WiseMAC: An Ultra Low Power MAC Protocol for the Downlink of Infrastructure Wireless Sensor Networks

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Presented by Angel Pagan
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Outline

- Introduction
- Infrastructure Network
- WiseMAC
- ZigBee
- Comparison
  - Power-delay characteristics
- Conclusion

Introduction

- Focus on infrastructure topology
- Propose WiseMAC (Wireless Sensor MAC) for the downlink
- Trade-off power consumption and transmission delay.
- WiseMAC is compared to ZigBee.

Power consumption

- Energy efficiency is important in the sensor nodes
- Power consumption of transceiver in receiver mode is considerable
- Minimize energy waste
  - Idle listening – active listening to idle channel.
  - Overhearing – reception of a packet or part of a packet destined to another node.

Infrastructure WSN

- Composed of a number of access points (AP).
- Each access point serves a number of sensor nodes.
- AP is energy unconstrained
  - Can listen continuously
  - Can send any amount of signaling traffic
  - Exploited by WiseMAC protocol

Traffic direction

- Focus on low traffic situations
- Downlink
  - From AP to sensor nodes
  - Transmit configuration data and query requests
  - Transmit without requiring sensor node continuously listening
- Uplink
  - From sensor node to AP
  - Transmit acquired data
  - AP can listen continuously with unlimited power
  - Only issue is multiple access of medium

WiseMAC

- **Medium Access Control protocol**
- **Based on CSMA with preamble sampling**
- **Sampling minimizes idle listening**
- **Exploit sensor nodes sampling schedules to minimize length of the wake-up preamble**
- **Data frames are repeated in long preambles to mitigate overhearing**

Sampling

- Sensor nodes regularly sample the medium – listen to the radio channel for a short duration
- If medium found busy listen until frame is received or until idle again
- Sensor node sample with constant period T_w
- Schedule offsets are independent of each other and constant

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Preamble

- AP transmits wake-up preamble of duration T_p in front of every data frame
- Ensures the receiver will be awake when the data frame arrives
- Provides low power consumption when channel is idle
- T_p is minimized by exploiting knowledge of sensor node sample schedule

Sampling schedules

- **AP keeps an up-to-date sampling schedule of all sensor nodes**
- **Sample schedules acquired from every acknowledgment packet**
- **ACK specifies the remain time until next scheduled sampling**

