# Low Power Consumption Features of the IEEE 802.15.4/ZigBee LR-WPAN Standard

**Ed Callaway**
**Florida Communication Research Lab**
**Motorola Labs**
**ed.callaway@motorola.com**

# Acknowledgement

This presentation contains the work of Monique Bourgeois, Paul Gorday, Jose A. Gutierrez, David Hayes, Jian Huang, Phil Jamieson, Fred Martin, Said Moridi, Bob O'Dea, Qicai Shi, and many others in the IEEE 802.15 Working Group and in ZigBee member companies

# Contents

- Introduction to IEEE 802.15.4™/ZigBee™
- Low-power features of the
  - Physical layer
  - Data Link layer
  - Network layer (briefly)
- Low-power features compatible with ZigBee
- Power-conscious implementation
- Conclusion

Institute of Electrical and Electronics Engineers, Inc., IEEE Std. 802.15.4-2003, IEEE Standard for Information Technology — Telecommunications and Information Exchange between Systems — Local and Metropolitan Area Networks — Specific Requirements — Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs). New York: IEEE Press. 2003.

http://www.zigbee.org

# IEEE What?

**IEEE 802 LAN/MAN Standards Committee**

… … …

- **802.1** Higher Layer LAN Protocols Working Group
- …
- **802.11** Wireless Local Area Network Working Group
- …
- **802.15** Wireless Personal Area Network Working Group
- …
- **802.20** MBWA Working Group

**802.15 Wireless Personal Area Network Working Group:**

- **TG1** WPAN/Bluetooth Task Group
- **TG2** Coexistence Task Group
- **TG3** WPAN High Rate Task Group
- **TG4** WPAN Low Rate Task Group → Formed in November, 2000

# IEEE 802.15.4--

- **What it is:**
  - An WPAN standard optimized for low (0.01-115.2 kb/s) data throughput applications with simple or no QoS requirements
  - Lower power, lower cost than other WPANs (e.g., Bluetooth)
  - Using ZigBee Alliance for marketing and compliance (like Wi-Fi/802.11b)
  - PHY and MAC layers only (upper layers defined by ZigBee)

- **What it is not:**
  - A WLAN
  - A Bluetooth replacement (e.g., no isochronous voice capability)
  - Optimized for multimedia, TCP/IP, or other high data rate applications
  - A system, network, or application set

**MCU requirements: 8-bit, 4 MHz, 32 kB ROM, 8 kB RAM**

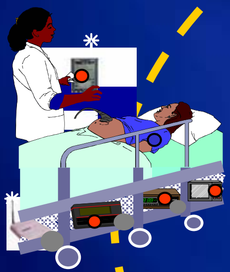
# The ZigBee Alliance--

- **What it is:**
  - An industry consortium of more than 50 companies, with the goal of promoting IEEE 802.15.4 WPANs
  - Composed of semiconductor houses, system integrators, and users
  - Performs marketing and compliance certification for 15.4
  - Defines higher layers (network, application profiles, …)

- **What it is not:**
  - An open standards-defining organization
  - Officially associated with the IEEE
  - Associated with the Bluetooth SIG
  - Specifying the PHY or MAC layers

**"Wireless Control that Simply Works™"**

# Wireless Sensor (and Actuator) Networks

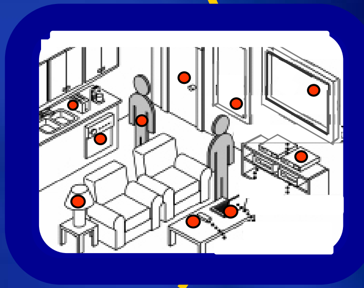


**Basic Requirement:**

**Provide the low rate, wireless interconnection of ultra low cost sensor/actuator/processing devices to enable the cyber-world to sense and affect the real physical environment.**

**Applications:**

- Industrial Control and Monitoring
- Environmental and Health Monitoring
- Home Automation, Entertainment and Toys
- Security, Location and Asset Tracking
- Emergency and Disaster Response



# IEEE 802.15.4/ZigBee Market Features

- Low power consumption
- Low cost
- Low offered message throughput
- Supports large network orders (<= 65k nodes)
- Low to no QoS guarantees
- Selectable levels of security (using AES-128)
  - Privacy (encryption)
  - Sender authentication
  - Message integrity
- Flexible protocol design suitable for many applications

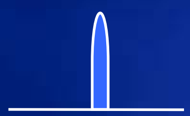
U.S. Department of Commerce, National Institute of Standards and Technology, Information Technology Laboratory, *Specification for the Advanced Encryption Standard (AES).* Federal Information Processing Standard Publication (FIPS PUB) 197. Springfield, VA: National Technical Information Service. 26 November 2001. http://csrc.nist.gov/CryptoToolkit/aes/.

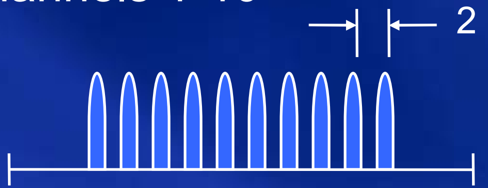
# 802.15.4 General Technical Characteristics

- Data rates of 250 kb/s (2.4 GHz) and 20/40 kb/s (868/915 MHz).
- 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz ISM band and one channel in the European 868 MHz band.
- CSMA-CA channel access.
- Fully handshaked protocol for transfer reliability.
- Extremely low duty-cycle (< 10 ppm) capability.
- Beaconless operation available.
- Support for low latency devices (Guaranteed Time Slots in star networks).
- Star or Peer-to-Peer network topologies supported.

