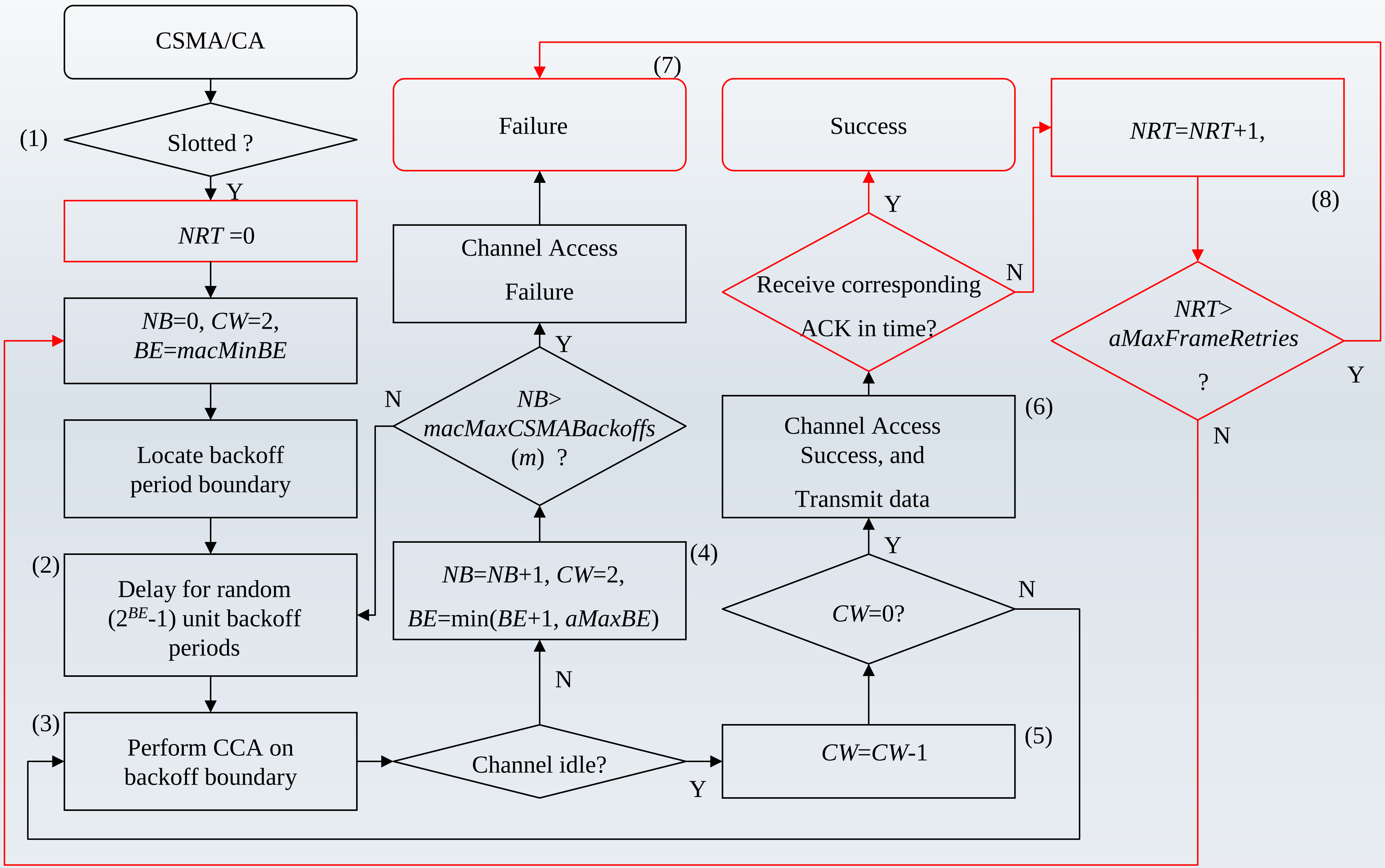
# Analytical Models

- Transmission Policy
- Packet Collision Probability
- Probability of Sensing Channel Busy
- The Markov Chain Model

# Definition of parameters

- *aMaxFrameRetries*: Maximum number of retries allowed after a transmission failure
- *macAckWaitDuration*: Maximum number of symbols to wait till receiving an ACK.
- *macMinBE*: Minimum value of the backoff exponent
- *aMaxBE*: Maximum value of the backoff exponent
- *macMaxCSMABackoffs* (*m*): Maximum number of backoffs the CSMA-CA algorithm will attempt before declaring a channel access failure