WiseMAC sampling activity

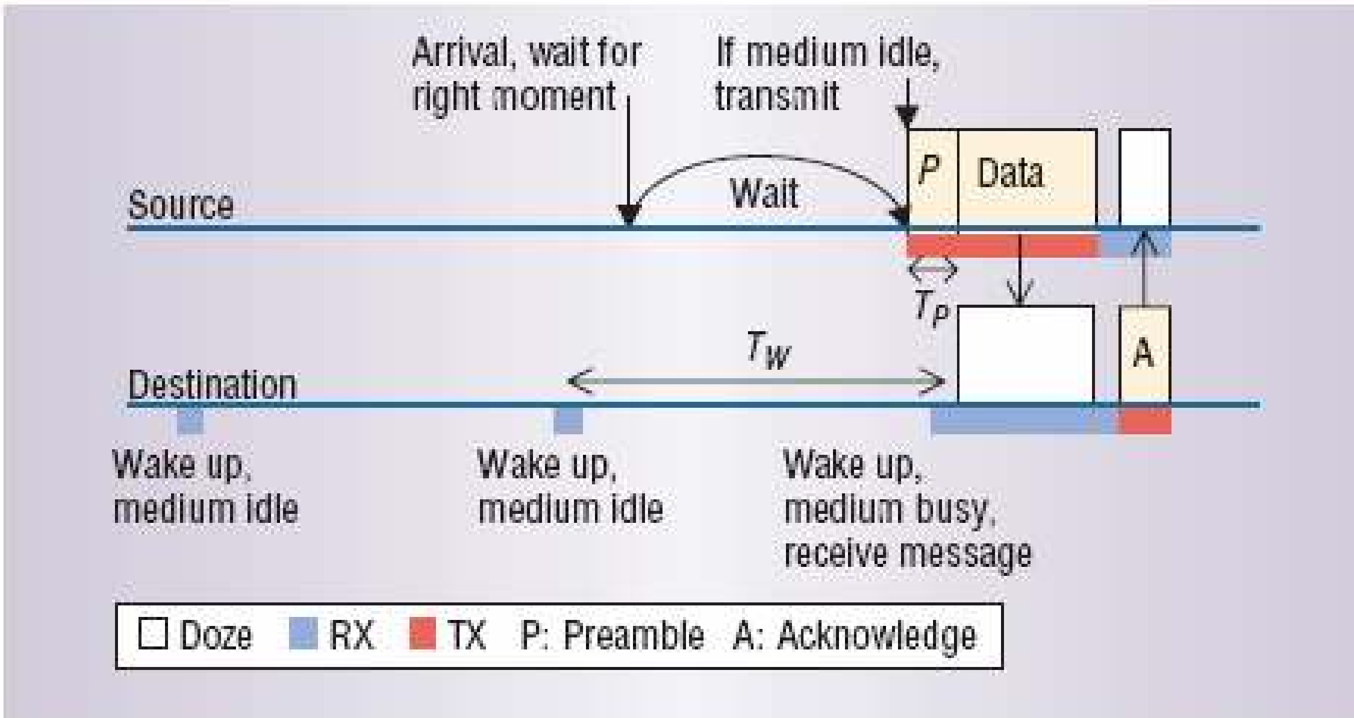

Figure 1. WiseMAC preamble minimization. A low-power, media access control protocol, WiseMAC uses a scheme that learns the sampling schedule of direct neighbors and exploits this knowledge to minimize the wake-up preamble length.

Diagram from IEEE Computer Journal feature article, WiseNET: an ultra low-power wireless sensor network solution, published by IEEE Computer Society, August 2004

Preamble duration

- T_p must compensate for drift between the clock at the AP and the sensor node

- Preamble duration must be $4\theta L$ if both quartz have a frequency tolerance of $\pm\theta$ and L is the interval between communications

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Drift Compensation

- AP may be late, while node may be early, start the preamble 2θL in advance
- Because the sensor node may be late while the AP is early the duration of preamble must be 4θL

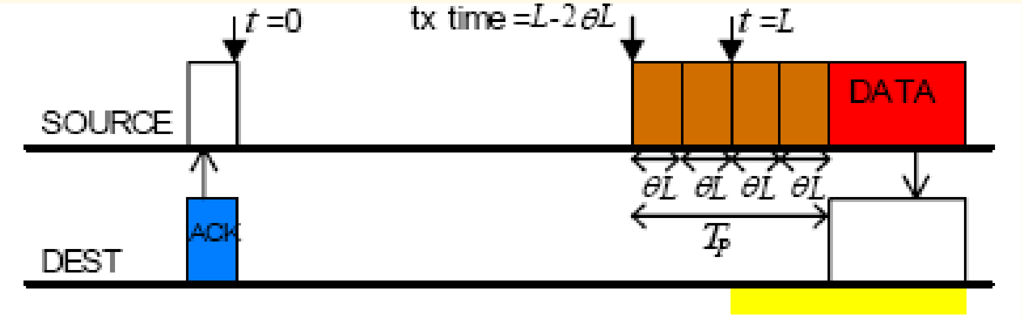


Diagram from presentation slides of Real-Time Networking Wireless Sensor Networks by Prof J.-D. Decotignie.

http://lamspeople.epfl.ch/decotignie/RTN_WSN.pdf

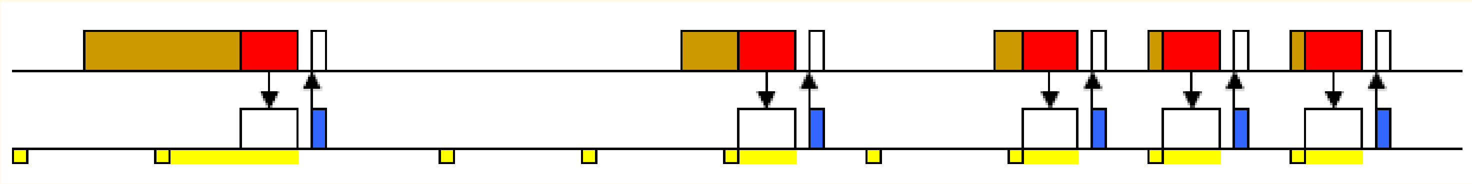
Drift Compensation (cont'd)