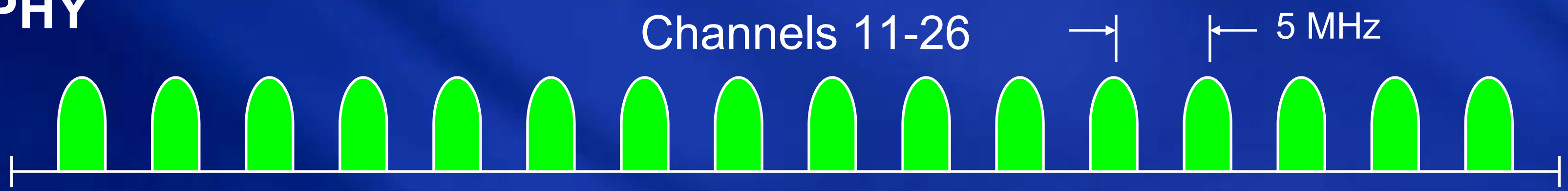
# The Two IEEE 802.15.4 PHY Layers

**868 MHz/**
**915 MHz**
**PHY**




**2.4 GHz**
**PHY**



# A Note About Cost

*Engineering is the art of building something for $1 that any idiot can build for $2.* – Anon.

- **Since ZigBee/802.15.4 networks are intended to be designed, built and operated largely by commercial interests, costs of ownership and operation will be a strong subtheme in this presentation.**

# IEEE 802.15.4 PHY Power Reduction Features



Ed Callaway 6 Nov 2003

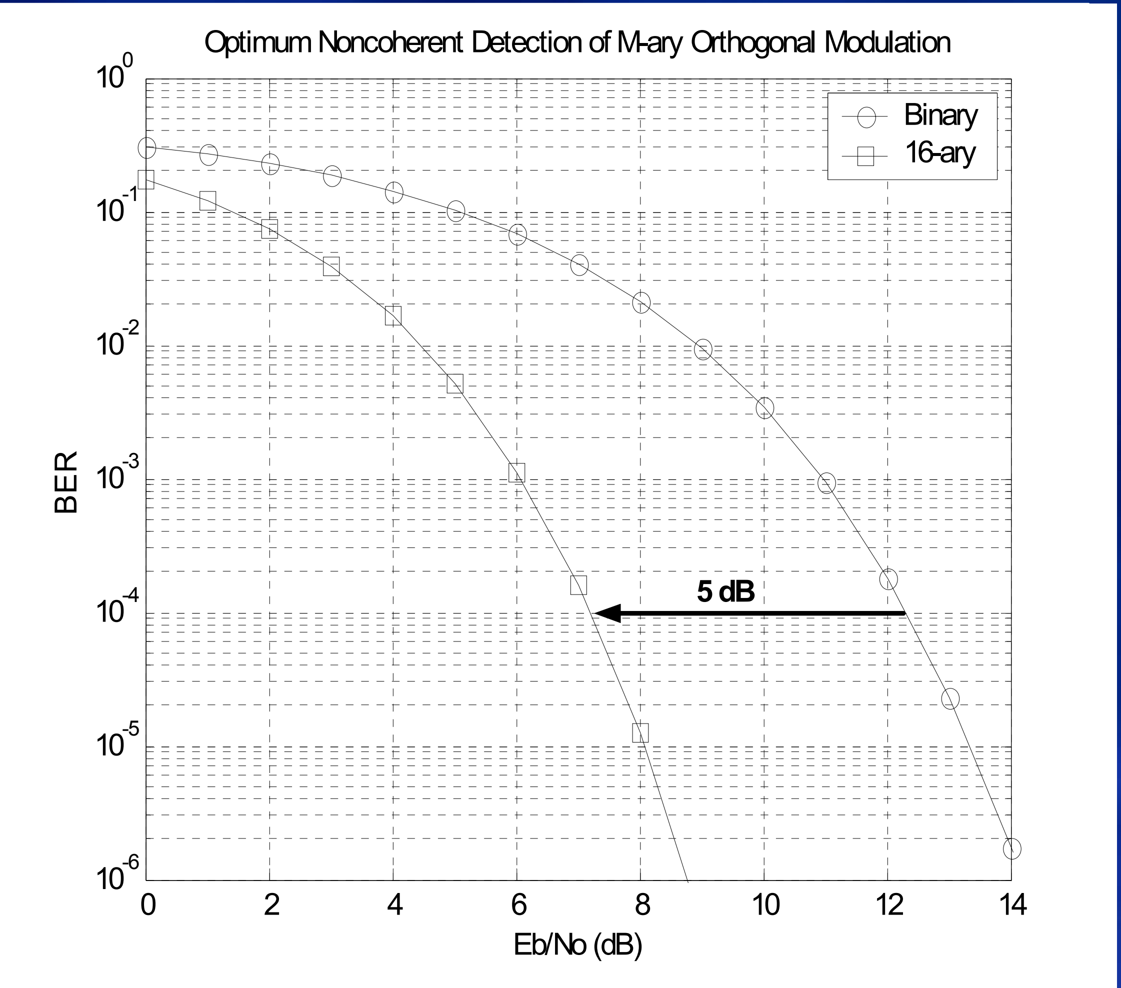
# Orthogonal multilevel Signaling

- Low $P_{avg}$ is achieved with a low overall system duty cycle, consistent with low peak currents
- At the physical layer, this encourages the use of a high data rate, but low symbol rate
  - Peak currents tend to track symbol rate, rather than data rate
- This implies the use of multilevel signaling
- However, simple multilevel signaling results in sensitivity loss that may defeat the low power goal
- Solution is the use of orthogonal signaling—trading bandwidth to recover sensitivity with coding gain

Isao Okazaki and Takaaki Hasegawa, Spread spectrum pulse position modulation and its asynchronous CDMA performance — a simple approach for Shannon's limit, *Proc. IEEE Sec. Intl. Symp. Spread Spectrum Techniques and Applications,* 1992, pp. 325–328.