# Transmission Policy

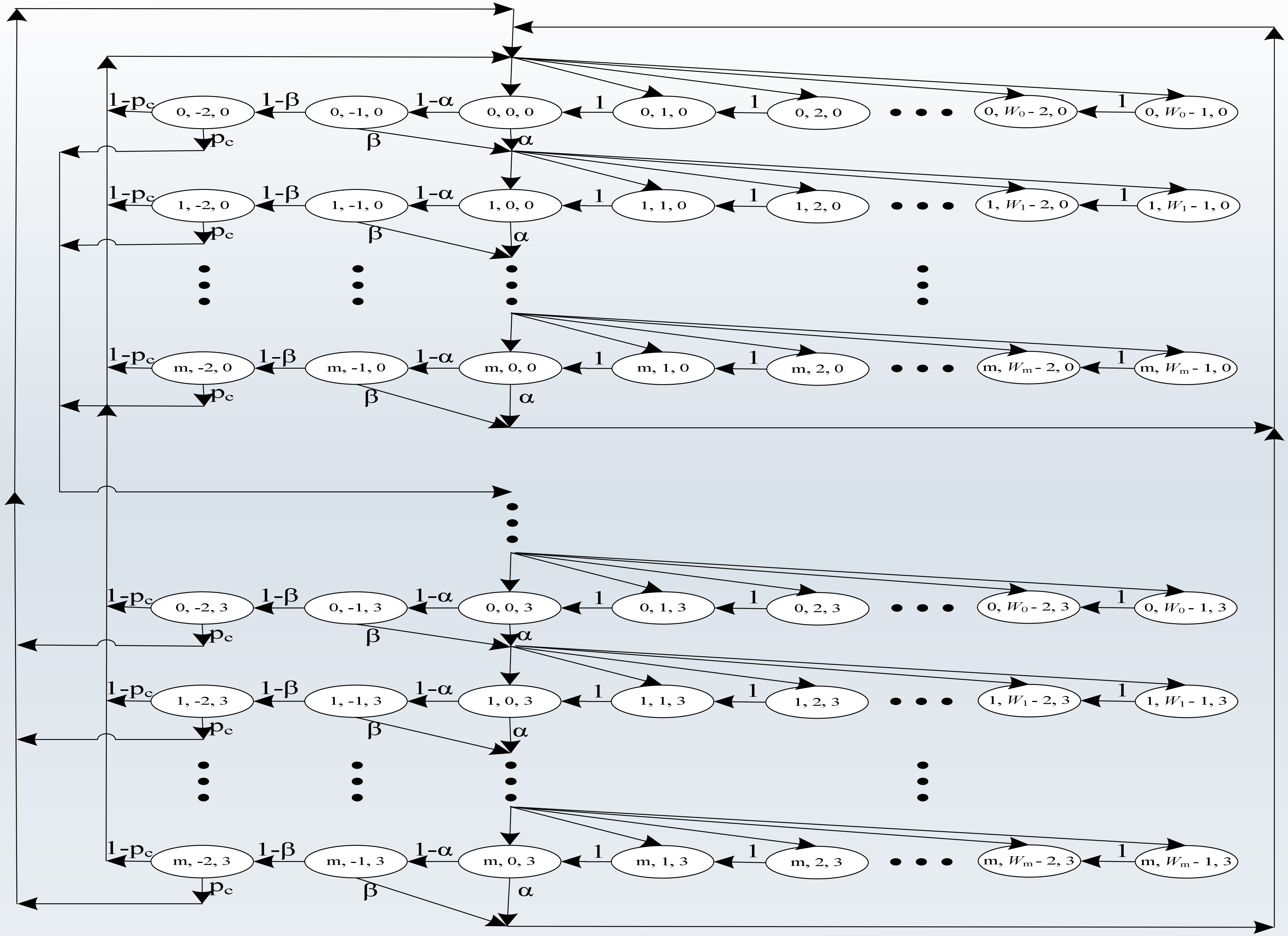


# Packet Collision Probability

- $p_c$: Probability of collision is seen by a packet, if it is transmitted after performing CCA twice.
  - $p_c = 1 - [1 - (1 - p_0)\tau]^{N-1}$
- *N:* Number of nodes associated to the coordinator
- $p_0$: Probability that the node has no packet ready to transmit.
- τ: Probability that the node is performing first CCA.

# Probability of Sensing Channel Busy

- $M_i(s)$=-1: Event that there is at least one transmission in the medium in slot ***i***
- $M_i(c)$=-1: Event that some station start sensing during slot ***i***
- $M_i(s)$□0: Event that no station in the medium is transmitting in slot ***i***
- $M_i(c)$□0 : Event that no station starts sensing during slot ***i***




# The Markov Chain Model

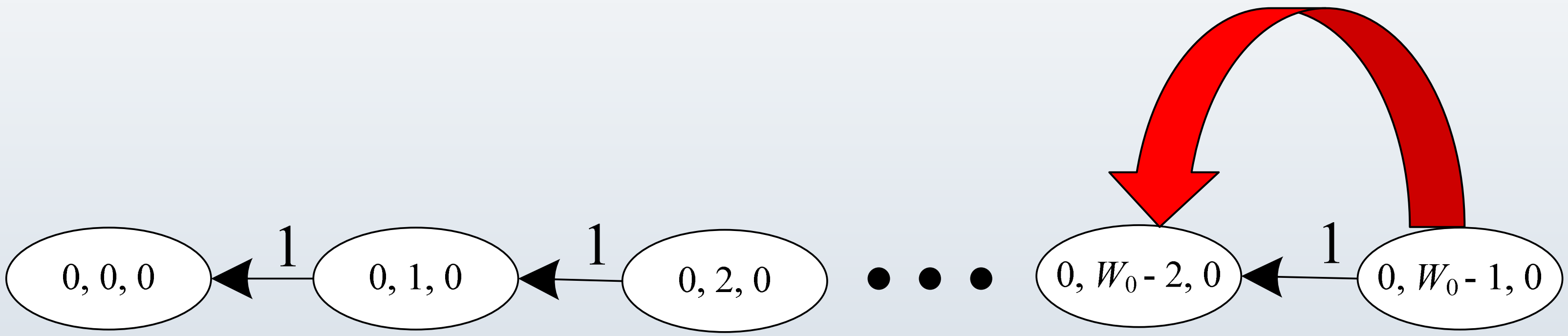
# The Markov Chain Model

- Three stochastic processes: s(t), c(t) and r(t)
- s(t): Represents the backoff stage for NB,
- c(t): Represents backoff counter for CW,
- r(t): Represents retransmission counter for NRT

# The Markov Chain Model

- $S_{j,x,k} = P\{s(t) = j, c(t) = x, r(t) = k\}$
- j: $\{0, 1, ..., m\}$,
- x: $\{-2, -1, ..., Wj - 1\}$,
- k: {0, 1, ..., aMaxFrameRetries},
- m: represents the macMaxCSMABackoffs
- $Wj = 2^{\min(j + macMinBE, aMaxBE)}$

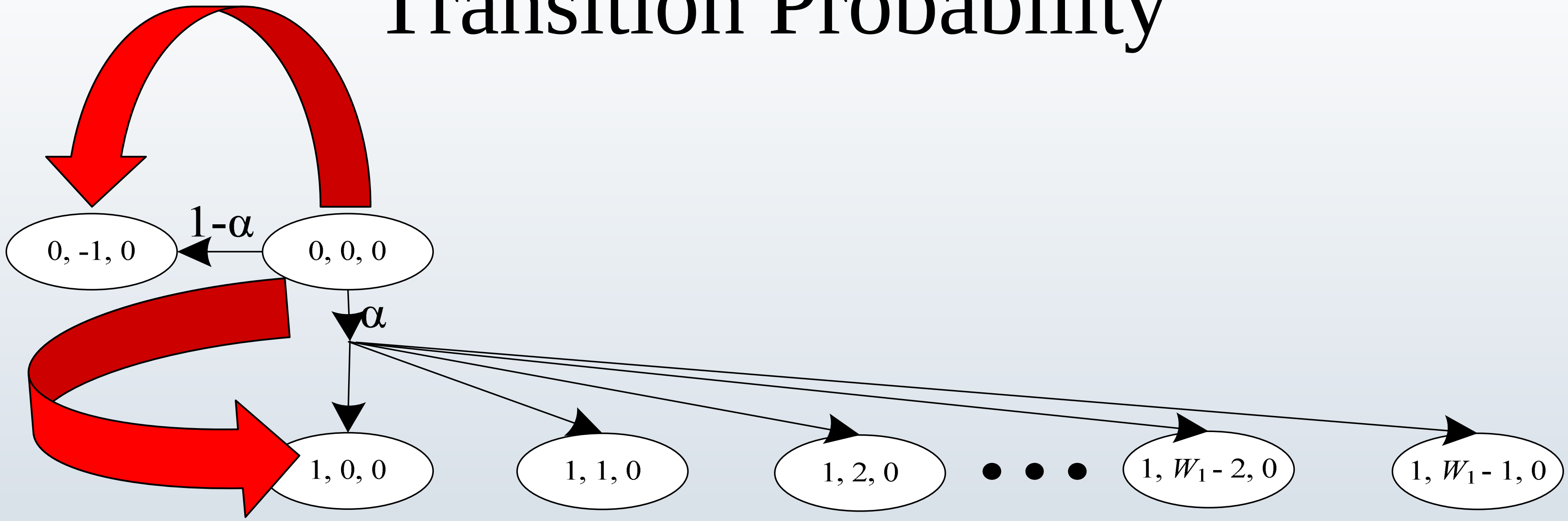
# Transition Probability




$$P(j, x-1, k \mid j, x, k) = 1, \text{ for} \begin{Bmatrix} 0 \le j \le macMaxCSMABackoffs; \\ 1 \le x \le W_j - 1; 0 \le k \le aMaxFrameRetries \end{Bmatrix}$$