- In cases where L is very large and $4\theta L$ is larger than the sampling period T_w, the preamble length of T_w is used.

$$T_p = \min(4\theta L, T_w)$$

WiseMAC is adaptive

- In high traffic, the interval L between communications is small
- In low traffic, the interval L between communications is large, with maximum equal to T_w
- WiseMAC is adaptive to the traffic; per packet overhead decreases in high traffic conditions



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High traffic conditions

- When traffic is high overhearing is mitigated due to the preamble sampling technique and minimized preamble
- Short transmissions are likely to fall in between sampling instants of potential overhearers

Low traffic conditions

- When traffic is low T_p can exceed the length of the data packet
- In which case the wake-up preamble is composed of padding bits and repetitions of the data frame

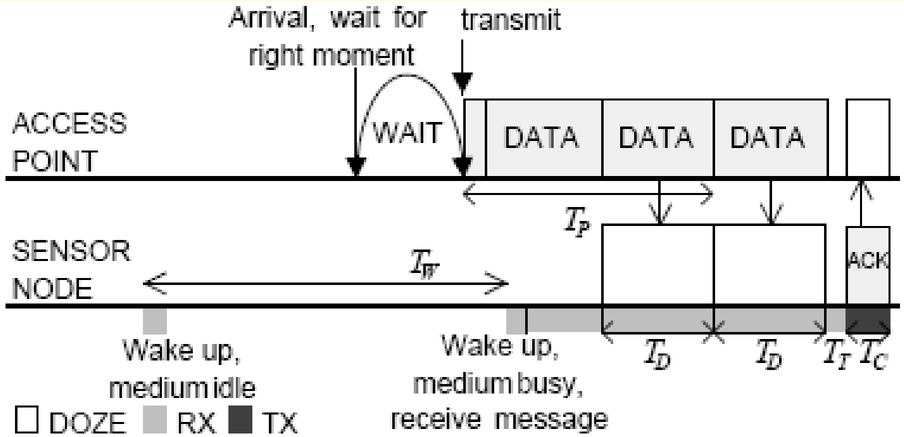

Figure 3. WiseMAC - Repetitions of the data frame in long wake-up preambles.

Frame pending bit

- In the header of the data packet
- If set, the sensor node will continue listening after having sent acknowledgment
- The AP will send the next data packet after receiving the acknowledgement
- Permits a larger wake-up interval and reduces queue delay at AP
- Cost of preamble is shared among multiple data packets

IEEE 802.15.4 ZigBee

- WiseMAC is compared to the power save MAC protocol in ZigBee
- Uses central coordinator labeled access point (AP) in this document
- AP buffers incoming traffic
- AP sends periodic beacon every T_w
- Beacon contains address of sensor node for which data is buffered

ZigBee Power Save Protocol

- All sensor nodes wake-up regularly to receive beacon
- Sensor node polls AP for the buffered data if the beacon contains its address
- Also uses frame pending bit in data packet header

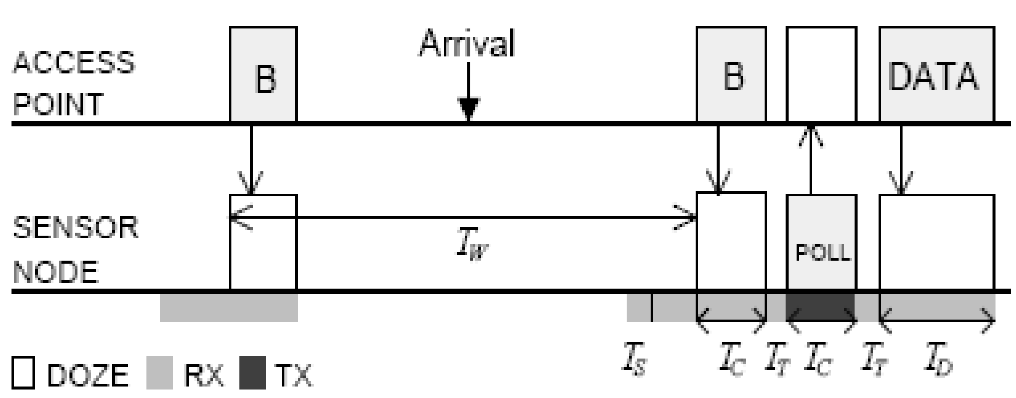

Figure 4. IEEE 802.15.4 ZigBee Power Save Protocol.