# Sensitivity of binary and 16-ary Orthogonal Signaling

- 250 kbps (4 bits/symbol, 62.5 kBaud)
- Data modulation is 16-ary orthogonal modulation
- 16 symbols are pseudo-orthogonal set of 32-chip PN codes
- Chip modulation is O-QPSK at 2.0 Mchip/s (1 Mchip/s each in I and Q)




Jose A. Gutierrez, Edgar H. Callaway, Jr., and Raymond L. Barrett, Jr., *Low-Rate Wireless Personal Area Networks: Enabling Wireless Sensors with IEEE 802.15.4™. New York: IEEE Press. 2003. Chapter 4.*

# Warmup Power Loss Reduction

- Since the active periods of IEEE 802.15.4 nodes can be very short, significant power can be lost if the transceiver warmup time is long
- Warmup time can be dominated by the settling of transients in the signal path, especially the (integrated active) channel filters
- Wideband techniques, such as Direct Sequence Spread Spectrum (DSSS), have an advantage in that their wide channel filters have inherently short settling times
- With their greater channel spacing, DSSS frequency synthesizers may also employ higher frequency references, reducing lock time

Eugene Shih et al., Physical layer driven protocol and algorithm design for energy efficient wireless sensor networks, *Proc. MOBICOM,* 2001, pp. 272–287.

Andrew Y. Wang et al., Energy efficient modulation and MAC for asymmetric RF microsensor systems, *IEEE Intl. Symp. Low Power Electronics and Design,* 2001, pp. 106–111.

# Additional Features of the IEEE 802.15.4 PHY

- Constant-envelope modulation: Use of half-sine shaped O-QPSK simplifies Tx PA design and reduces active current
- No duplex operation: Reduces peak current
- Rx blocking spec reduced: Allows lower active power consumption of Rx front end
- Appropriate carrier frequency: Avoided use (for now) of the 60 GHz ISM band due to cost, power consumption concerns
- Low power output acceptable: Must be "capable" of -3 dBm $P_{out}$, but can reduce as desired in operation

# Tx vs. Rx Power Drain

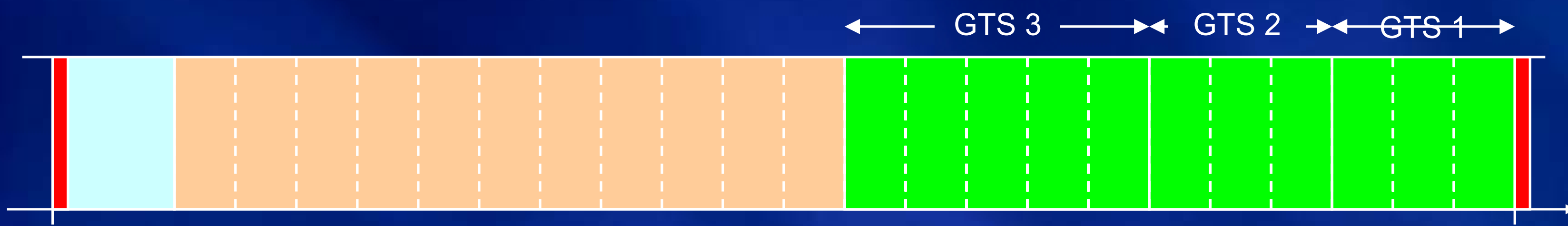
- There is little point to reduce Tx $P_{out}$ below 0 dBm (1 mW) or so to reduce power consumption, since practical implementations will require ~10 mW fixed power just to run frequency synthesizers, etc., regardless of power output
- In these low-power systems, **Rx active power is often greater than Tx active power**, due to the larger number of signal processing circuits that must be active in receivers
- This can have a significant effect on power consumption strategies: **It's more power-efficient to blindly transmit than to blindly receive**—for the same amount of time

# IEEE 802.15.4 MAC Power Reduction Features



Ed Callaway 6 Nov 2003

# MAC Optional Superframe




$15.36\ \text{ms} * 2^n$
where $0 \le n \le 14$

| | |
|---|---|
| Network beacon | Transmitted by network coordinator. Contains network information, frame structure and notification of pending node messages. |
| Beacon extension period | Space reserved for beacon growth due to pending node messages |
| Contention period | Access by any node using CSMA-CA |
| Guaranteed Time Slot | Reserved for nodes requiring guaranteed bandwidth. |

