REAL-TIME NETWORKS Wireless sensor networks (aka Internet of Things – IoT)

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Jaquet-Droz 1, 2007 Neuchâtel

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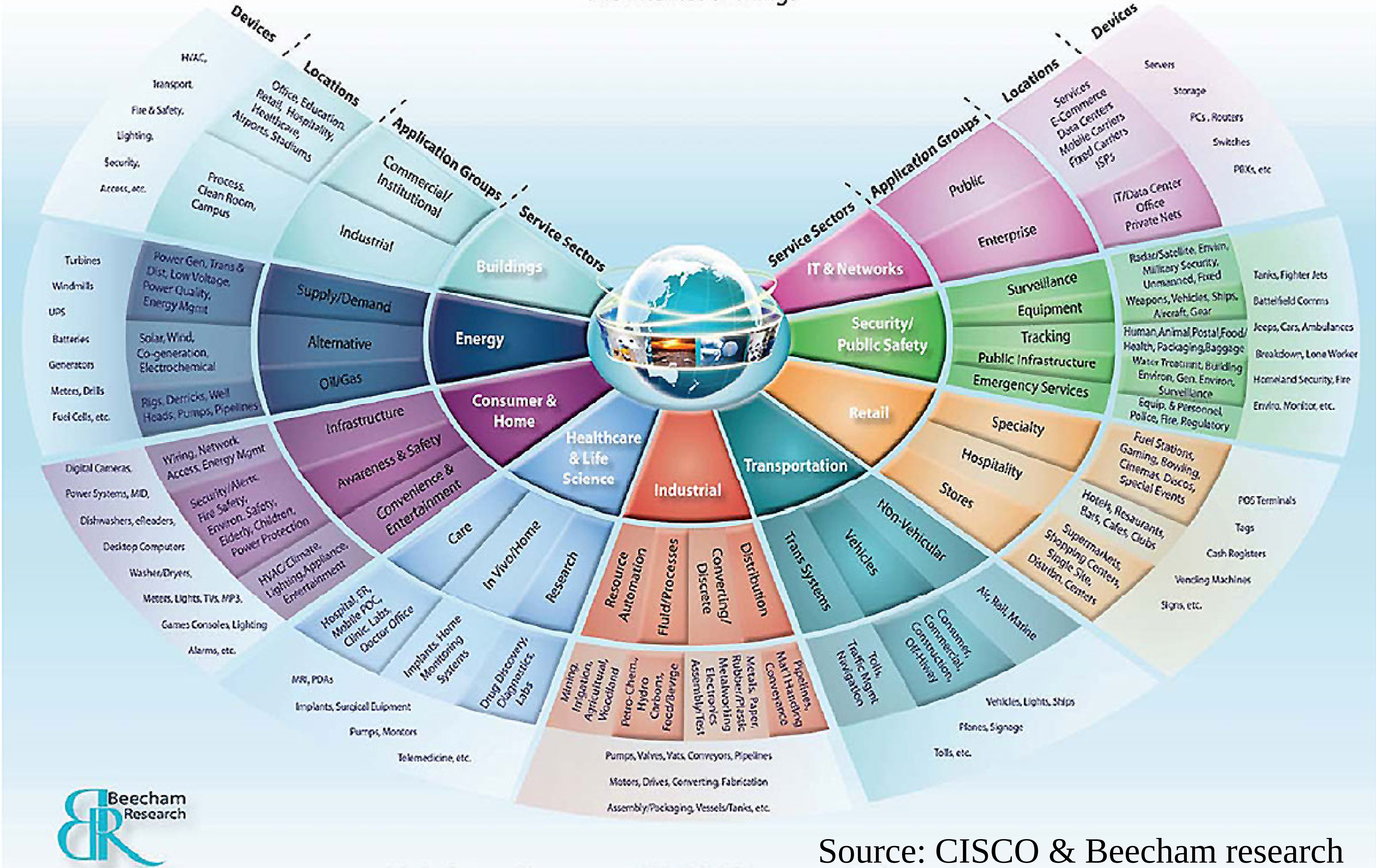
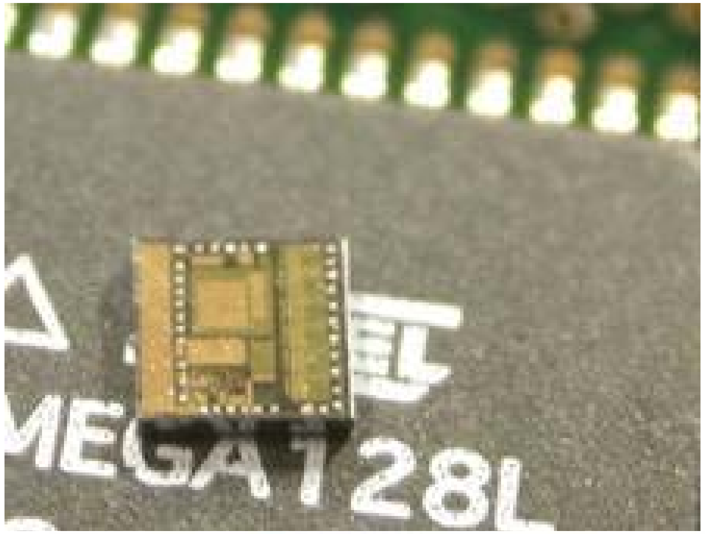
A new device has been found
Run Auto-configuration?
Start
Cancel

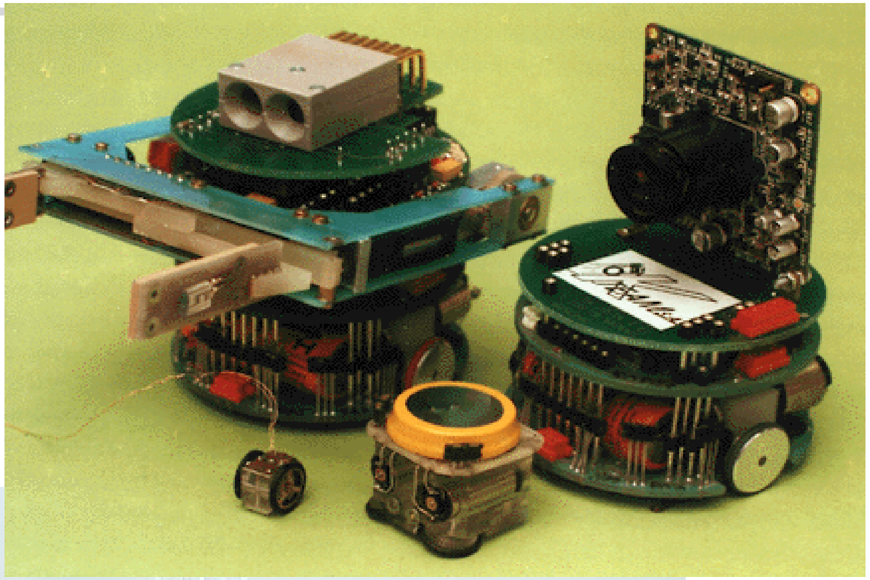
The Internet of Things

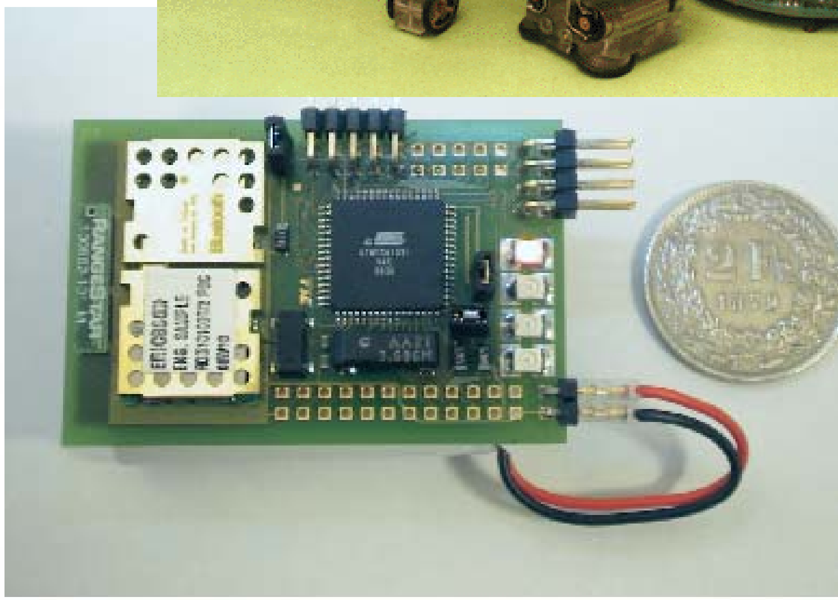


Source: CISCO & Beecham research

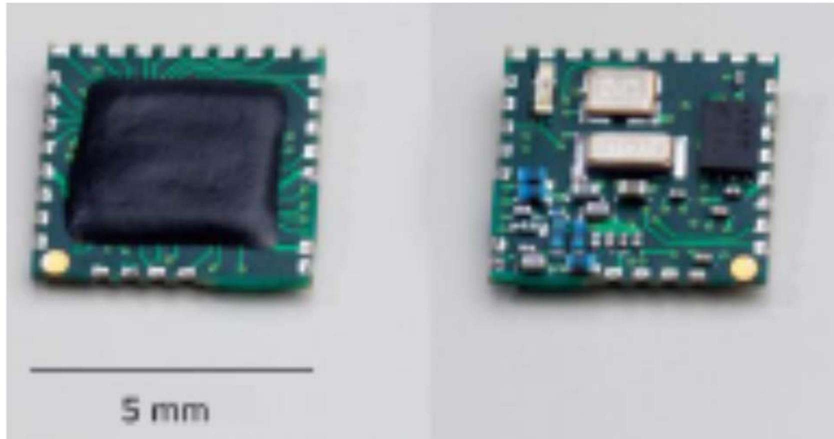
Y2K devices: Motes, BT nodes, Smart-Its, Cyclope, …