$$\text{, where } W_j = 2^{\min(j+macMinBE,\ aMaxBE)}$$

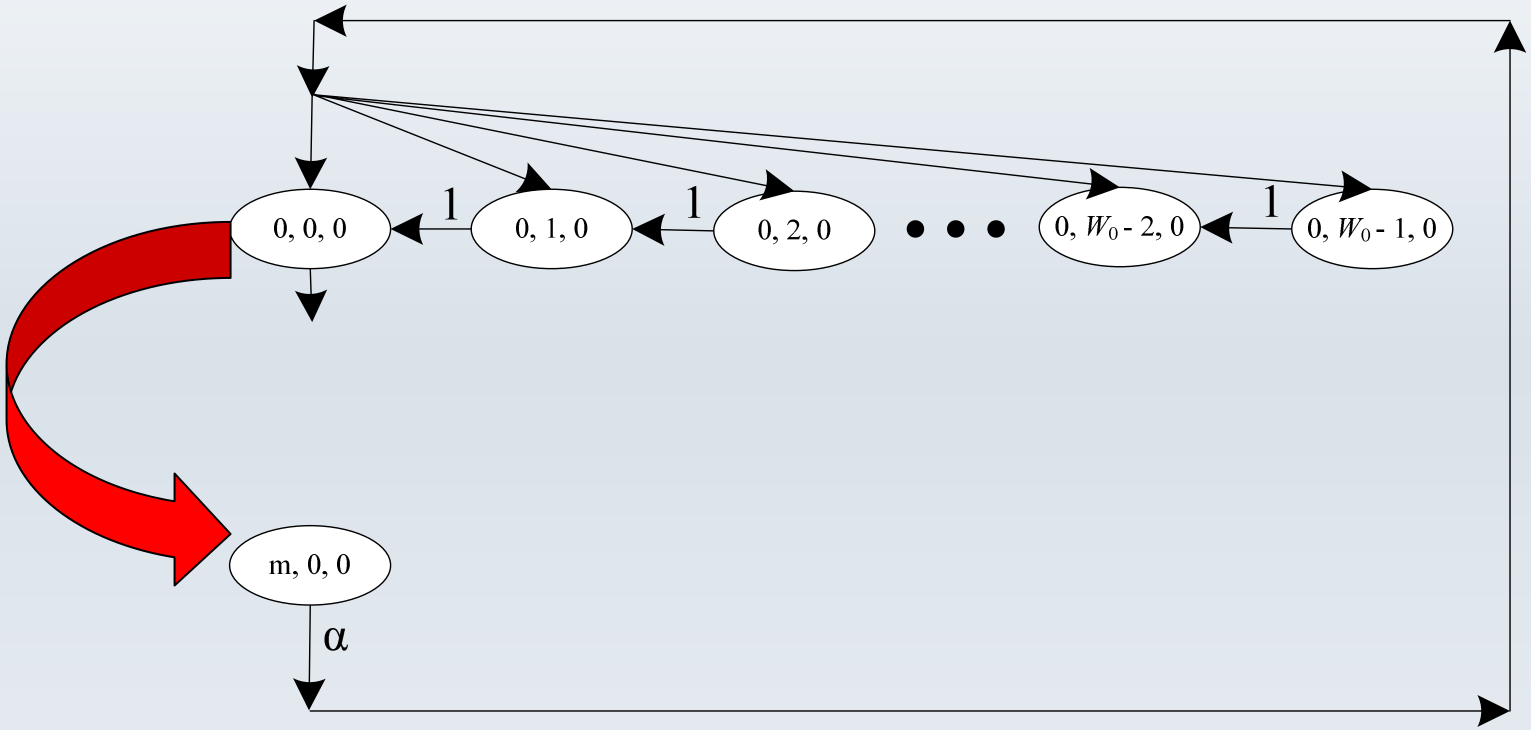
# Transition Probability




$$P(j,-1,k \mid j,0,k) = 1-\alpha, \text{ for} \begin{Bmatrix} 0 \le j \le macMaxCSMABackoffs; \\ 0 \le k \le aMaxFrameRetries \end{Bmatrix}$$

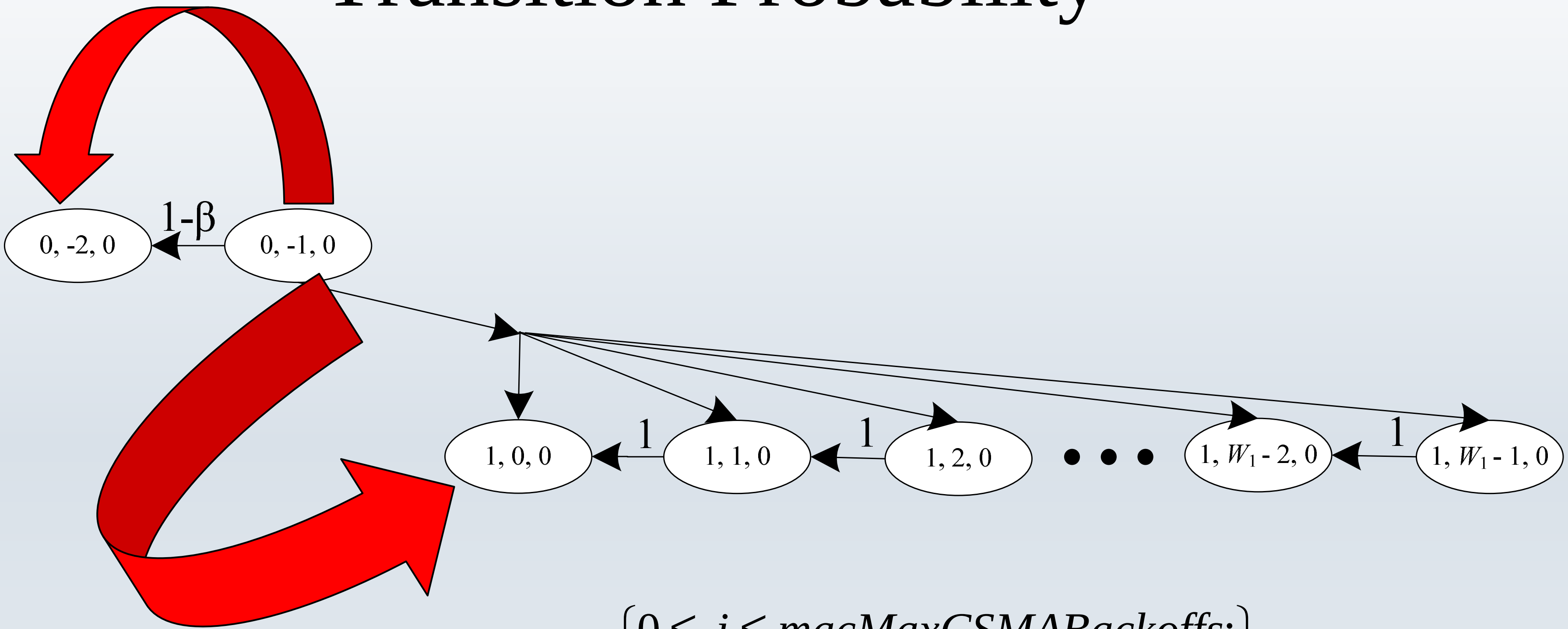
$$P(j+1,x,k \mid j,0,k) = \frac{\alpha}{W_{j+1}}, \text{ for} \begin{Bmatrix} 0 \le j \le macMaxCSMABackoffs - 1; \\ 0 \le x \le W_{j+1} - 1; 0 \le k \le aMaxFrameRetries \end{Bmatrix}$$

# Transition Probability




$$P(0, x, 0 \mid macMaxCSMABackoff, 0, k) = \frac{\alpha}{W_0}, \text{ for} \left\{ \begin{matrix} 0 \le x \le W_0 - 1; \\ 0 \le k \le aMaxFrame\mathrm{Re}tries \end{matrix} \right\}$$