Optimize Zigbee

- For fair comparison, consider optimized version of ZigBee
- In practice polling procedure consist of POLL-ACK-DATA-ACK
- Interested in performance of basic protocol that uses beacon indication
- For low power consumption, consider POLL packet followed by DATA packet
- ACK is piggy-backed on following POLL packet

Performance Analysis

- Model transition delays between transceiver states and power consumption in each state
- Transceiver states
  – DOZE – The transceiver is not able to transmit nor receive, but is ready to quickly power-on into the receive or transmit state
  – RX – The transceiver is listening to the channel possibly receiving data
  – TX – The transceiver is transmitting data

Radio Model

- T_s – the setup time required to turn on the transceiver from DOZE state into the RX or TX state
- T_T – the turn-around time required to switch the transceiver between RX and TX
- P_z, P_R, P_T – power consumed, respectively, in the DOZE, RX, and TX states
- $\hat{P}_R = P_R - P_Z$; the increment in power consumption caused by being in the RX state
- $\hat{P}_T = P_T - P_Z$; the increment in power consumption caused by being in the TX state

Traffic Model

- Population of N sensor nodes
- Downlink Poisson traffic arrives at the AP at global rate λ
- Average packet inter-arrival time at sensor node is $L = {}^{N}/_{\lambda}$
- Data packet duration is T_D
- Control packet (pollings, acks, beacons) duration is T_c
- Assume low traffic conditions

$$ {}^{1}/_{\lambda} >> T_D + T_T + T_c $$

WiseMAC Power Consumption

- **Average power consumed by WiseMAC**

$$P_{WiseMAC} = P_Z + \frac{\widehat{P}_R(T_S + 1/B)}{T_W} + \frac{\widehat{P}_R(\overline{X} + T_D + T_T) + \widehat{P}_T T_C}{L} + \widehat{P}_R(N-1)\frac{\overline{Y}}{L}$$

where

$$\overline{X} = 2\theta L \left(1 - e^{-\frac{T_D}{4\theta L}}\right)$$

$$\overline{Y} = \frac{T_D^2 + 12 T_D \theta L}{2T_W}\left(1 - e^{-\frac{T_W}{4\theta L}}\right)$$

- P_Z: **Power consumed in DOZE state**
- $\frac{\widehat{P}_R(T_S + 1/B)}{T_W}$: **Power consumed by sampling activity**
- $\frac{\widehat{P}_R(\overline{X} + T_D + T_T) + \widehat{P}_T T_C}{L}$: **Power consumed while receiving the packet and ACK it**
- $\widehat{P}_R(N-1)\frac{\overline{Y}}{L}$: **Power consumed overhearing the packet by N-1 neighbors**
- $\overline{X}$: **Duration destination node listens to preamble prior to detect of start of the data frame**
- $\overline{Y}$: **Average duration a potential overhearer listens to a transmission**

ZigBee Power Consumption

- **Average power consumed by ZigBee**

$$P_{ZigBee} = P_Z + 2\theta \widehat{P}_R + \frac{\widehat{P}_R(T_S + T_C)}{T_W} + \frac{\widehat{P}_T T_C + \widehat{P}_R(T_D + 2T_T)}{L}$$

Power consumed in DOZE state

Power consumed while listening to cover the drift between AP and node

Power consumed to power on and listen to the beacon length T_c

Power consumed while polling and receiving of data packet every L seconds

Transmission delay

- The time elapsed between the arrival of a packet at the AP and the end of its transmission to the destination

$$D_{WiseMAC} = T_D + \frac{T_W}{2}\left(1 - e^{-\frac{T_W}{4\theta L}}\right) + 2\theta L\left(2 - e^{-\frac{T_D}{4\theta L}} - e^{-\frac{T_W}{4\theta L}}\right)$$

Transmission delay with WiseMAC

$$D_{ZigBee} = \frac{T_W}{2} + 2T_C + 2T_T + T_D$$

Transmission delay with ZigBee

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Radio Transceiver

- Consider the transceiver used for WiseNET low power radio transceiver

Table 1. System Parameters.