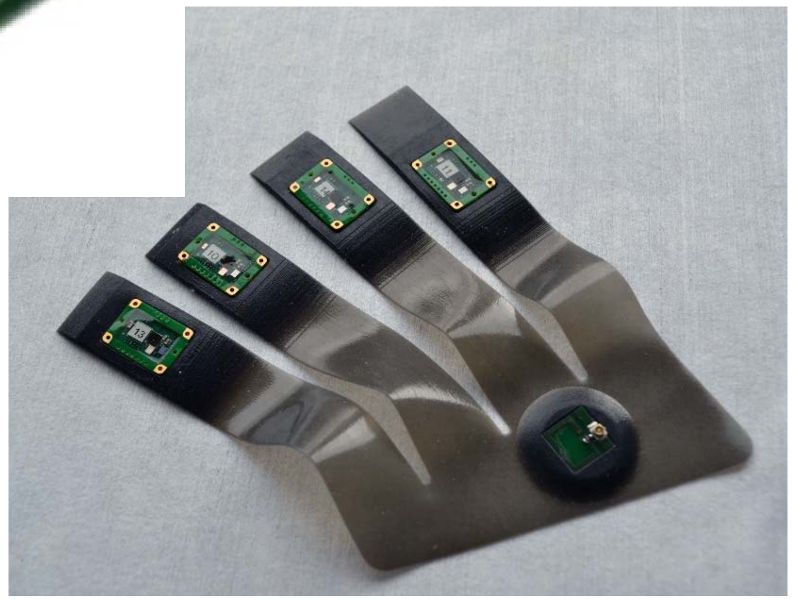






More recent example





Source: CSEM

Outline

- Characteristics of wireless transmission
- Features of wireless sensor networks
- Medium access control schemes for WSNs
- WiseMAC
- Comparison with other protocols
- Conclusion

Characteristics of radio transmission

- higher BER
- lower signalling rate
- limited possibility to detect collisions
- low spatial reuse
- prone to interference
- lower distances
- security concerns
- remote powering

- radio transmission
  - fading
  - incompatible regulations
  - higher cost
  - longer turn on and switching times
  - hidden terminal effect
- light transmission
  - line of sight
  - sensitive to heat
  - health concerns

Wireless tx properties implications

- MAC
  - master-slave (switching time ⇒ longer timeouts)
  - bus arbiter (hidden node ⇒ limitation in broadcast, reliable detection of silence ⇒ BA redundancy)
  - tokens (hidden node ⇒ token loss, switching time ⇒ longer timeouts)
  - virtual token (reliable detection of silence ⇒ token passing)
  - CSMA (no collision detection ⇒ use timeouts)
  - TDMA (switching time ⇒ longer gaps)

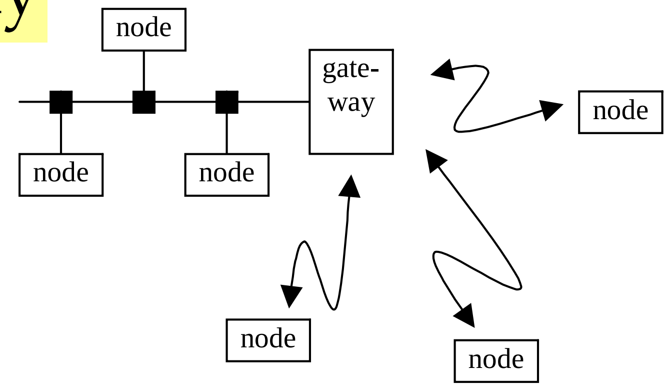
Implications of wireless tx prop (2)

- Error recovery
  - immediate retransmission
    - lower bandwidth, impact on higher layers
  - no immediate retransmission (cyclic transmission)
    - likelihood that errors will last
  - use forward error correction codes to lower apparent FER

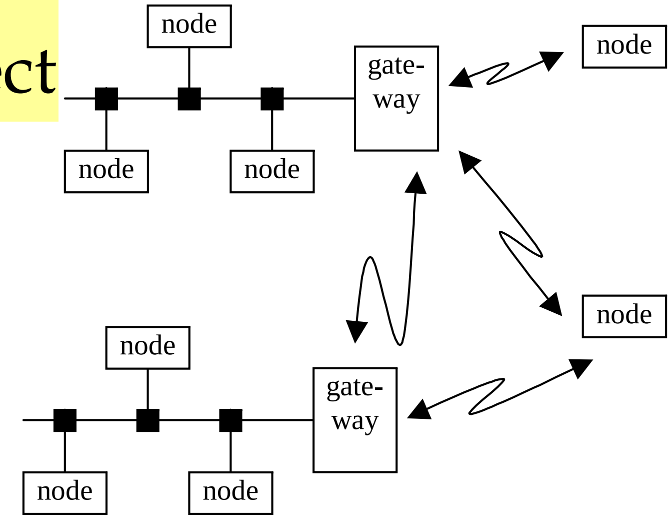
source: Ph. Morel, EPFL 1996

Examples of mixed architecture

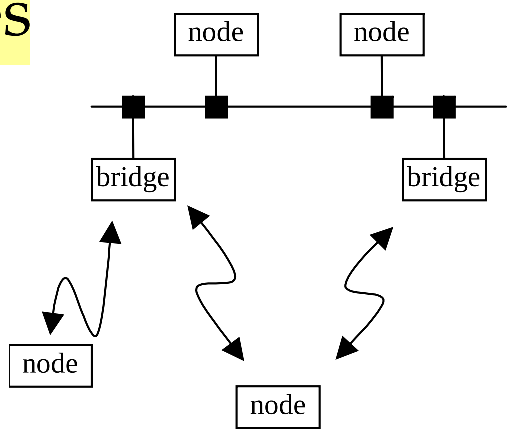
gateway



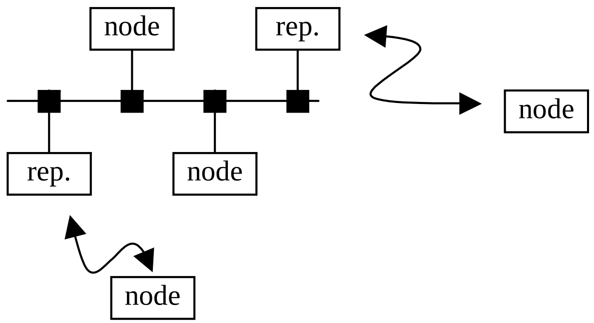
gateway interconnect



isolated nodes



repeater



source: Decotigne et al., FeT'2001

Possible architectures

- single or multiple wireline segments
- single or multiple wireless cells
- single or multiple points of connection
- connection through repeater, bridge, router or gateway
- ad hoc (self organising) wireless cell or base station
- single hop / multiple hops
- use of satellites

Approaches

- put a wireless physical layer to an existing solution
  - IEC 61158 fieldbus standard
  - ESPRIT project OLCHFA
  - LON
  - European Project R-Fieldbus
- adapt (or use) an existing wireless solution
- build a new solution

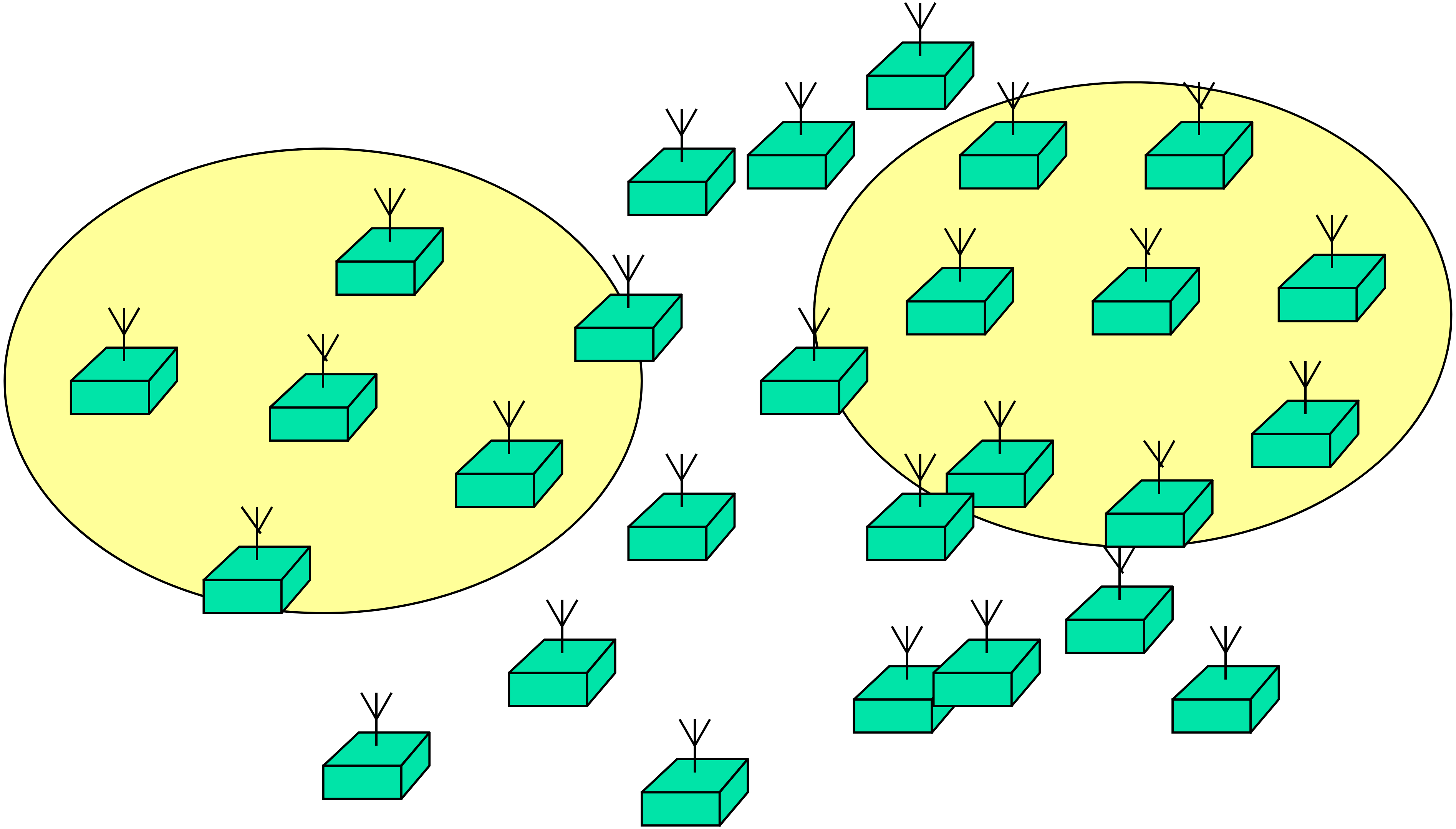
The change cannot be done so easily. It implies a number of changes at higher layers

Use an existing solution

- Radio modems
- Bluetooth
- ZigBee
- 802.11
- DECT
- IrDA
- Proprietary (Ant+, ..