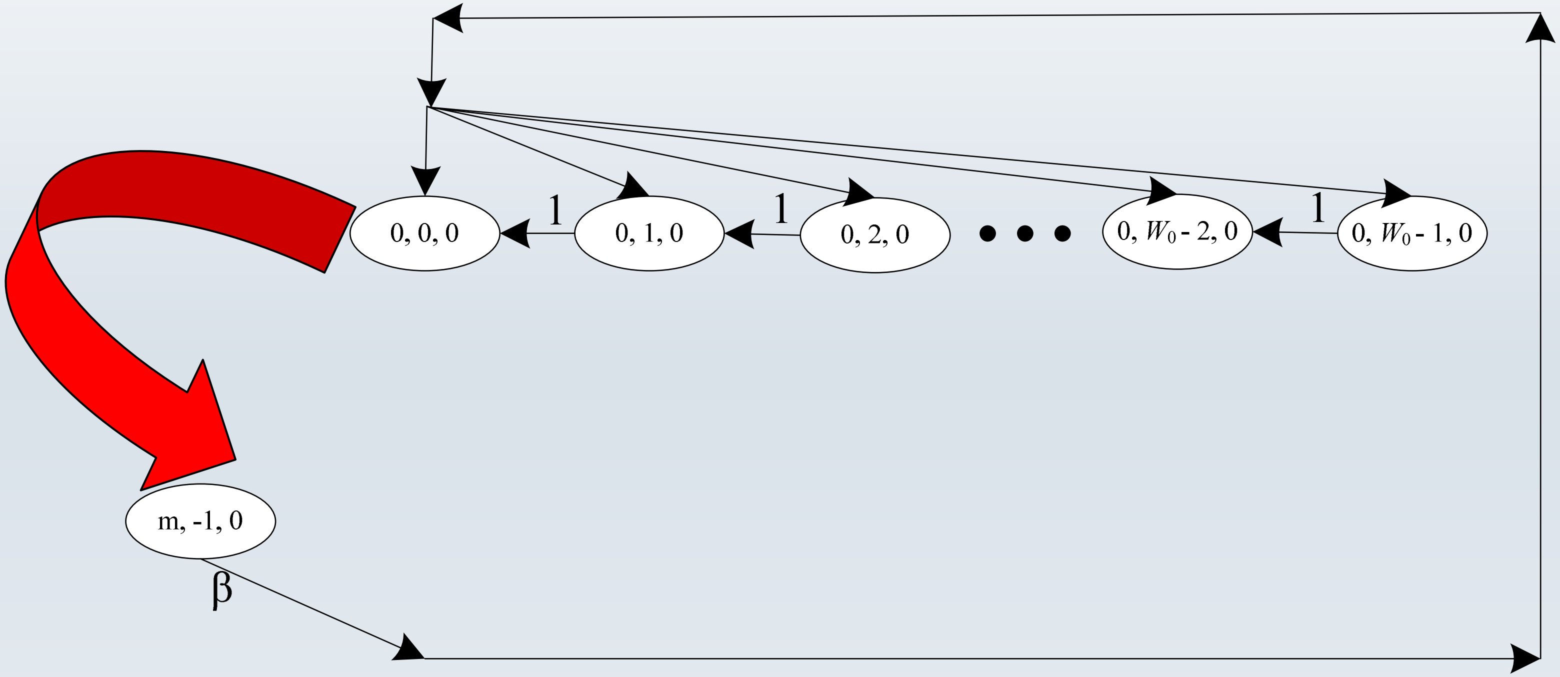
# Transition Probability




$$P(j,-2,k \mid j,-1,k) = 1-\beta,\ \text{for}\begin{Bmatrix} 0 \le j \le macMaxCSMABackoffs; \\ 0 \le k \le aMaxFrame\text{Re}tries \end{Bmatrix}$$

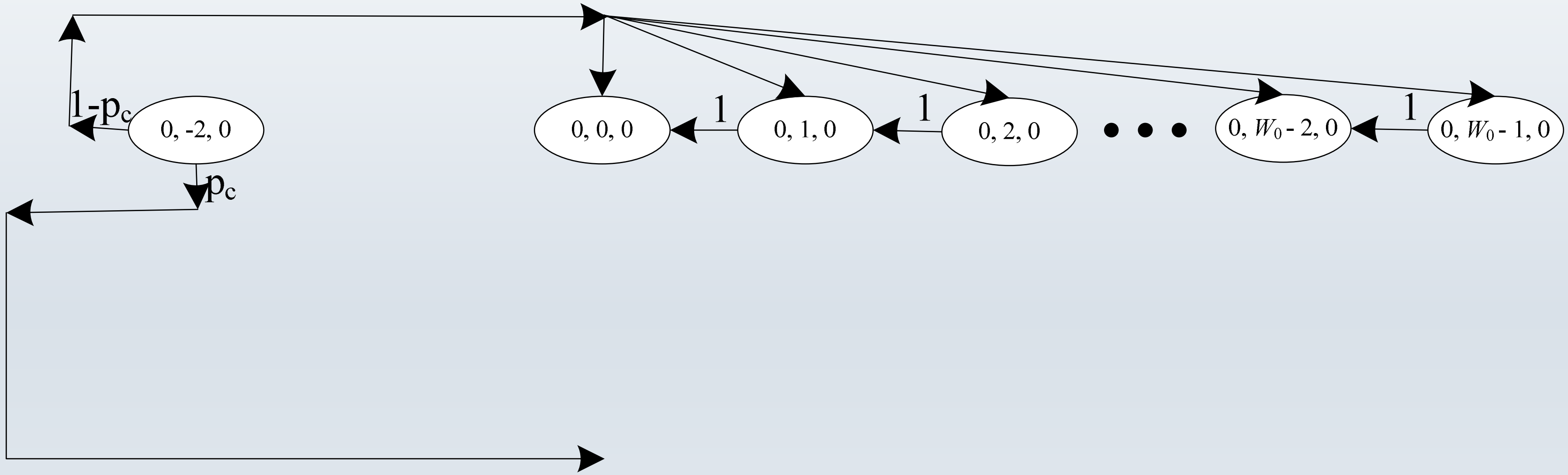
$$P(j+1,x,k \mid j,-1,k) = \frac{\beta}{W_{j+1}},\ \text{for}\begin{Bmatrix} 0 \le j \le macMaxCSMABackoffs-1; \\ 0 \le x \le W_{j+1}-1;\ 0 \le k \le aMaxFrame\text{Re}tries \end{Bmatrix}$$

# Transition Probability




$$P(0, x, 0 \mid macMaxCSMABackoff, -1, k) = \frac{\beta}{W_0}, \text{ for} \begin{Bmatrix} 0 \le x \le W_0 - 1; \\ 0 \le k \le aMaxFrameRetries \end{Bmatrix}$$