**A beaconless, superframe-less mode is also available.**

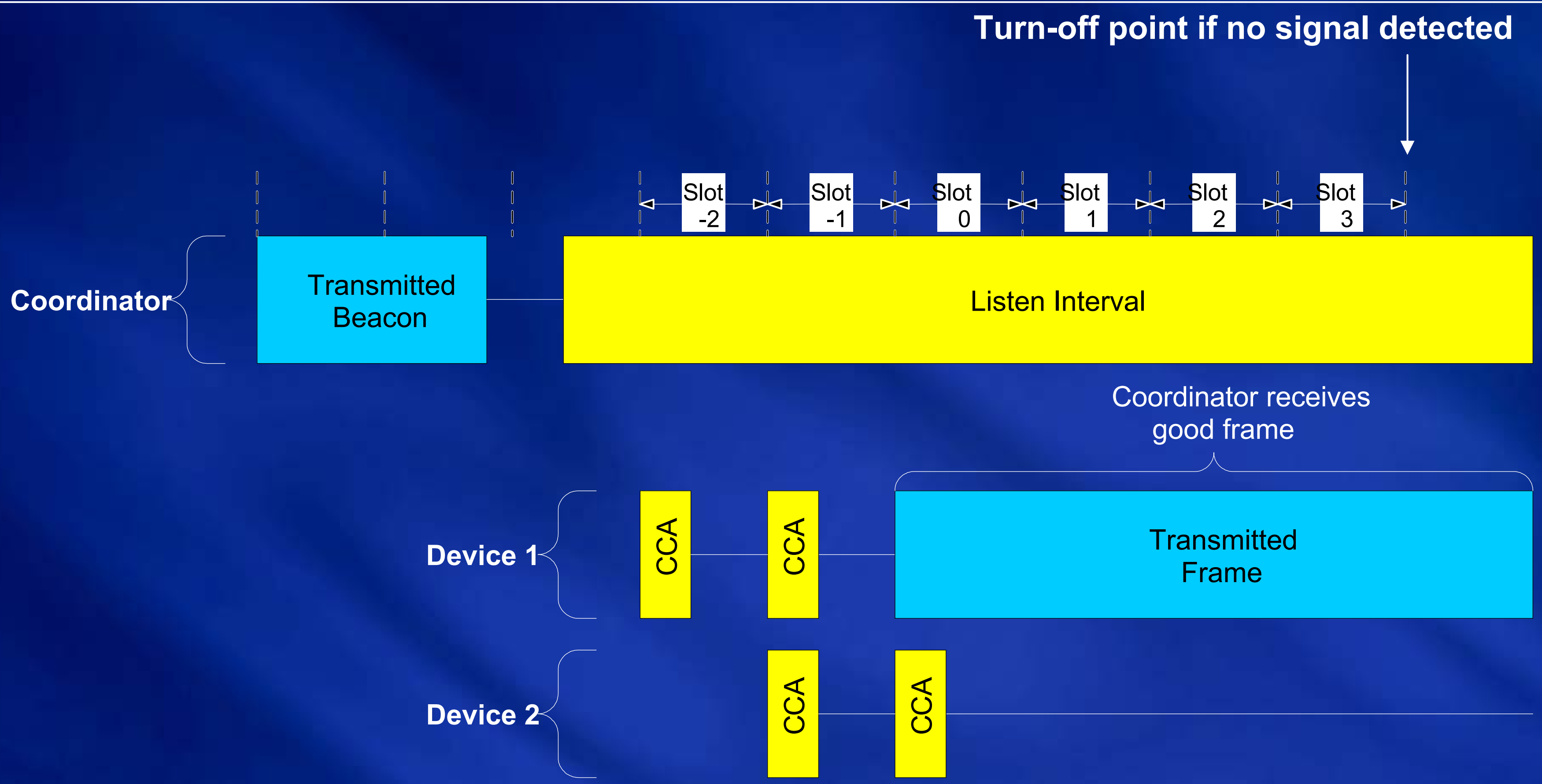
# Beaconless Mode

- An asymmetrical channel access mode for asymmetrically powered devices
- Textbook case is wireless light switch operating a lamp
  - Lamp has mains power and therefore can be in near-constant receive mode
  - Switch is battery powered; stays in standby until pressed by user, when it transmits

# CSMA-CA vs. Polling

- For low offered traffic applications, activity associated with polling can create a lower bound on attainable duty cycle and, therefore, power consumption
- In "conventional" CSMA-CA, most power consumption is due to the receiver, due to the long monitoring periods required to support operation during high offered traffic periods
- IEEE 802.15.4 supports a "Battery Life Extension" (BLE) mode, in which the CSMA-CA backoff exponent is limited to the range 0-2
- This greatly reduces receiver duty cycle in low offered traffic applications

# BLE Mode




Using BLE with n = 14 (beacon period = 251.65824 s), total system duty cycle (both Tx and Rx) can be less than 10 ppm.

# The Recovery Effect in Batteries

- All types of batteries exhibit a recovery effect, in which their lifetimes may be extended if current is drawn from them in bursts, rather than an equivalent average current
- The shorter the burst, the more battery life is extended
- This effect is used to advantage in low-power communication protocols, such as IEEE 802.15.4


S. Okazaki, S. Takahashi, and S. Higuchi, Influence of rest time in an intermittent discharge capacity test on the resulting performance of manganese-zinc and alkaline manganese dry batteries, *Progress in Batteries & Solar Cells,* 1987, v. 6, pp. 106–109.

C. F. Chiasserini and R. R. Rao, A model for battery pulsed discharge with recovery effect, *Proc. Wireless Commun. Networking Conf.,* 1999, v. 2, pp. 636–639.

C. F. Chiasserini and R. R. Rao, Routing protocols to maximize battery efficiency, *Proc. MILCOM,* 2000, v. 1, pp. 496–500.

# ZigBee NWK Power Reduction Features



Ed Callaway 6 Nov 2003

# Routing Algorithm

- **The cost-based routing algorithm in ZigBee 1.0 employs both link quality and hop count**
  - Attempts to maximize quality of the end-to-end communication link (minimizing hop count while avoiding poor-quality links)
  - Reduces power consumption by minimizing message retransmissions and repeated route discovery routines
- **Future releases likely will include specific power metrics in the cost function**
  - Node power remaining
  - Node power source (mains, battery, etc.)
  - Transmitter $P_{out}$
  - Etc.

Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris, A high-throughput path metric for multi-hop wireless routing, *Mobicom '03*, September 2003.