Solutions can be used to solve a
number of problems,
but none fulfills entirely
the requirements
(additions are needed)

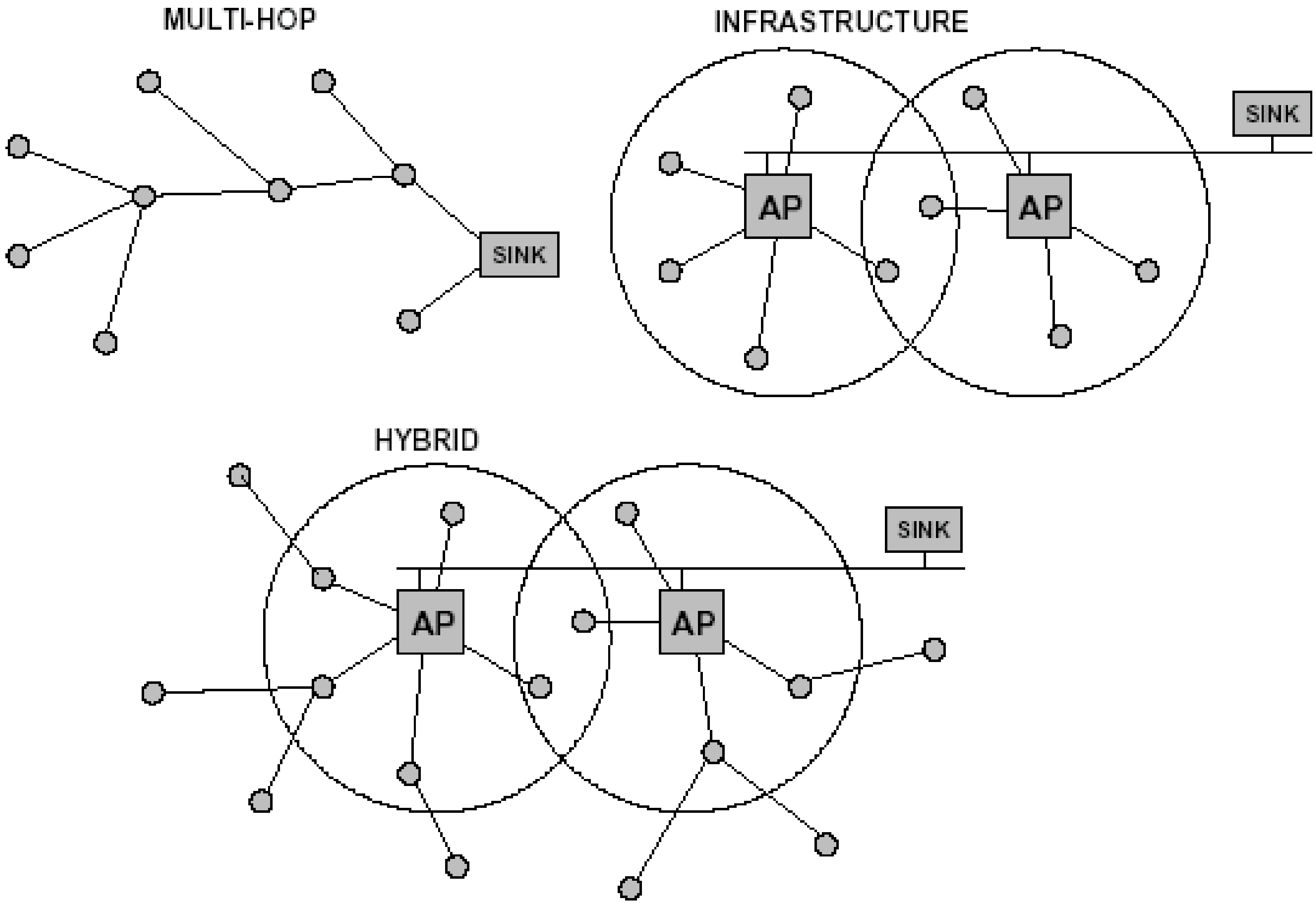
Wireless Sensor Networks



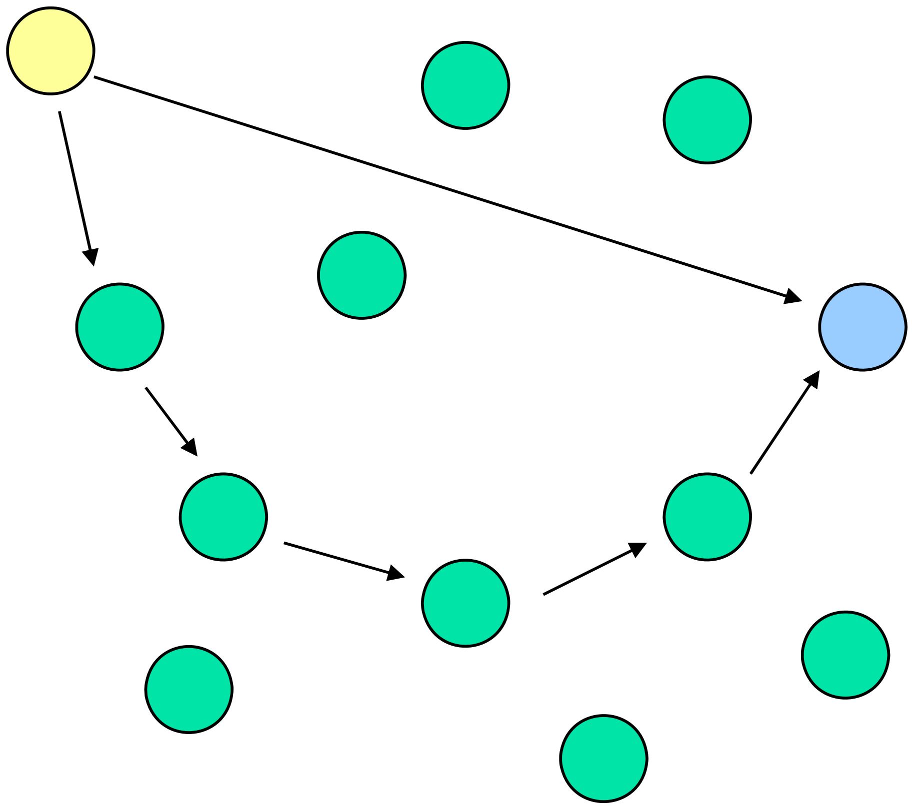
WSN expected features

- self organized
- no infrastructure (no base station, etc.)
- battery operated (low energy)
- multihop transmission
- small (< $1cm^3$), low cost (target <0.5$)
- low data rate (up to 10 Kbit/s/node)
- large number of nodes (0.05 to 1 nodes/m^2)
- sensor information temporal consistency

Topologies



The energy problem



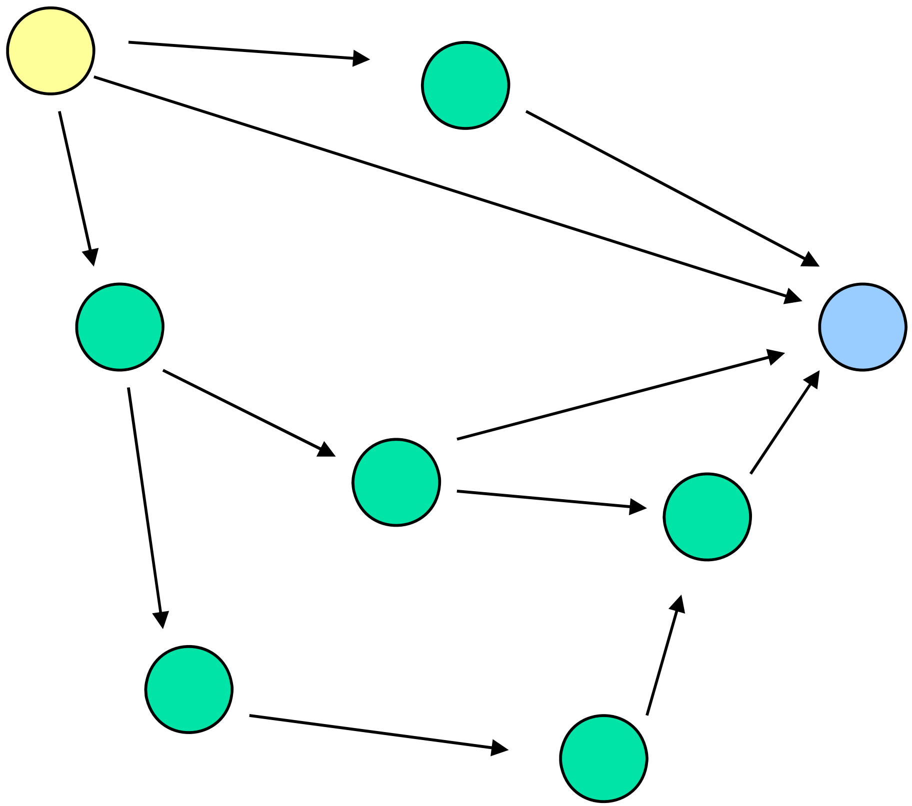
- 1 hop over 50m
  - 1.25 nJ/bit (thermal limit)
- 5 hops of 10m each
  - 5 x 2 pJ/bit = 10 pJ/bit