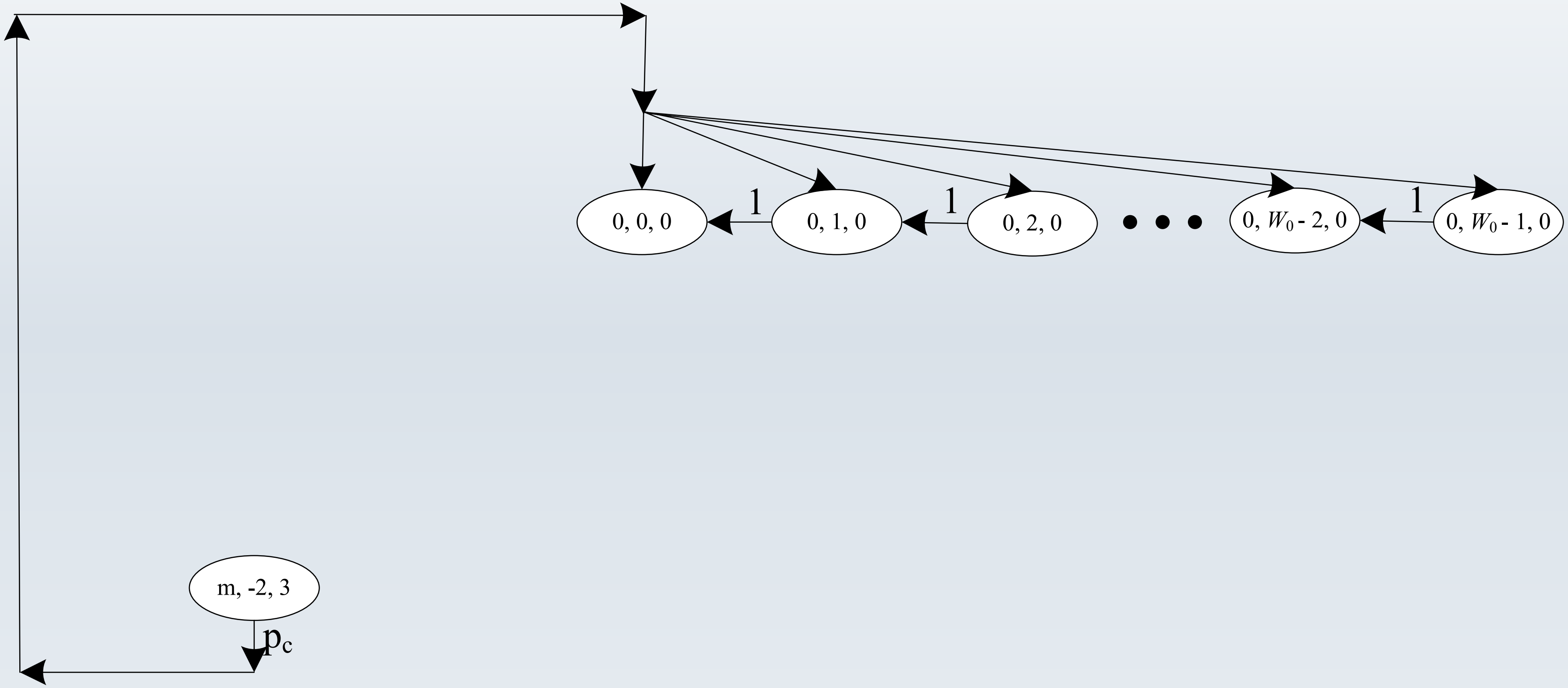
# Transition Probability




$$P(0,x,k+1 \mid j,-2,k)=\frac{p_c}{W_0},\ \text{for}\begin{Bmatrix}0\le j\le macMaxCSMABackoffs;\\ 0\le x\le W_0-1;\ 0\le k\le aMaxFrame\mathrm{Re}tries-1\end{Bmatrix}$$

$$P(0,x,0 \mid j,-2,k)=\frac{1-p_c}{W_0},\ \text{for}\begin{Bmatrix}0\le j\le macMaxCSMABackoffs;\\ 0\le x\le W_0-1;\ 0\le k\le aMaxFrame\mathrm{Re}tries\end{Bmatrix}$$

# Transition Probability




$$P(0, x, 0 \mid j, -2, aMaxFrameRetries) = \frac{p_c}{W_0}, \text{ for} \begin{Bmatrix} 0 \le j \le macMaxCSMABackoffs; \\ 0 \le x \le W_0 - 1 \end{Bmatrix}$$

# Throughput Estimation

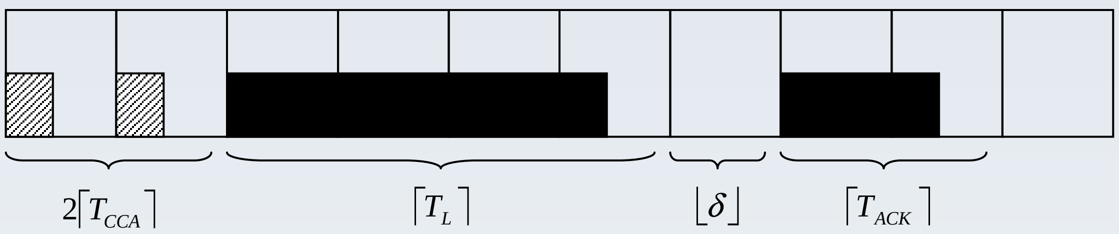
- In order to demonstrate that the IEEE 802.15.4 is suitable for low-rate WSNs, we develop the analytical model for throughput.
- $p_{tr}$: probability that there is at least one transmission in the considered slot time
  - $p_{tr} = L(1-\alpha)(1-\beta)\left\{ 1-[1-(1-p_0)\tau]^N \right\}$
- $p_s$: the probability that a transmission occurring on the channel is successful
  - $$p_s = \frac{L(1-\alpha)(1-\beta)N \times (1-p_0)\tau\left[1-(1-p_0)\tau\right]^{N-1}}{p_{tr}}$$

# Throughput Estimation

- Taking $S$ as the average amount of payload successfully transmitted in one backoff period
  - $$S = \frac{p_s p_{tr} T_{pl}}{(1 - p_{tr})\sigma + p_{tr} p_s T_s + p_{tr}(1 - p_s)T_c}$$
- $T_{pl}$: duration of payload transmission
- σ: duration of an empty slot time
- $T_c$: duration of a collision
- $T_s$: duration of a successful transmission

# Throughput Estimation

- $T_s = 2\lceil T_{CCA} \rceil + \lceil T_L \rceil + \lfloor \delta \rfloor + \lceil T_{Ack} \rceil, T_c = 2\lceil T_{CCA} \rceil + \lceil T_L \rceil + \lfloor \delta_{\max} \rfloor$
- $T_{CCA}$: duration for performing CCA
- $T_L$: duration for transmitting L-slot packet
- δ: duration for waiting an ACK
- $T_{ACK}$: duration for receiving an ACK
- An example for $T_s$:



# Energy Consumption Estimation

- Es: Energy consumption for each succeful transmission
- Ec: Energy consumption due to each collision.

$$E_s = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} + \delta_{max}P_{RX}$$

$$E_c = 2T_{CCA}P_{RX} + T_{ta}P_{ta} + T_L P_{TX} + T_{ta}P_{ta} + (\delta - T_{ta} + T_{ACK})P_{RX}$$