Parameter	Value	Parameter	Value
P_Z	5 μW	T_D (50 bytes)	16 ms
P_R	1.8 mW	T_C (10 bytes)	3.2 ms
P_T	27 mW	N	10
T_S	0.8 ms	L	1000 s
T_T	0.4 ms	θ	30 ppm
B	25 kbps		

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Power consumption and delay

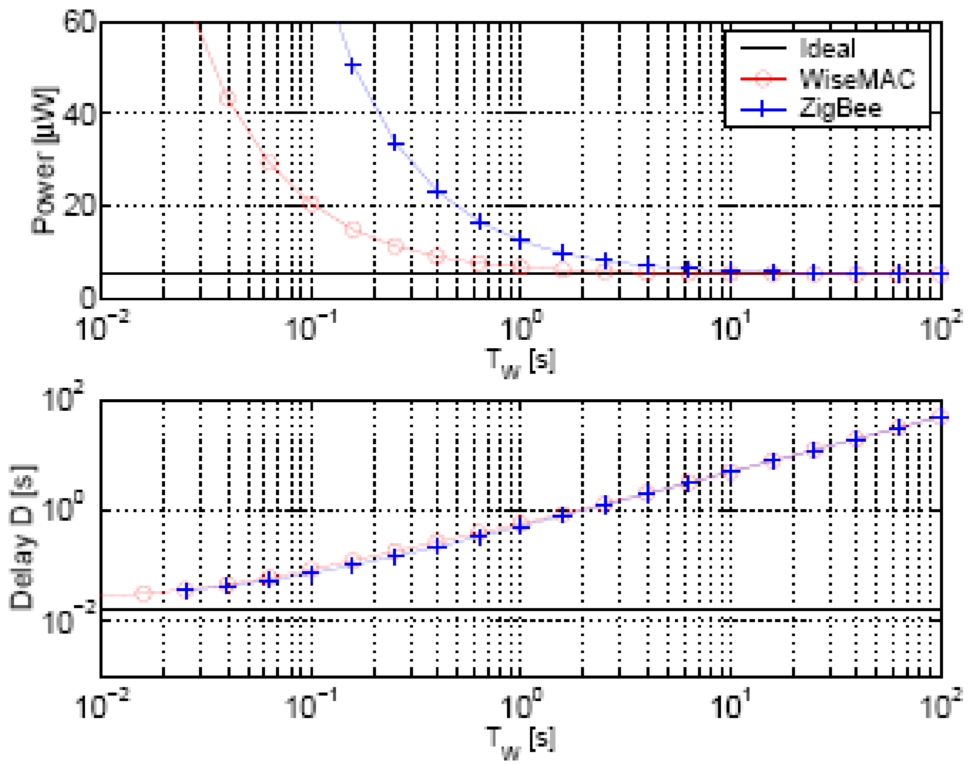

Figure 5. Power consumption and delay of WiseMAC and ZigBee as a function of the wake-up period T_W (L = 1000 s).

$$P_{Ideal} = P_Z + \frac{\hat{P}_R(T_S + T_D + T_T) + \hat{P}_T T_C}{L} = 5.12\mu W$$