Assumes ~R^4 losses

ignores overhead and retransmissions

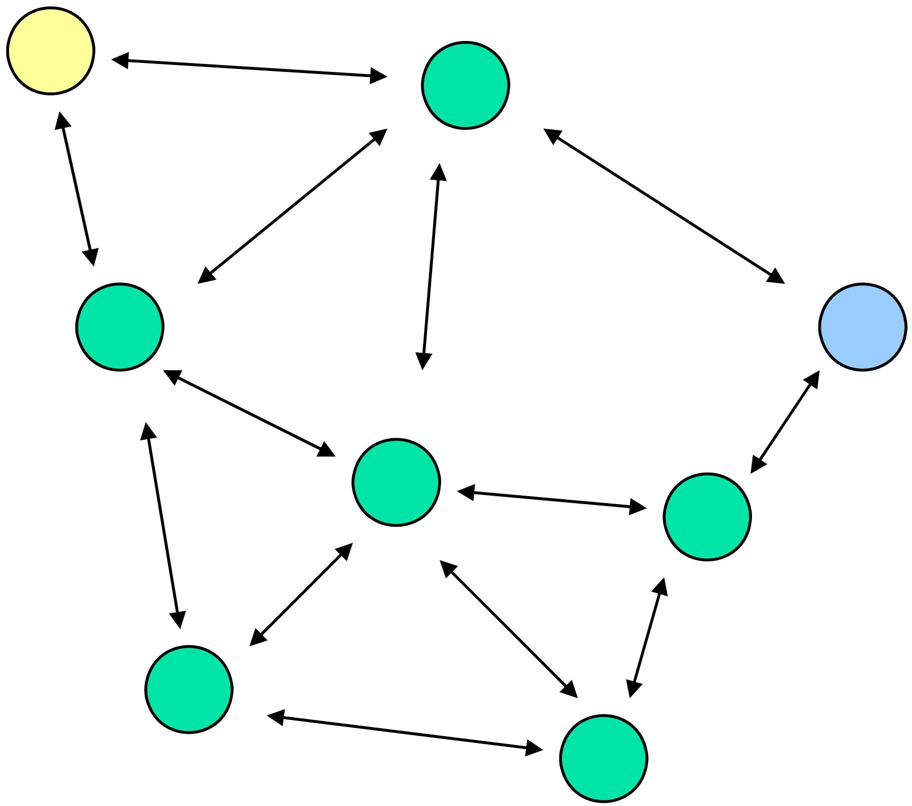
source: J. Rabaey, UCB

Fading and reliability



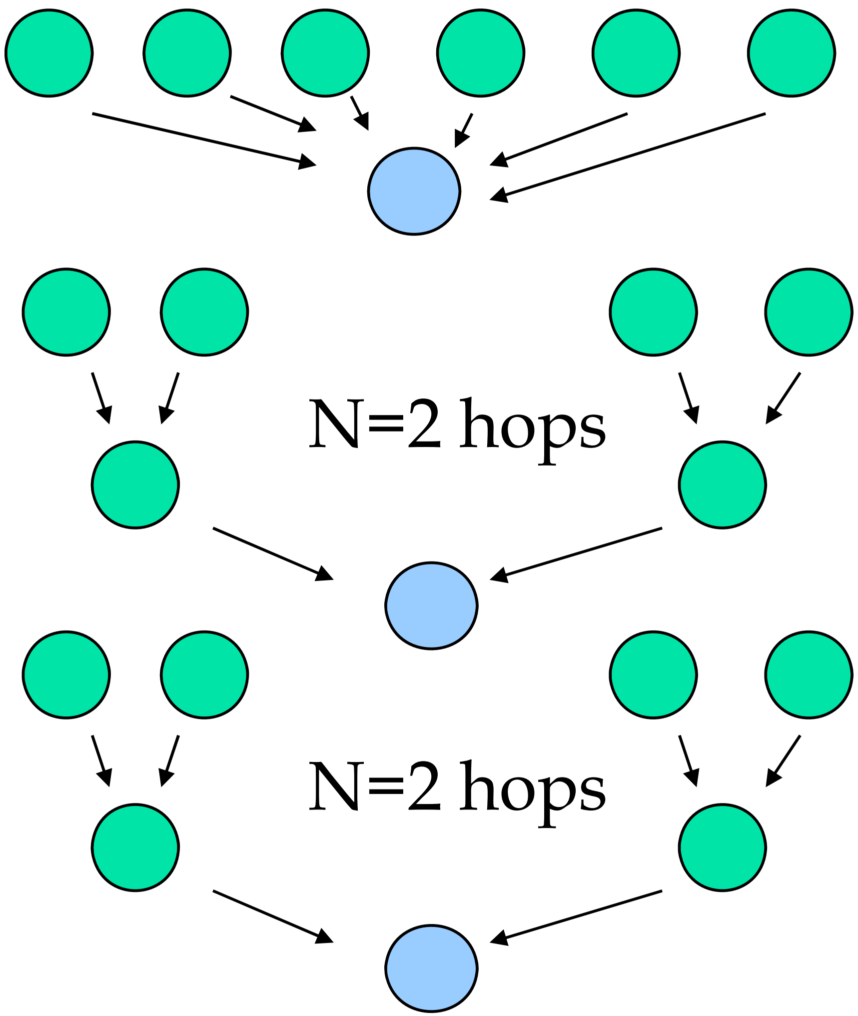
- Fading
  - There will exist multiple paths
- Reliability
  - multiple paths
  - no central point of failure
  - node redundancy

Localization



- relative positioning
- need for some know points (anchor points)

What about delay ?



- 2^{N+1}-2 sensors
- time for one message

$$D = T_{sync} + (L_o + L_M)T_{bit}$$

- central consumer, direct link

$$T = (2^{N+1} - 2)D$$

- central consumer multihop
  - serialized

$$T = (2^{N+1} - 2)D + \left((N-1)2^{N+2} + 4\right)L_M T_{bit}$$

  - in parallel

$$T = 2ND + 4L_M T_{bit}\left(2^N - N - 1\right)$$

Some Projects on WSNs

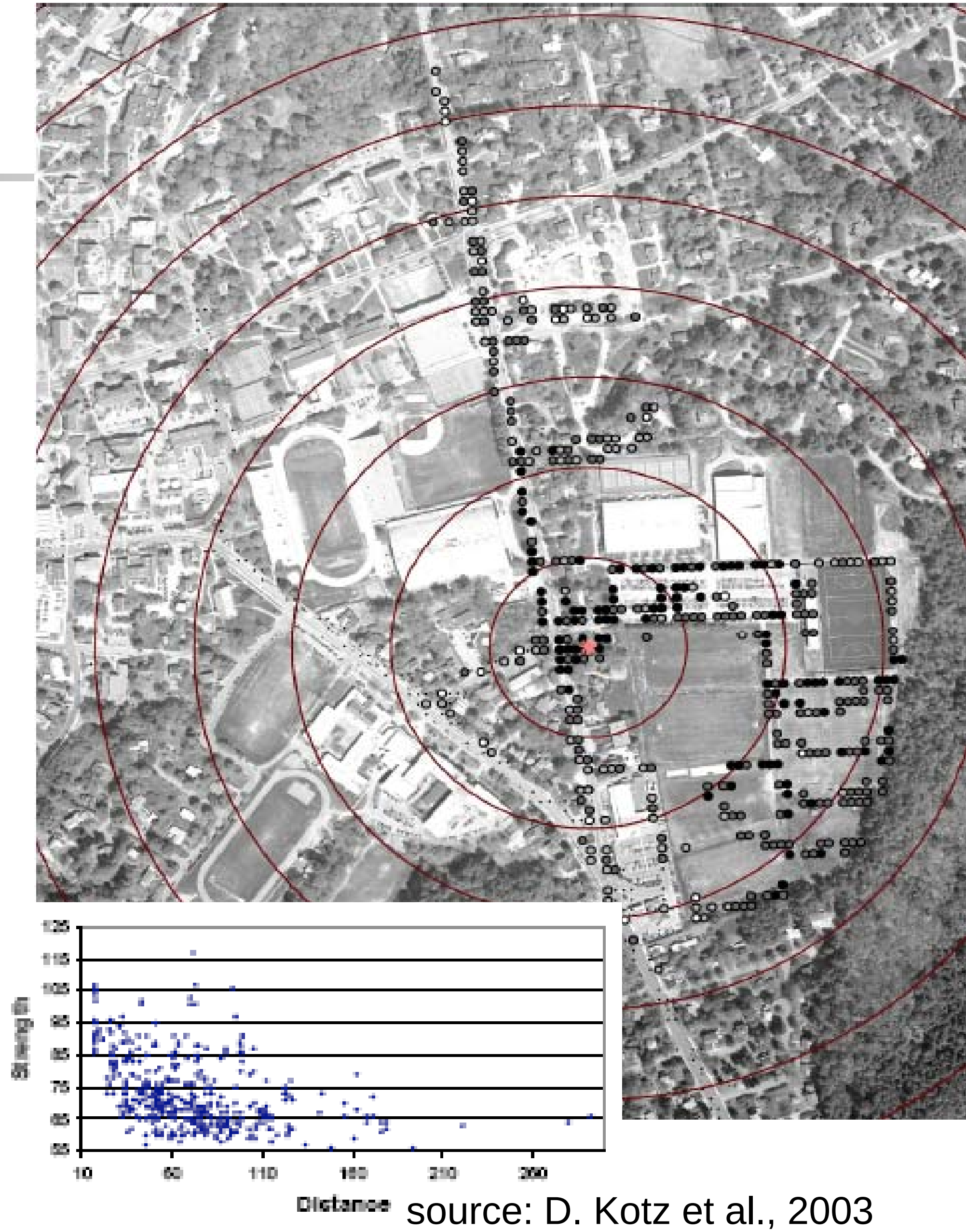
- Early projects
  - PicoRadio: Berkeley Wireless Research Center
  - Wireless Integrated Network Sensors (WINS): UCLA
  - Wireless Network of Devices (WIND): MIT
  - Wisenet: CSEM
- EU projects: EYES, WiseNts, Cruise, eSense, …
- MICS project led by EPFL

7 myths about wireless transmission

- the world is flat
- a radio transmission area is circular
- all radios have equal range
- if I can hear you, you can hear me
- if I can hear you at all, I can hear you perfectly
- signal strength is a simple function of distance
- link quality does not change

Some truths about wireless communication

- links fall into 3 categories
  - connected, transitional, disconnected
- transitional links are often unreliable and asymmetric (even for static nodes)
- packet error does not mean collision
- radio coverage is not at all circular
  - obstacles, height, fading, …
- signal strength is loosely related with distance



source: D. Kotz et al., 2003

Other challenges

- severe resource constraints
  - energy, bandwidth, memory size, processing
- unbalanced traffic
  - sink nodes
- network dynamics
- scalability
- multiple traffic requirements

So what’s new for RTN research ?

- not only MAC
  - mulithop must be taken into account
- impossible to ignore errors
- highly dynamic cases
- limited resources
  - energy (means good models for that)
  - memory (buffers)

MAC for Wireless Sensor Networks

- Same objectives as a conventional MAC
  - Fair access
  - Minimize waiting time
  - Maximize network utilisation
- In addition
  - preserve energy

Sources of Energy Waste (@MAC)