# Energy Consumption Estimation

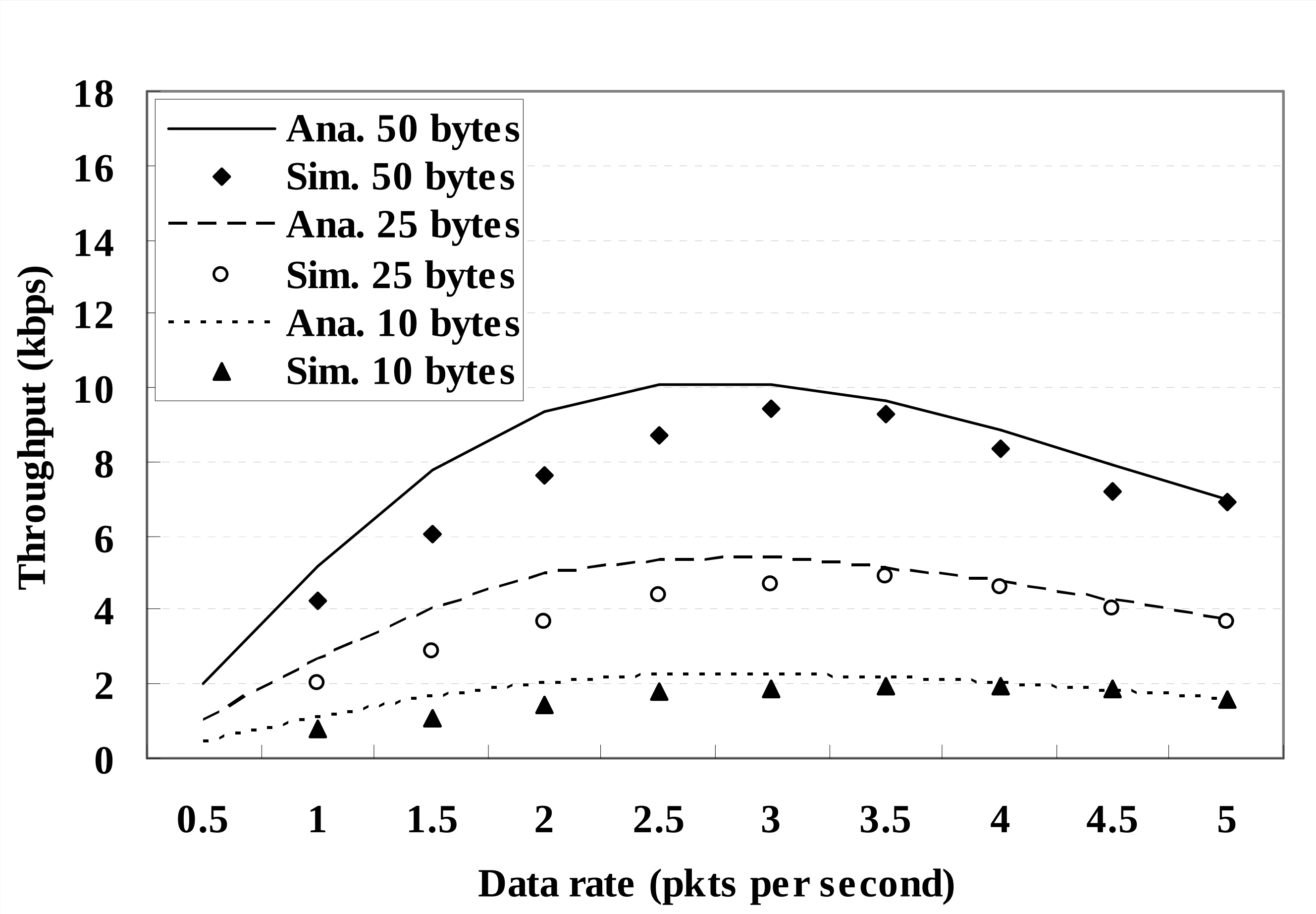
$$E = \frac{\tau \alpha T_{CCA} P_{RX} + \tau(1-\alpha)\beta \times 2T_{CCA} P_{RX}}{\tau(1-\alpha)(1-\beta) p_s T_{pl}}$$

$$+ \frac{\tau(1-\alpha)(1-\beta)[(1-p_s)E_c + p_s E_s]}{\tau(1-\alpha)(1-\beta) p_s T_{pl}}$$

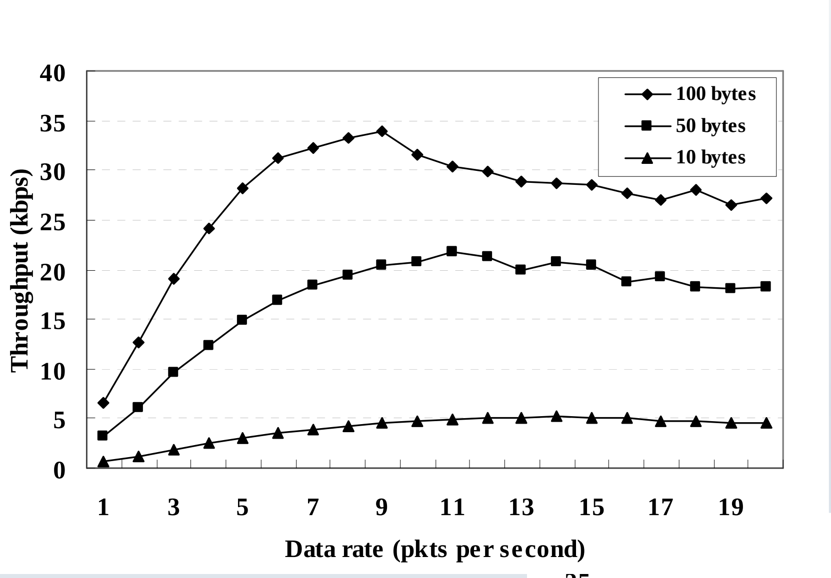
# Performance Evaluation

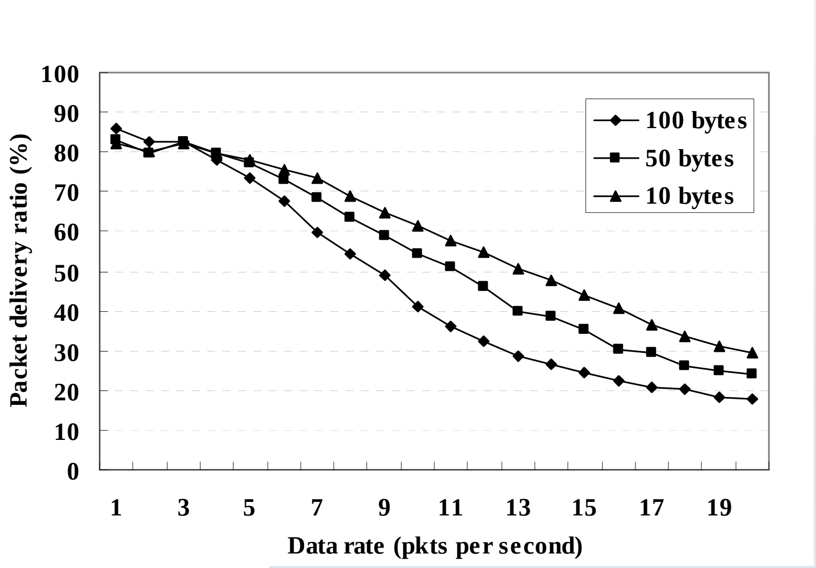
- We use ns-2 as the simulator
- A star topology with 30 nodes
- Transmission range: 7 meters
- Transceiver configured as CC2420
  - Carrier frequency: 2.4 GHz
  - Effective data rate: 250 kbps
- Provide various data rates per flow
  - unsaturated traffic conditions