WiseMAC consumes less power than ZigBee

$$D_{Ideal} = 16ms$$

Trade-off between consumed power and average transmission delay

Power-delay characteristics

Ideal delay

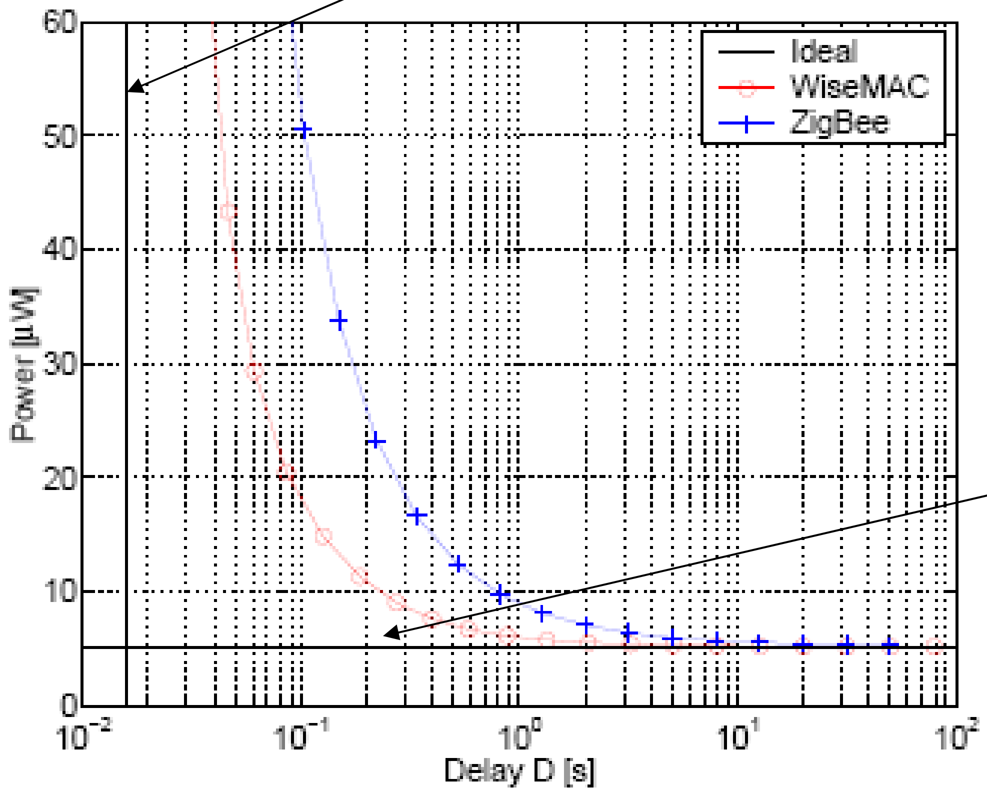

Figure 6. Power-delay characteristics of WiseMAC and ZigBee (L = 1000 s).

Combine power plot with delay plot and draw power-delay characteristics for varying T_w

Ideal power consumption

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Compare wake-up schemes

- **WiseMAC wake-up scheme consumes less power than the one of ZigBee**
- **As L approaches infinity the power consumption of WiseMAC and ZigBee becomes**

$$\lim_{L \to \infty} P_{WiseMAC} = P_Z + \frac{\widehat{P}_R(T_S + 1/B)}{T_W}$$

$$\lim_{L \to \infty} P_{ZigBee} = P_Z + 2\theta\widehat{P}_R + \frac{\widehat{P}_R(T_S + T_C)}{T_W}$$

- **WiseMAC – node powers up every Tw with a duration of a radio symbol**
- **ZigBee – transceiver periodically receives a beacon with a duration larger than a radio symbol**

Sensitivity Analysis

- Vary the traffic and the number sensor nodes
- Compare WiseMAC, ZigBee, and WiseMAC*
- WiseMAC* - a sub-optimal version where long wake-up preambles are not composed of repeated data frames