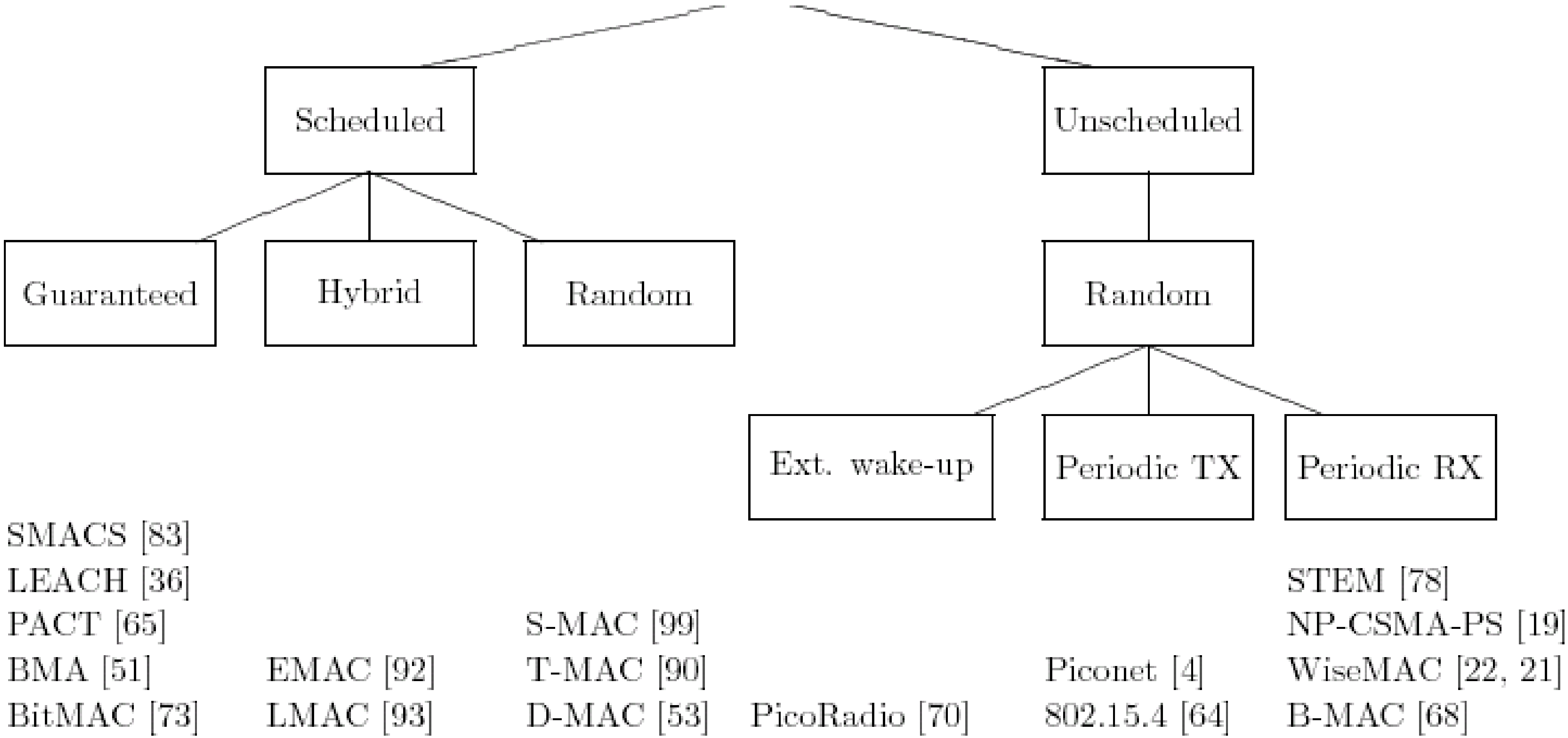
- Idle listening
  - Channel expected to be idle during long periods in sensor networks
- Overhearing
  - Not to be underestimated. Can become important in case of dense ad-hoc networks. Limits scalability in infrastructure sensor networks
- Collisions
  - To be avoided as retransmissions cost energy
- Over Emitting
  - Sending while there is no receiver ready to get the information
- Protocol Overhead
  - Required frame header and signaling to implement the MAC

Intuition

- Transmission does not cost too much energy
  - as long as there are not too many collisions
  - As long as we do not need to retransmit because the receiver did not receive the message

- Sleep most of the time
- Wake up when there is something to receive

MAC for Wireless Sensor Networks

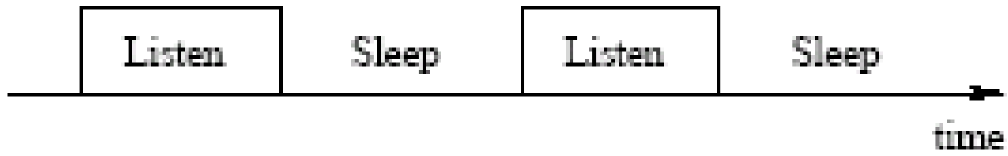


source: El-Hoiydi, 2005

See also K. Langendoen, A. Meier. 2010.

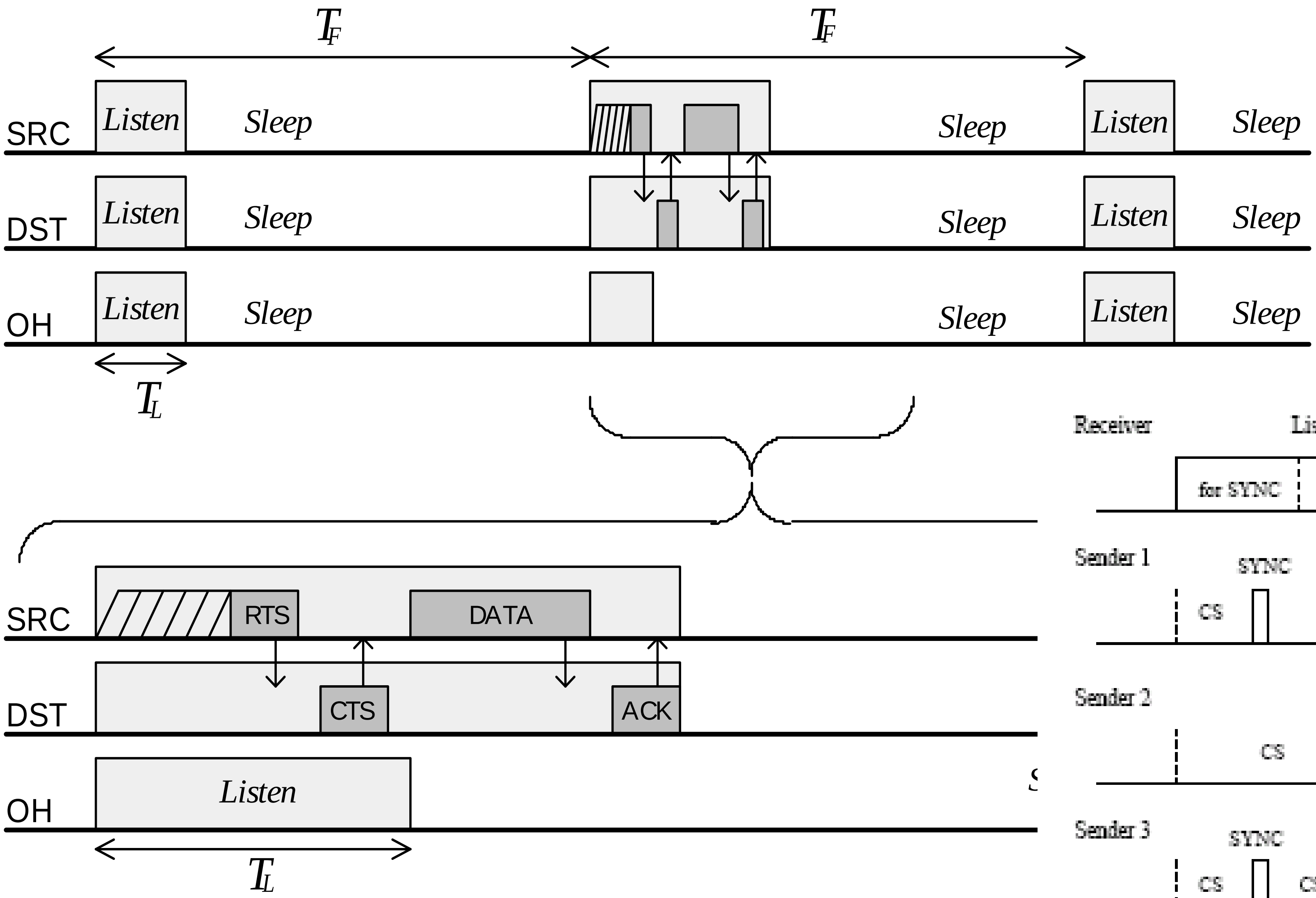
S-MAC

- Nodes have a listen/sleep periodic schedule

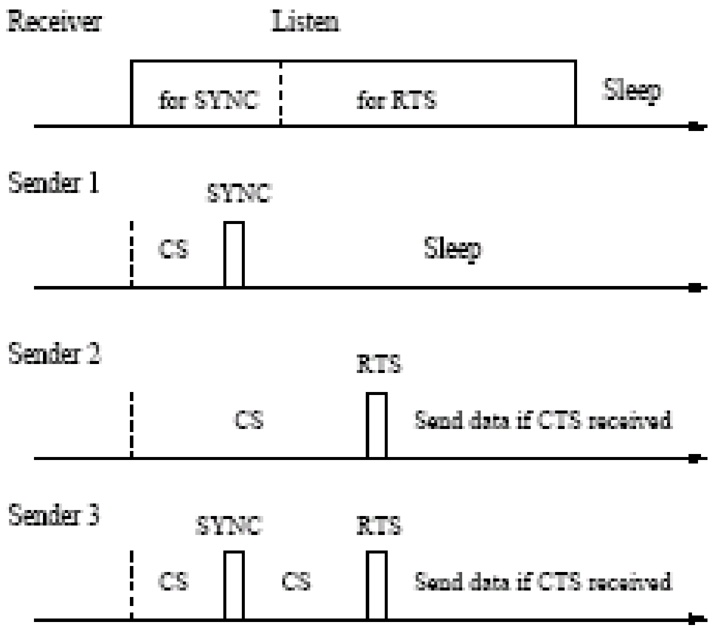


- A starting node
  - Listens to for a neighbor schedule
    - If found, adopts it / if not, selects one randomly (if it hears another schedule late, it adopts both)
  - then regularly broadcasts its schedule (SYNC packets)
- CSMA protocol with RTS/CTS to reduce collisions

SMAC



T_F
T_F
SRC
Listen
Sleep
Sleep
Listen
Sleep
DST
Listen
Sleep
Sleep
Listen
Sleep
OH
Listen
Sleep
Sleep
Listen
Sleep
T_L
SRC
RTS
DATA
DST
CTS
ACK
OH
Listen
T_L