# Power-Reduction Techniques Supported by, but not Part of, IEEE 802.15.4/ZigBee



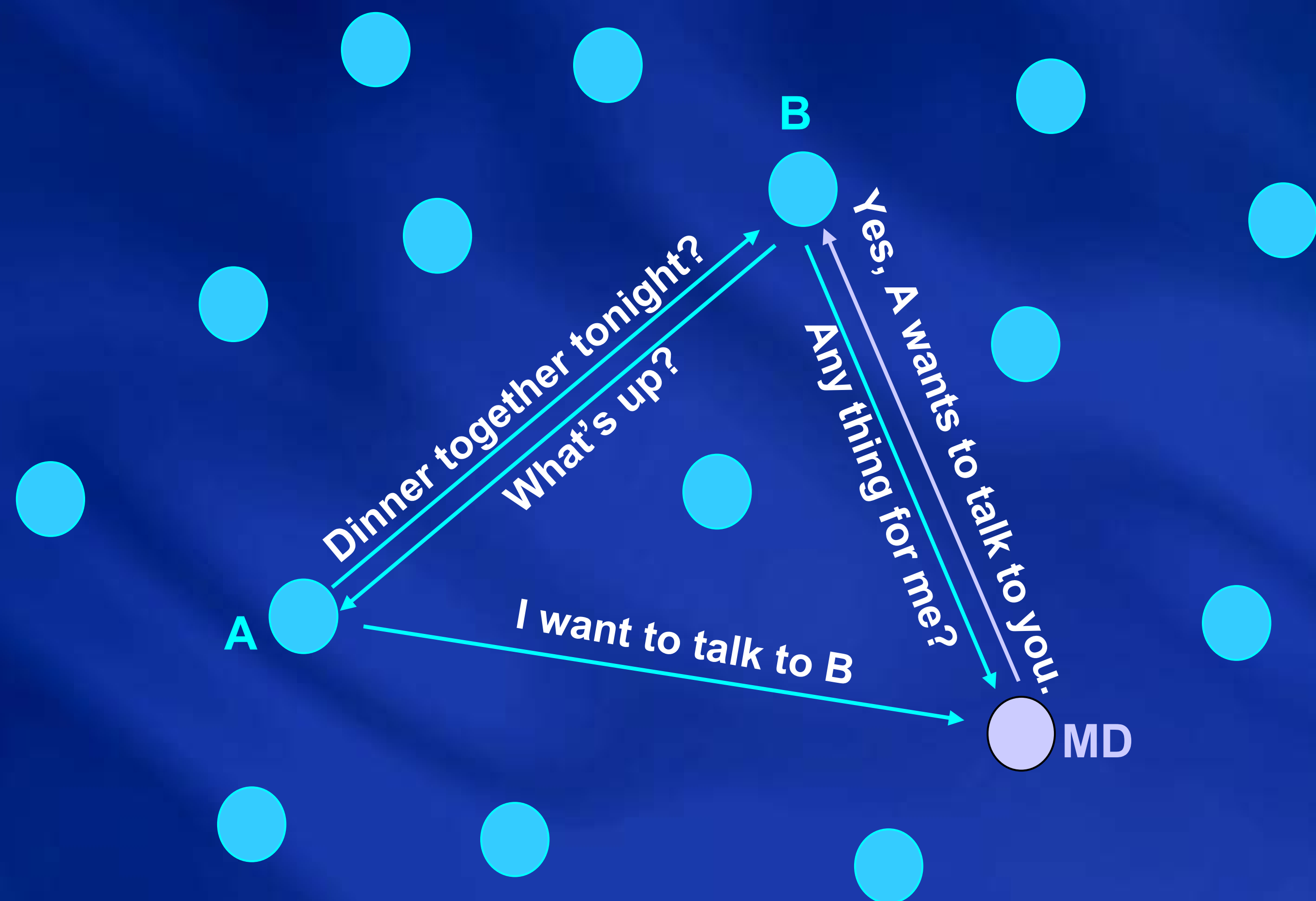
Ed Callaway 6 Nov 2003

# MAC Synchronization in Multi-hop networks

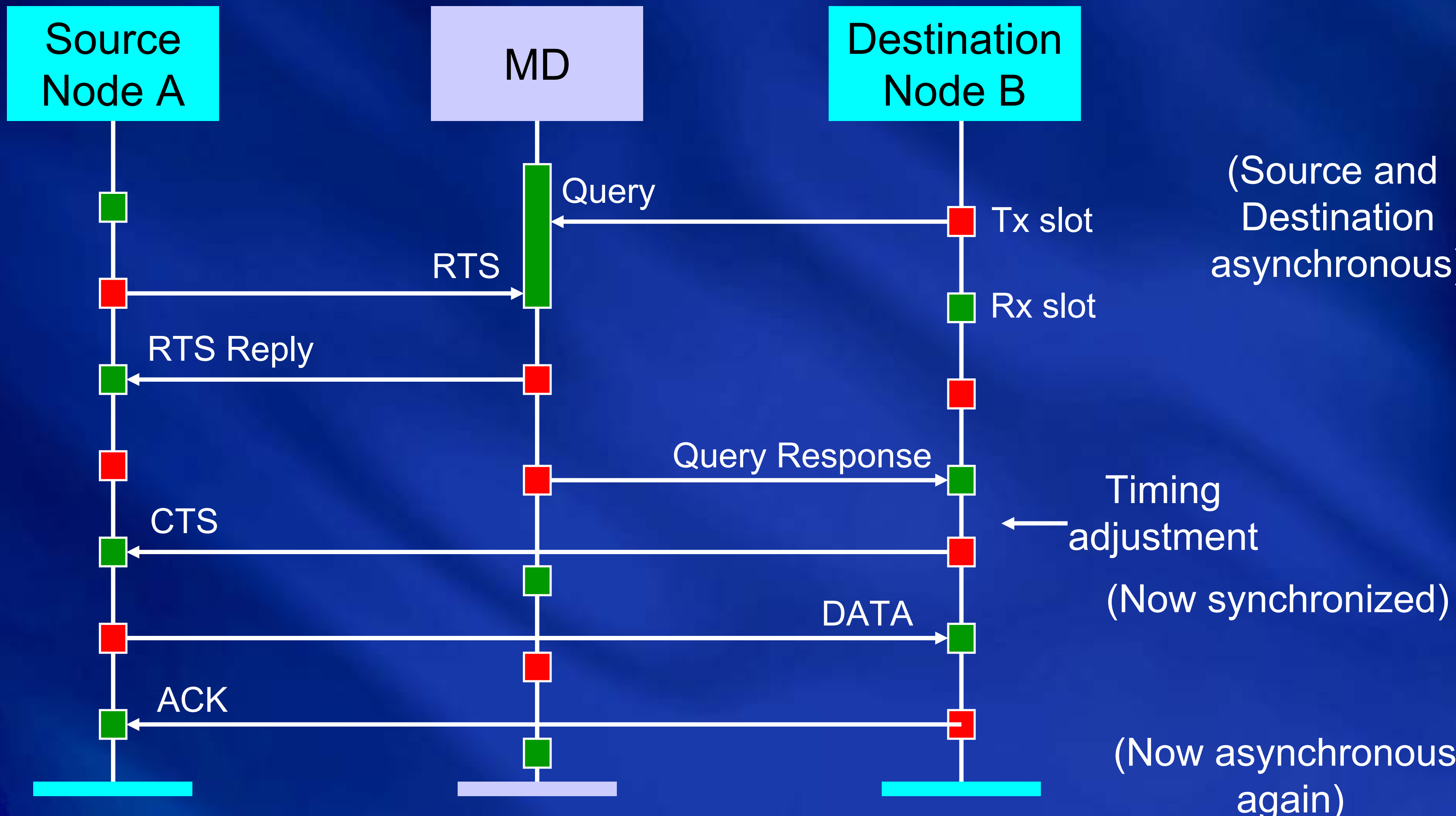
- **Global synchronization is difficult in ad hoc multi-hop networks**
- **Problem is exacerbated by low device duty cycle**
- **A solution is to draw an analogy to the telephone answering machine**
  - **Caller leaves message, saying when he will be available to receive a return call**
  - **Recipient returns call at the appointed time, the two parties are (temporarily) synchronized, and communication takes place**
  - **After the call, the parties lose synchronization again**
- **We call this process "dynamic synchronization"**