Varying traffic

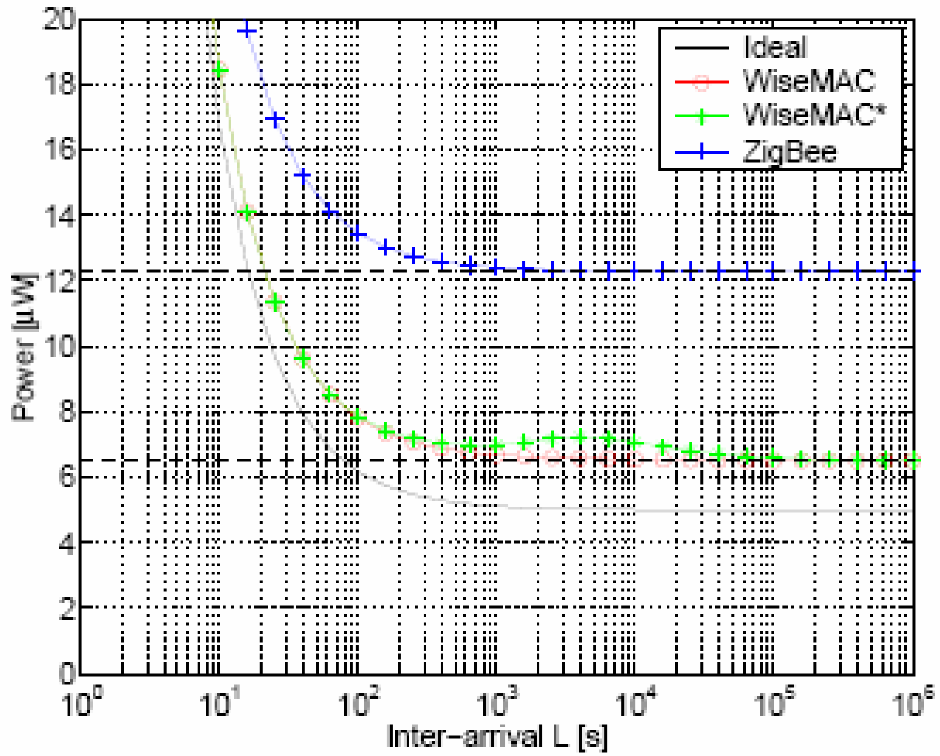

Figure 7. Power consumption of WiseMAC and ZigBee as a function of the inter-arrival L (T_W = 1 s).

WiseMAC has low power consumption in both high and low traffic conditions

WiseMAC* has more power consumption than WiseMAC for medium traffic – overhearing is maximized for L ≈ 4000

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Varying number of sensor nodes

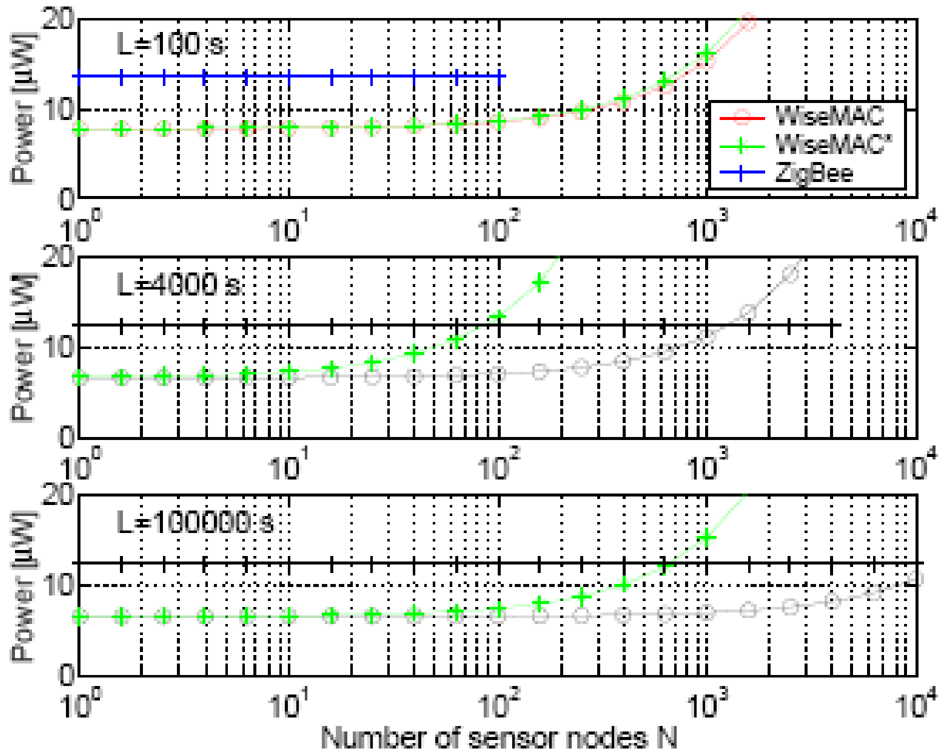

Figure 8. Scalability of WiseMAC with and without repetition of data frames in long wake-up preambles (T_W = 1 s).

Power consumption of ZigBee is independent of the number of nodes

Power consumption of ZigBee is independent of the number of nodes – no overhearing, scales better than WiseMAC

WiseMAC suffer from overhearing component – overhearing component is proportional to the number of nodes

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Conclusion

- Proposed WiseMAC for the downlink of infrastructure wireless sensor networks
- Analyzed power consumption-delay trade-off in low traffic condition and analytically compared it against ZigBee
- WiseMAC is more power efficient than ZigBee up to hundreds of nodes
- WiseMAC can provide a lower power consumption than ZigBee for the same delay

Observations

- **Repetition of data frames in wake-up preamble explained?**