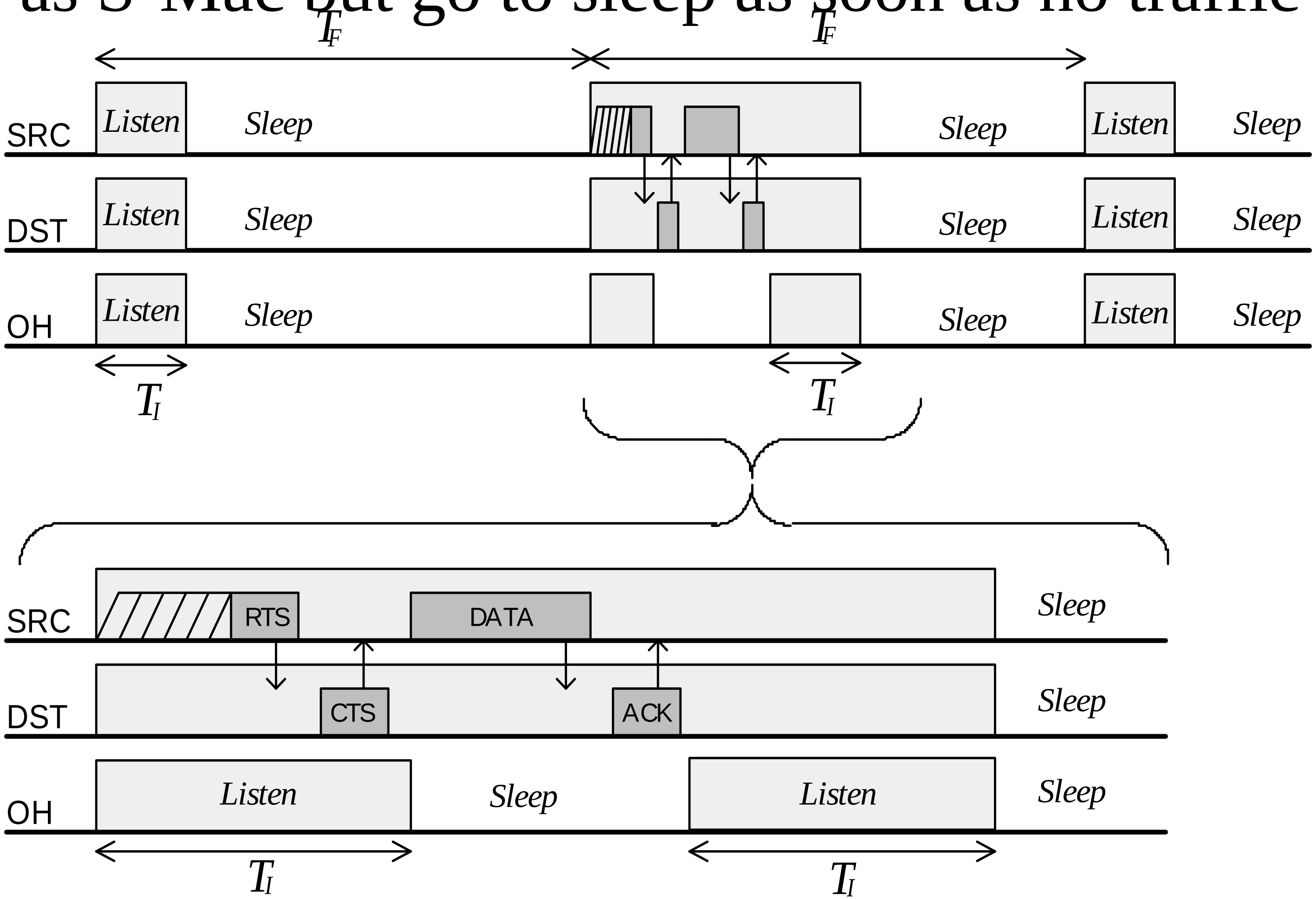
Receiver
Listen
for SYNC
for RTS
Sleep
Sender 1
SYNC
CS
Sleep
Sender 2
RTS
CS
Send data if CTS received
Sender 3
SYNC
RTS
CS
CS
Send data if CTS received

S-MAC Analysis

- No guarantee
- Average latency is half of listen/sleep period
- Power consumption directed linked to fixed duty cycle
  - Does not adapt to traffic
- Mitigates
  - overhearing (RTS/CTS)
  - Idle listening (listen/sleep)
  - Collisions (RTS/CTS)
    - But higher due to concentration of traffic in the listen period

TMAC

- Same as S-Mac but go to sleep as soon as no traffic

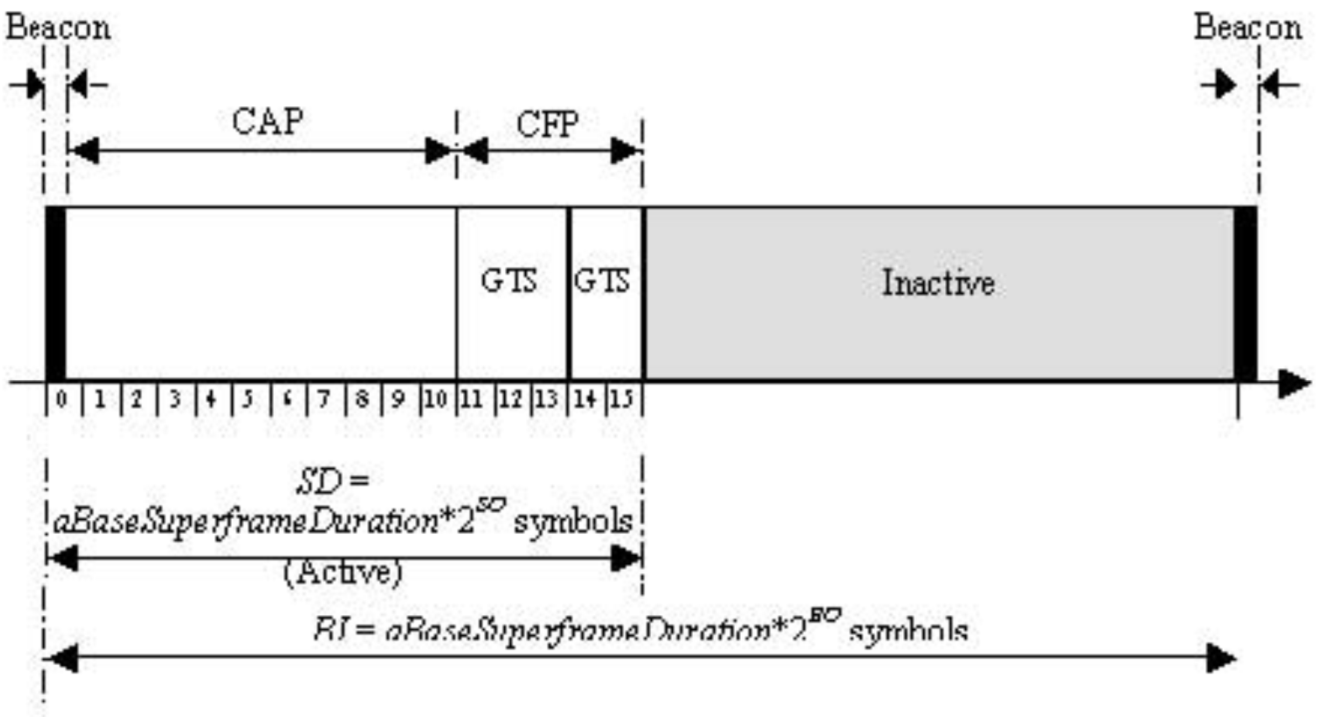


IEEE 802.15.4

- Part of IEEE 802 standards (only layer 1 & mac) international standard
- wireless LAN with 2 operating modes
  - station to station without coordination (ad hoc network or DCF)
  - coordinated by a single base station per cell
  - Provision for multihop (beacon offsets)
- 3 physical layer options (2.4 GHz – 16 ch., 902MHz and 868MHz)
- MAC: CSMA/CA + contention-less period
- Lower layers of many solutions
  - ZigBee industrial standard
  - ISA 100 / WirelessHART, ….

IEEE 802.15.4 (improperly called ZigBee)

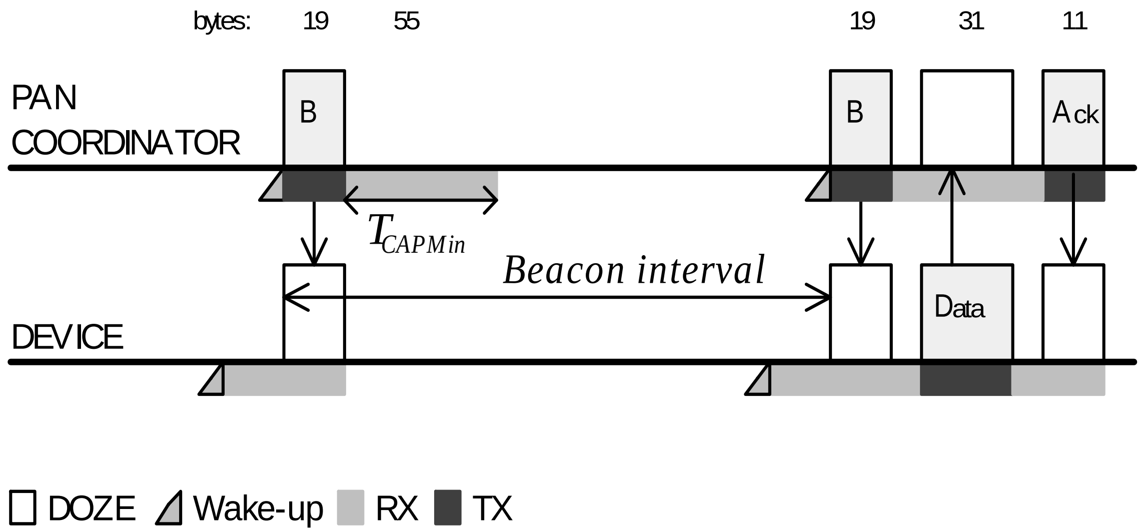
- 2 modes: peer-to-peer and star

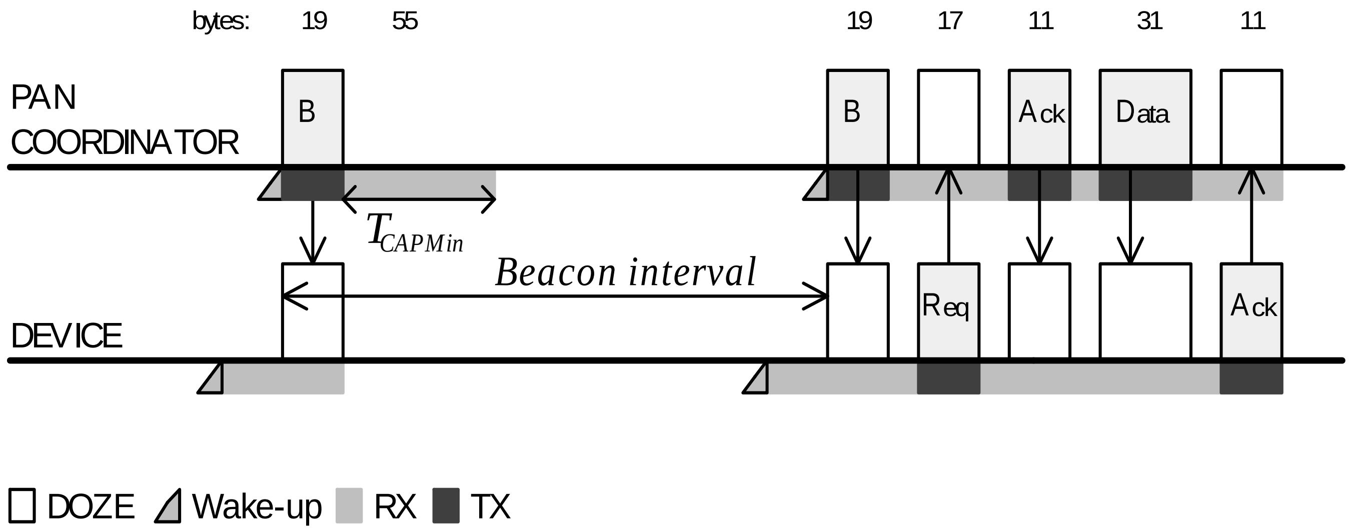


IEEE 802.15.4 – low power

- Duty cycle
- Power save mode
  - Nodes goes to sleep as soon as no traffic for a given time
- Traffic indication map
  - Coordinator indicates downlink traffic in beacon
  - Nodes may wake-up at their convenience, listen for beacon and check if incoming traffic