Qicai Shi and Edgar H. Callaway, An ultra-low power protocol for wireless networks, *Proc. 5th World Multi-Conference on Systemics, Cybernetics and Informatics,* 2001, v. IV, pp. 321–325.

# The (Dedicated) Mediation Device



# Mediation Device Operation



# The Distributed Mediation Device

- **Mediation device functionality may be distributed among all network nodes**
- **Each network node enters "MD mode" periodically**
  - **Period is relatively long, so that total duty cycle of any individual node is not adversely affected**
- **Exploits dense nature of many wireless sensor networks, plus low offered throughput and message latency requirements**
  - **In a dense network, the likelihood that a neighbor is (or will soon be) in MD mode when a message is generated is relatively high**

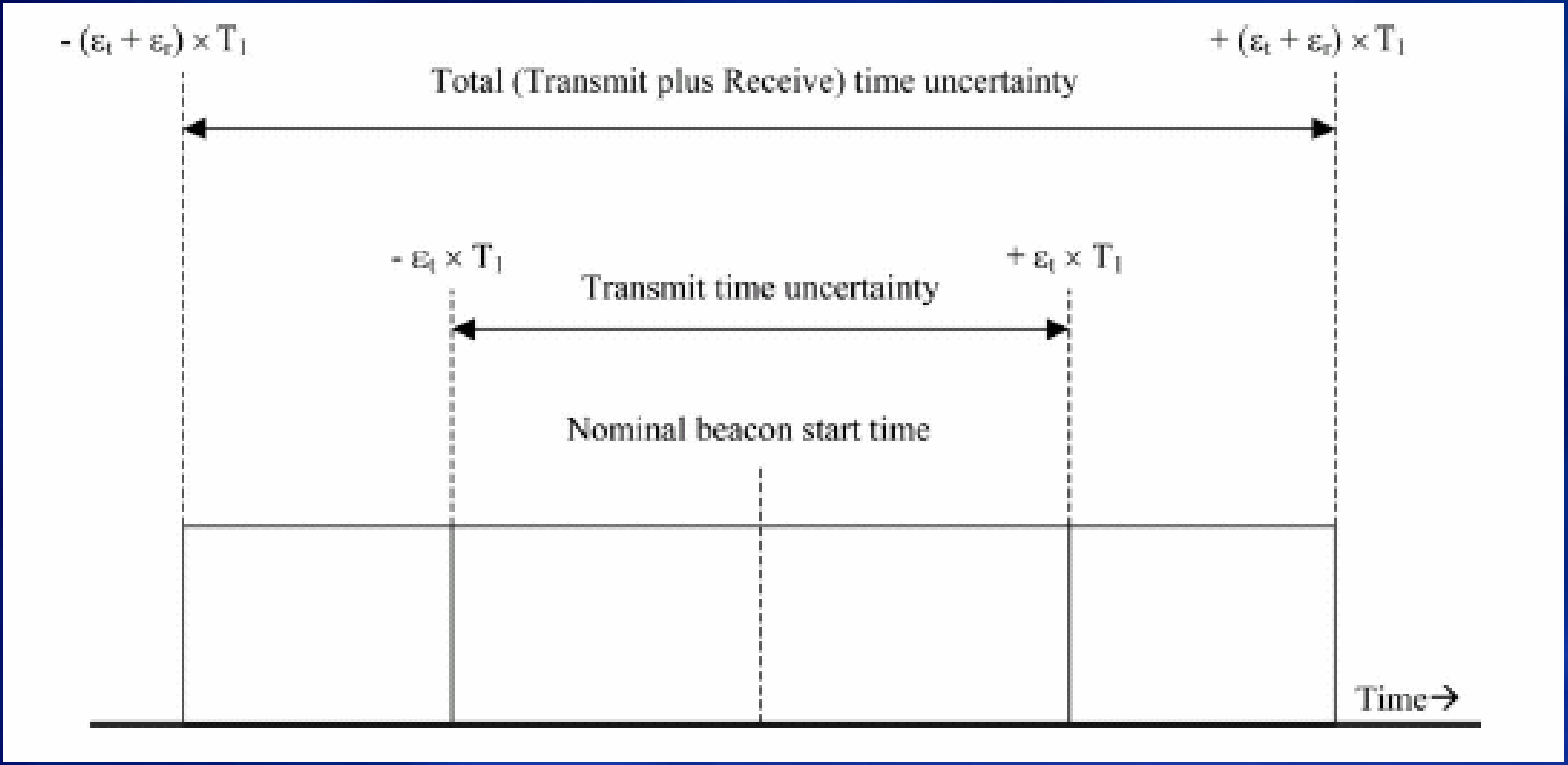
Edgar H. Callaway, Jr., *Wireless Sensor Networks: Architectures and Protocols*. New York: Auerbach Publications (an imprint of CRC Press). 2003. pp. 74-84.