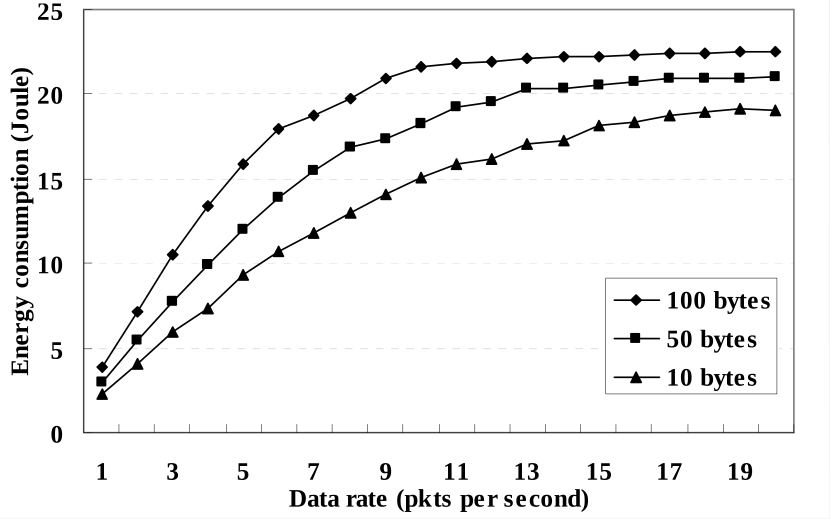
# Analytical and Simulated Results



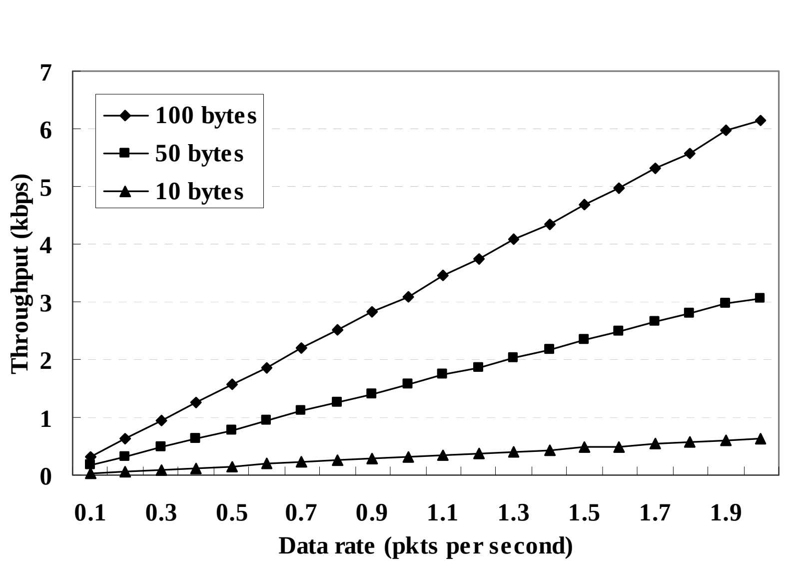
# High Data Rate

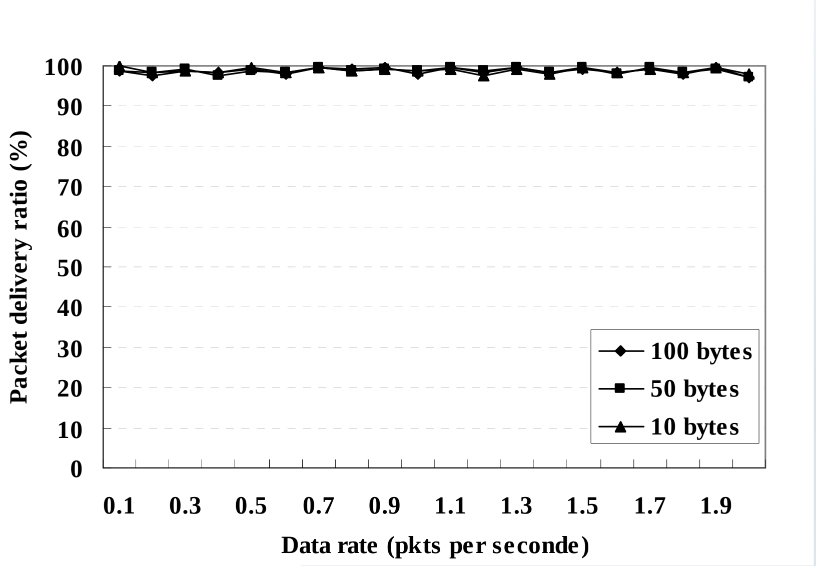


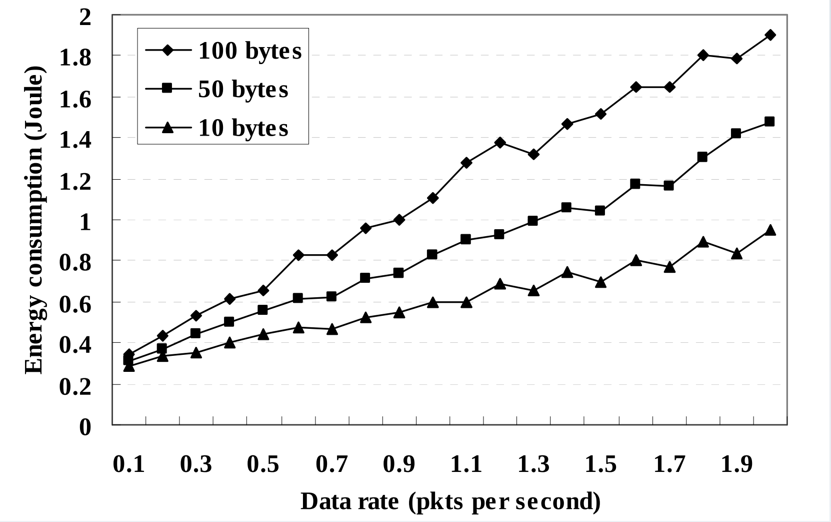



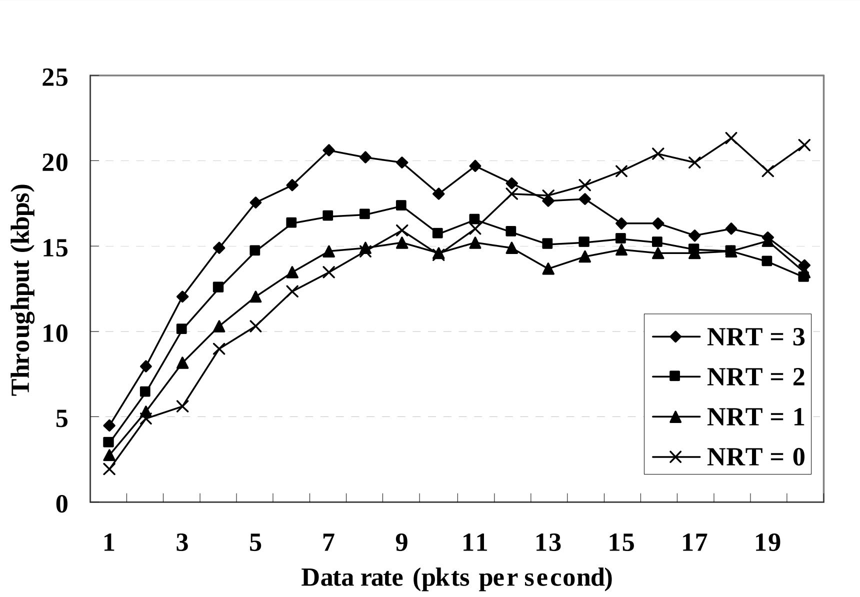
# Low Data Rate

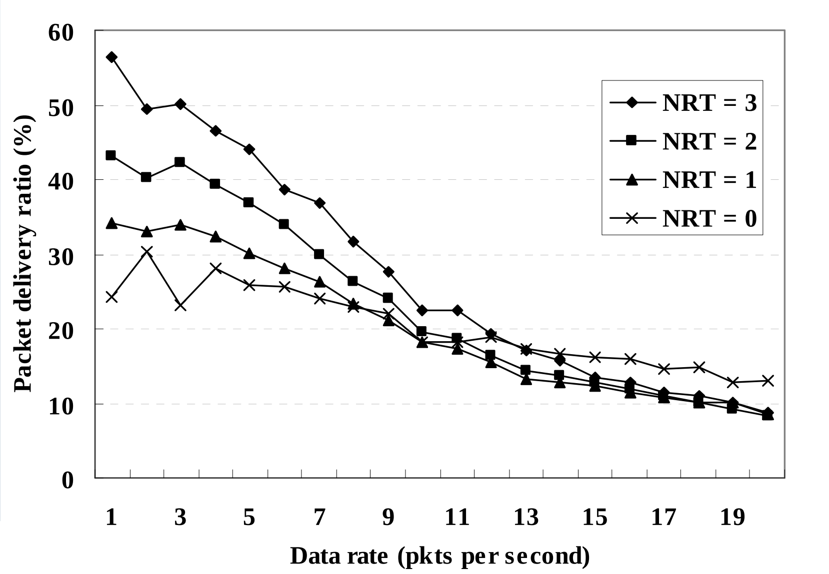


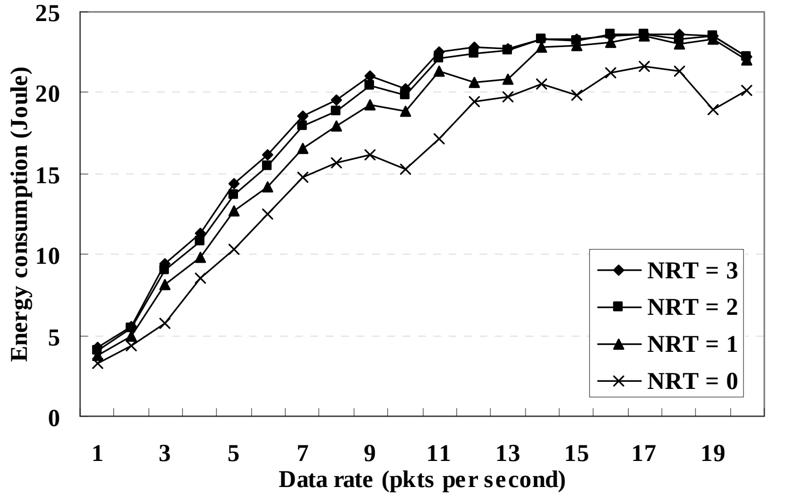



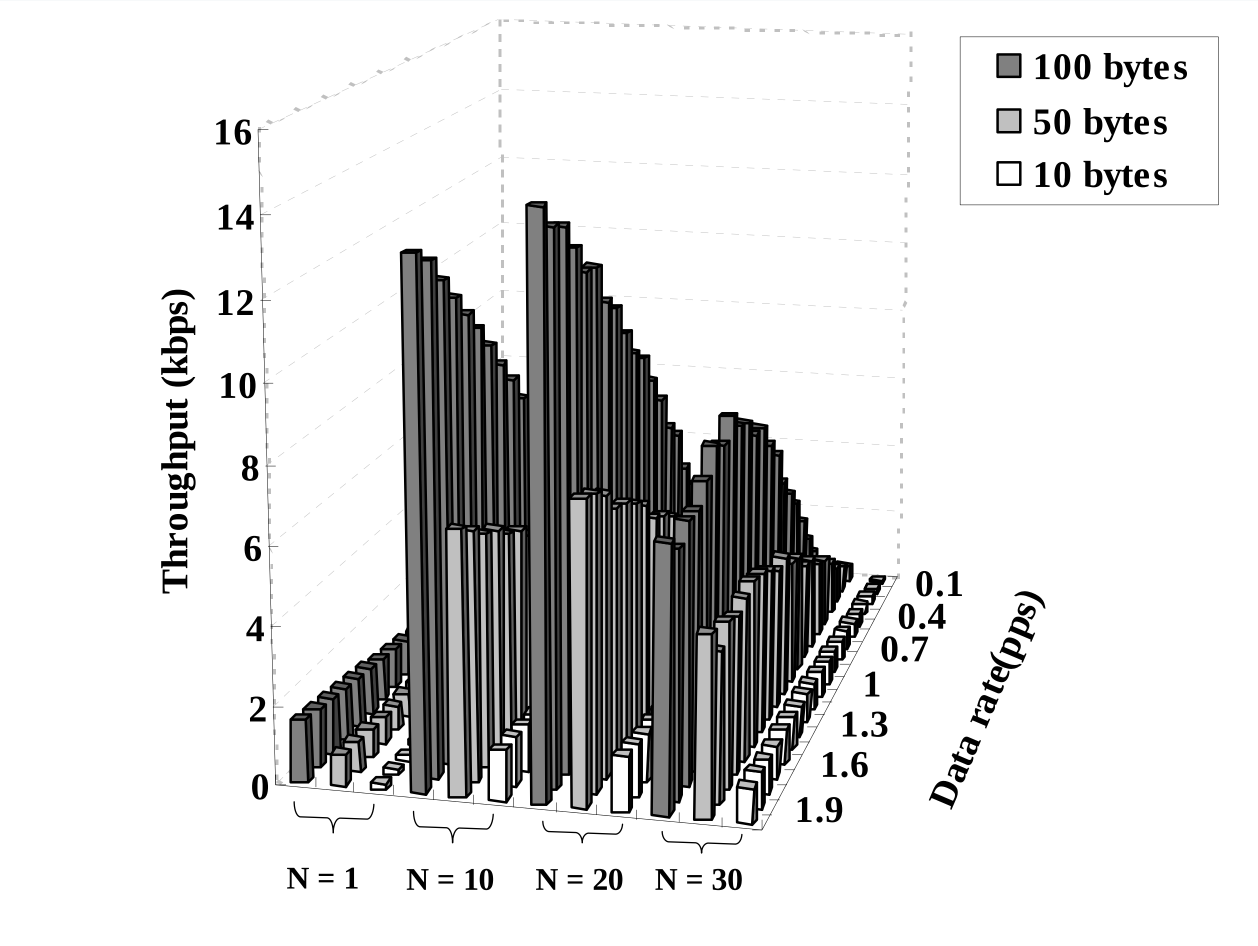
# Different NRT Values



# Different Node Numbers



# Conclusions

- We consider a beacon-enabled slotted CSMA-CA of IEEE 802.15.4
- Develop analytical models for throughput and energy consumption under unsaturated traffic conditions.
- Simulated results show that the standard is suitable for low data rate transmission.
- In order to get better throughput, the payload size should be as large as possible.
- Retransmission of collided packets should be considered for a network of lower data rate (WSN).

**Thank you**
**for your kind attention!**