IEEE 802.15.4


bytes: 19 55 19 31 11
PAN COORDINATOR
B
B
Ack
T_{CAPMin}
Beacon interval
DEVICE
Data
DOZE
Wake-up
RX
TX

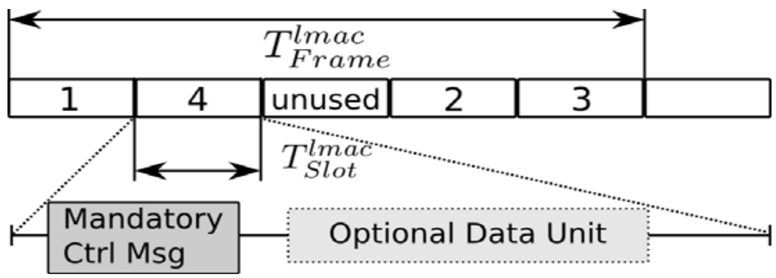

bytes: 19 55 19 17 11 31 11
PAN COORDINATOR
B
B
Ack
Data
T_{CAPMin}
Beacon interval
DEVICE
Req
Ack
DOZE
Wake-up
RX
TX

802.15.4 Analysis

- Star with beacon
  - Guarantees with GTS
  - Low consumption for “slaves”
- Peer-to-peer without beacon
  - No guarantee
  - Rather high idle listening (CSMA)
- Multihop with beacons
  - High energy consumption in relay nodes (coordinators)
  - Protocol not yet stabilized

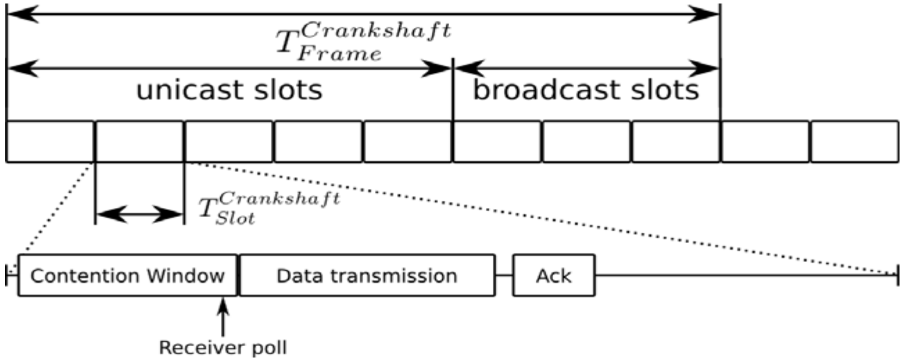
LMAC (Hoesel 2004)

- TDMA, time divided in
  - frames
  - and then in slots
- one node
  - owns one slot
    - Assigned in a distributed way
    - Slots are reused spatially
  - has to send a message at each instance of its slot
    - message = control part + data part
    - control part include id, slot id, slot used, slot with collision, dest,
  - must listen to control part of all neighbours
- The gateway starts the network



L. van Hoesel and P. Havinga, “A Lightweight Medium Access Protocol (LMAC) for Wireless Sensor Networks,” INSS 2004.

Crankshaft (Halkes 2007)



- For dense networks
- TDMA (frames and slots)
  - requires clock sync.
  - Nu unicast slots
    - assigned to a receiving node (MAC address modulo Nu)
    - 2 windows : contention and data transfer
    - Senders contend to access medium (3 retries in subsequent frames)
  - Nb broadcast slots
    - all nodes must be listening
- synchronization
  - Every node has to send a broadcast packet every Tsync

G. P. Halkes, K. G. Langendoen. Crankshaft: an energy-efficient MAC-protocol for dense wireless sensor networks. EWSN'07, 228-244.

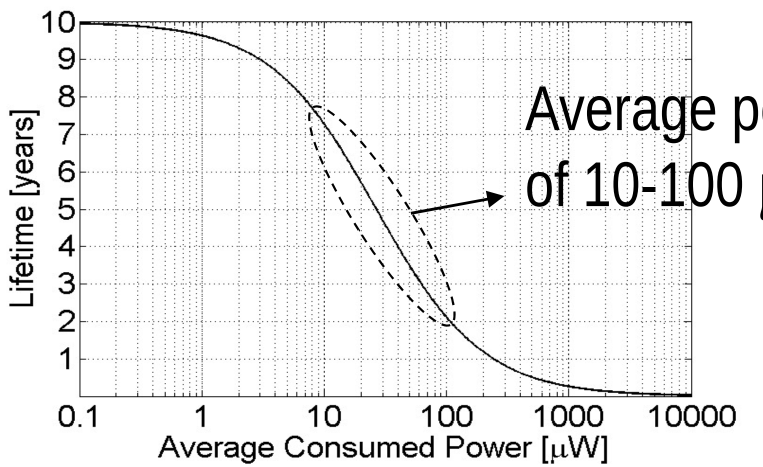
TDMA analysis

- All require tight synchronization
  - Often chicken and egg problem
- Slot time must be long enough to accommodate longest packet
- LMAC is in principle able to sustain RT traffic
  - In absence of errors
- Suited for regular traffic
  - How to accommodate different periods ?
  - How to accommodate varying demands ?

WiseMAC Req. & Assumptions

- Designed for the WiseNET System-on-a-chip
  - FSK Radio, 2 mA RX, 800 µs setup time, 35 mA TX, 5 µW DOZE
  - SoC operates down to 0.9V to require a single battery
  - 8 bits CoolRisc µC, little memory available
- Target lifetime of years on a single AA alkaline battery
- Multi-hop, Low average data rate, High latencies tolerated

AA alkaline battery
- 2.6 Ah
- Power leakage of 27 µW

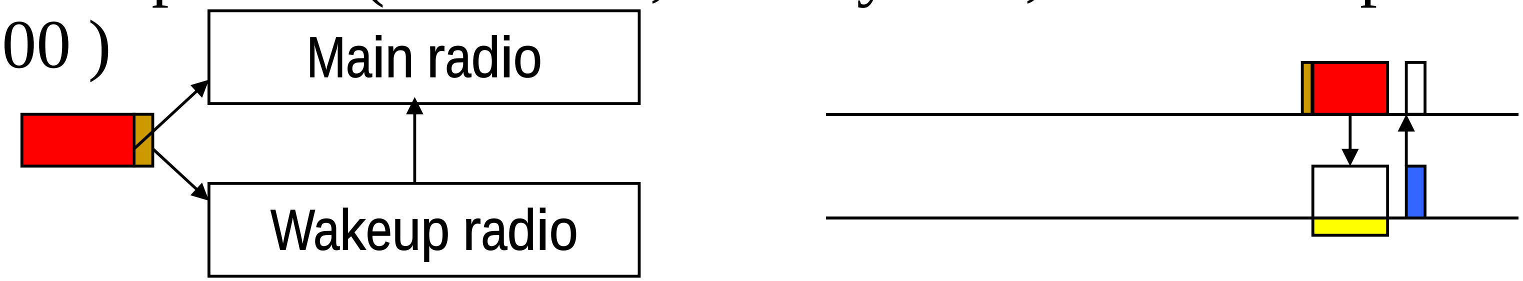


Average power budget of 10-100 µW

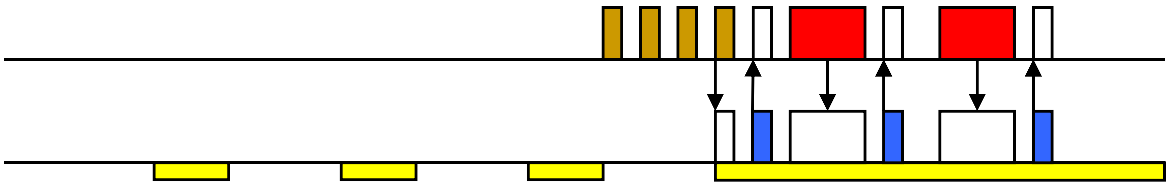
Average duty cycle of max 0.5-5 %

Wake-Up Schemes

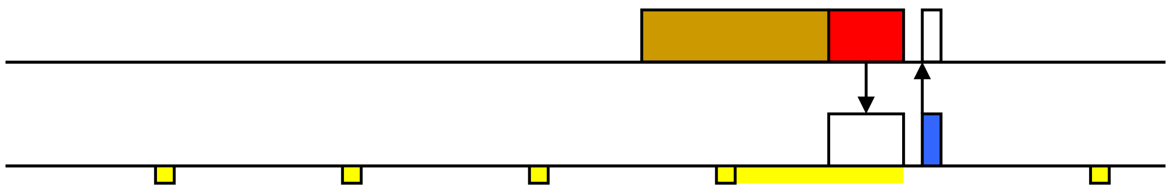
- Wake-up radio (Picoradio, Rabaey et al, IEEE Computer Mag., 2000)



- Wake-up channel (STEM, Schurgers et al, IEEE Aerospace Conf. 2002)

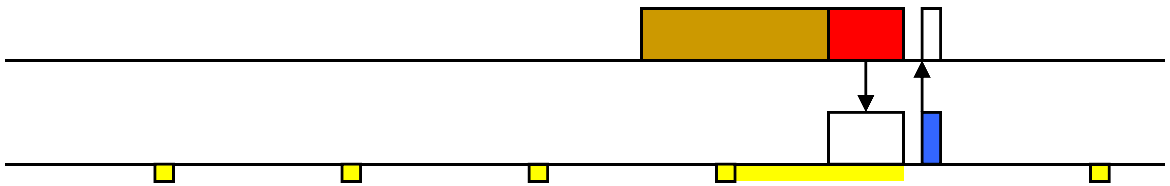


- Preamble Sampling (Aloha with P. S., El-Hoiydi, IEEE ICC 2002)