# Power-Conscious Implementation

# Effect of Time Base Accuracy on Duty Cycle

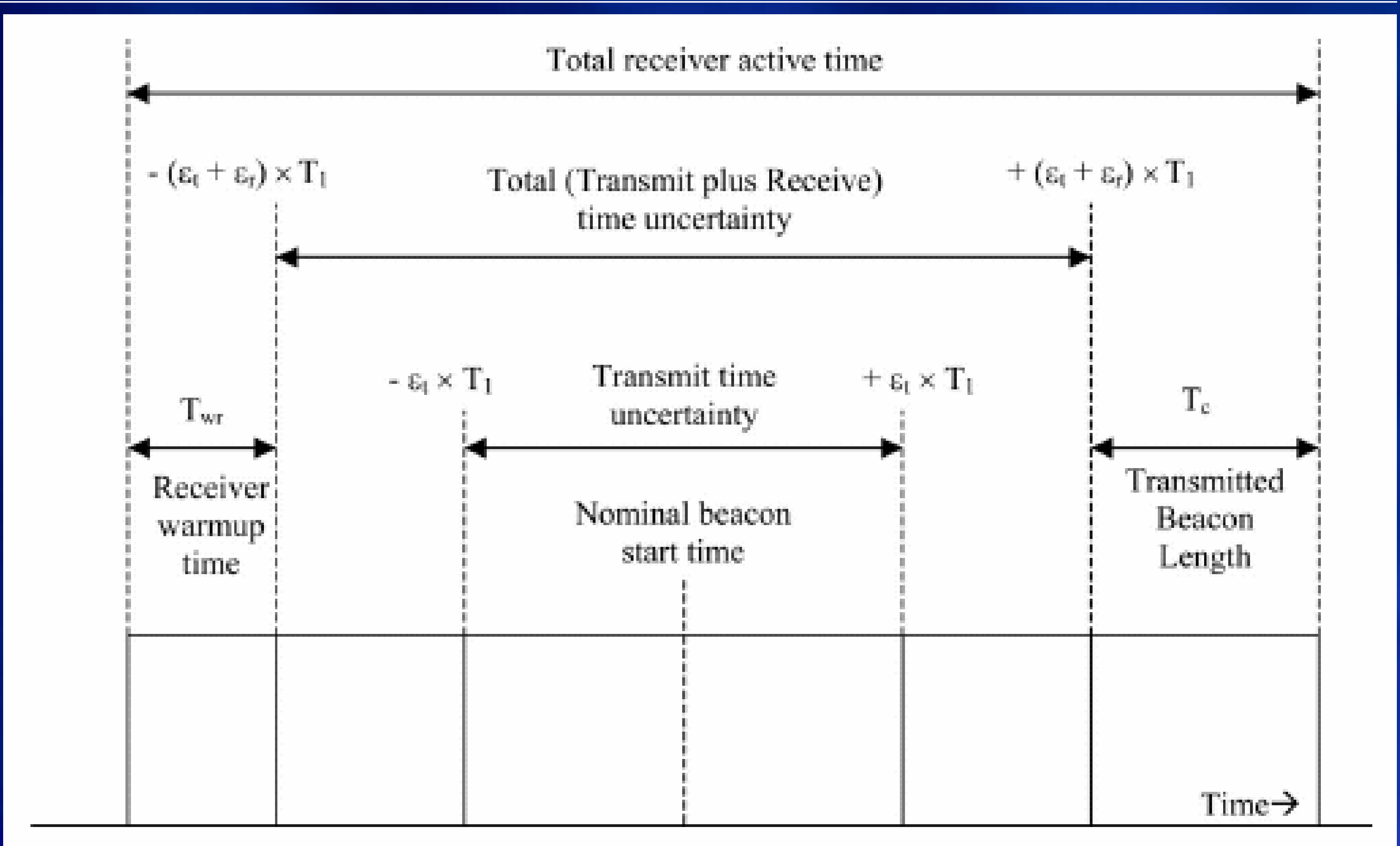
- To receive a scheduled transmission, the receiver must be on at the appointed time
- However, the receiver's time base is of finite accuracy, and this accuracy may be none too good, due to product cost concerns
- In an ad hoc network, a similar situation exists at the transmitter
- The resulting time uncertainty forces the receiver to turn on "early," in order to avoid missing the desired transmission
- This "extra" receiving time can dominate power consumption figures

# Beacon Start Time Uncertainty Stackup




Edgar H. Callaway, Jr., *Wireless Sensor Networks: Architectures and Protocols*. New York: Auerbach Publications (an imprint of CRC Press). 2003. pp. 130-135.

# Receiver Active Time



# Time Base Error Mitigation

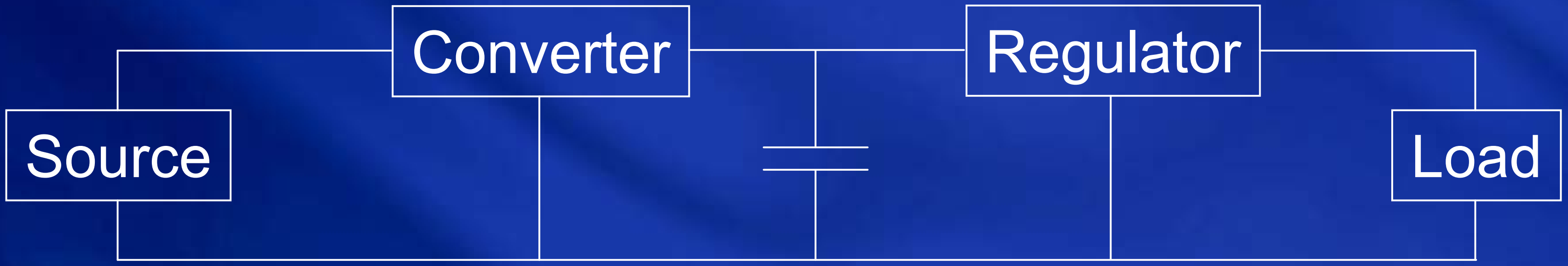
- A learning algorithm may be employed
  - Algorithm tracks the apparent time offset at the receiver, then starts the receiver warmup $T_{buffer}$ seconds early (to provide some margin for error)
- However, note that many ZigBee nodes may be small, with very low heat capacity (thermal inertia)
  - Nodes may have large changes of temperature in the time between beacons, especially for high ($n > 10$) beacon orders
  - May result in large timing errors (greater than $T_{buffer}$) and loss of packet
  - Even a packet-to-packet timing drift specification will not help, since performance is limited by time base temperature stability

# Matching Power Source and Load

- Many power sources are available
  - Batteries (many types)
  - Energy scavenging (again, many types)
- Each source has unique characteristics
  - $I_{avg}$, $I_{peak}$, $V_{out}$, $R_{out}$, …
- Each load has unique characteristics
  - $I_{avg}$, $I_{peak}$, $V_{in}$, $R_{in}$, …
- Source characteristics should be matched to the load for best power efficiency (i.e., to minimize power conditioning/converting inefficiency)

# Power Conditioning of Scavenged Sources

- **Most energy scavenging sources have $V_{out}$ < 1 V; low $I_{peak}$**
  - **Photovoltaic**
  - **Vibration**
  - **Etc.**
- **System efficiency is maximized when load can be supplied from < 1 V, too**
  - **Eliminates converter/conditioning loss**
  - **Minimizes digital power consumption**




Conditioning energy storage element

# Conclusion

The IEEE 802.15.4 / ZigBee communication protocol offers a wide variety of power-conservation features, at all layers of the protocol stack

In addition to the features in the protocol proper, ZigBee is flexible enough to meet the needs of many commercial applications. It can also perform as a test bed for power conservation algorithm research

# Bibliography (1)


Institute of Electrical and Electronics Engineers, Inc., IEEE Std. 802.15.4-2003, IEEE Standard for Information Technology — Telecommunications and Information Exchange between Systems — Local and Metropolitan Area Networks — Specific Requirements — Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs). New York: IEEE Press. 2003.

http://www.zigbee.org

U.S. Department of Commerce, National Institute of Standards and Technology, Information Technology Laboratory, *Specification for the Advanced Encryption Standard (AES).* Federal Information Processing Standard Publication (FIPS PUB) 197. Springfield, VA: National Technical Information Service. 26 November 2001. http://csrc.nist.gov/CryptoToolkit/aes/.

Isao Okazaki and Takaaki Hasegawa, Spread spectrum pulse position modulation and its asynchronous CDMA performance — a simple approach for Shannon's limit, *Proc. IEEE Sec. Intl. Symp. Spread Spectrum Techniques and Applications,* 1992, pp. 325–328.

Jose A. Gutierrez, Edgar H. Callaway, Jr., and Raymond L. Barrett, Jr., *Low-Rate Wireless Personal Area Networks: Enabling Wireless Sensors with IEEE 802.15.4™. New York: IEEE Press. 2003.*

Eugene Shih et al., Physical layer driven protocol and algorithm design for energy efficient wireless sensor networks, *Proc. MOBICOM,* 2001, pp. 272–287.

Andrew Y. Wang et al., Energy efficient modulation and MAC for asymmetric RF microsensor systems, *IEEE Intl. Symp. Low Power Electronics and Design,* 2001, pp. 106–111.

# Bibliography (2)

S. Okazaki, S. Takahashi, and S. Higuchi, Influence of rest time in an intermittent discharge capacity test on the resulting performance of manganese-zinc and alkaline manganese dry batteries, *Progress in Batteries & Solar Cells,* 1987, v. 6, pp. 106–109.

C. F. Chiasserini and R. R. Rao, A model for battery pulsed discharge with recovery effect, *Proc. Wireless Commun. Networking Conf.,* 1999, v. 2, pp. 636–639.

C. F. Chiasserini and R. R. Rao, Routing protocols to maximize battery efficiency, *Proc. MILCOM,* 2000, v. 1, pp. 496–500.

Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris, A high-throughput path metric for multi-hop wireless routing, *Mobicom '03*, September 2003.

Qicai Shi and Edgar H. Callaway, An ultra-low power protocol for wireless networks, *Proc. 5th World Multi-Conference on Systemics, Cybernetics and Informatics,* 2001, v. IV, pp. 321–325.

Jose A. Gutierrez et al. IEEE 802.15.4: A developing standard for low-power, low-cost wireless personal area networks, *IEEE Network,* v. 15, n. 5, September/October 2001, pp. 12–19.

Ed Callaway et al., Home networking with IEEE 802.15.4: a developing standard for low-rate wireless personal area networks, *IEEE Commun. Mag.,* v. 40, n. 8, August 2002, pp. 70–77.

Edgar H. Callaway, Jr., *Wireless Sensor Networks: Architectures and Protocols*. New York: Auerbach Publications (an imprint of CRC Press). 2003.