B-MAC

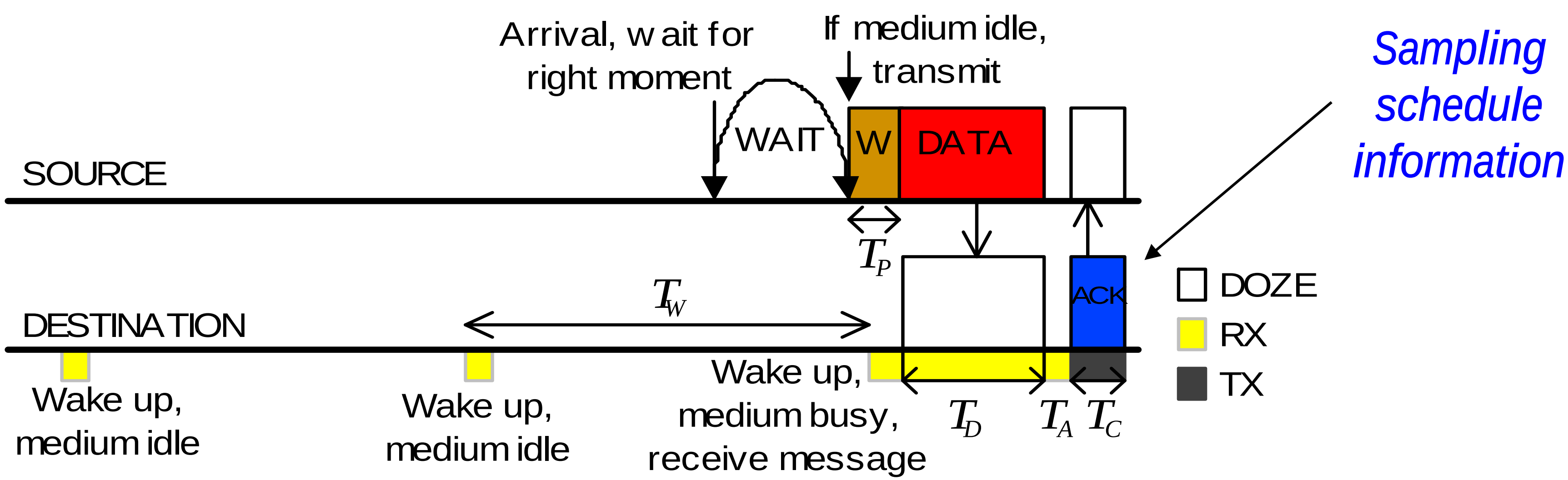
- Same principles as Aloha with Preamble Sampling
- Meant to be a generic MAC by allowing to change parameters by upper layers
  - CCA and ACK on/off, sampling period, preamble length



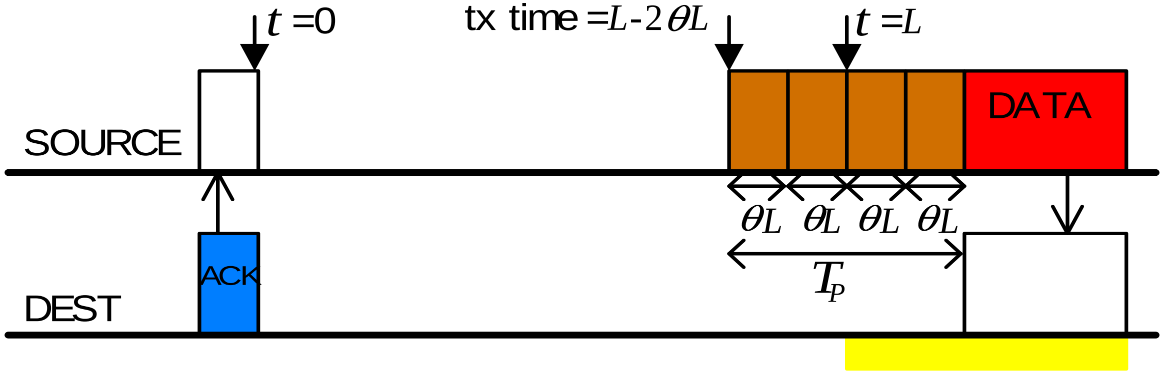
J. Polastre, J. Hill, D. Culler. Versatile low power media access for wireless sensor networks. SenSys '04, , 95-107.

WiseMAC

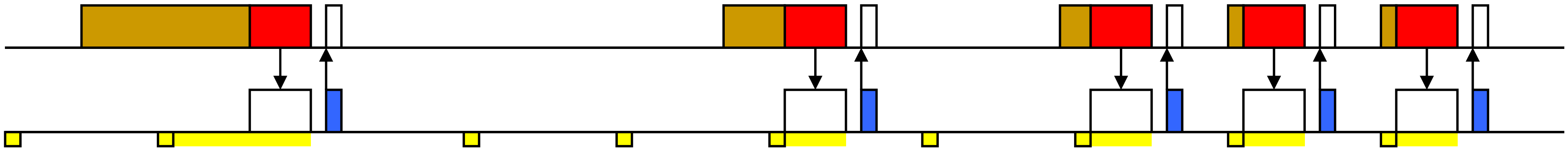
- Based on Synchronized CSMA with Preamble Sampling
  - Preamble sampling to minimize consumption of idle listening
  - wake-up preamble minimized by exploiting knowledge of sampling schedule of direct neighbors, less transmit, receive & overhearing overheads.
  - No setup-signalling. Self local synchronisation and re-synchronization
  - Choice of T_W is a trade-off between energy and latency



Minimum Preamble Length

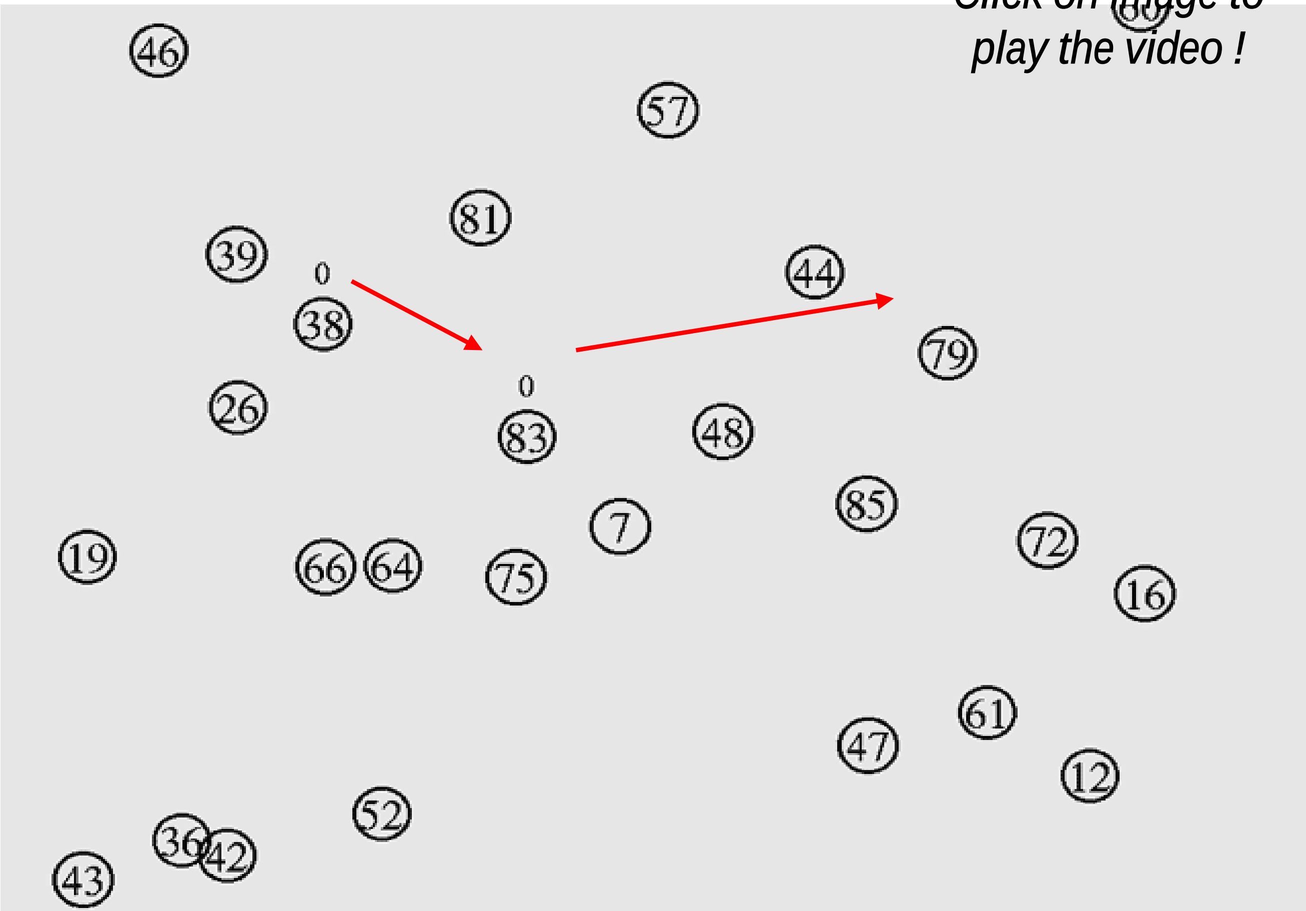


- Sampling schedule information inserted in every ack.
- Clocks drift of at most ±θ per second (typically θ =30 ppm)
- With L seconds in between two communications, the length of the preamble must be $T_P = \min(4\theta L, T_W)$



Preamble Length Reduction

Click on image to play the video !



Node
- Black: Sleeping
- Green flash: Sampling
- Yellow: Listening
- Purple: Waiting for the right tx time
- Circled: Backoff

Message
- Brown: Preamble
- Red: Data
- Dark Blue: Ack

Sequence takes 1 second in real time (40 times faster)

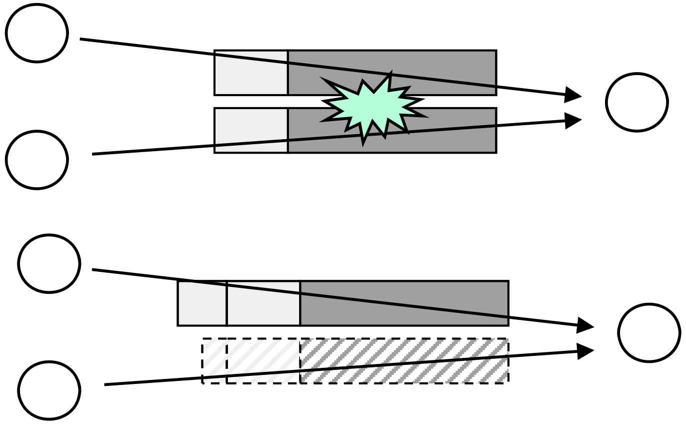
1st transmission: no sampling schedule info, using long preamble

2nd transmission: sampling schedule info gained through previous communication, using short preamble → less overhearers !

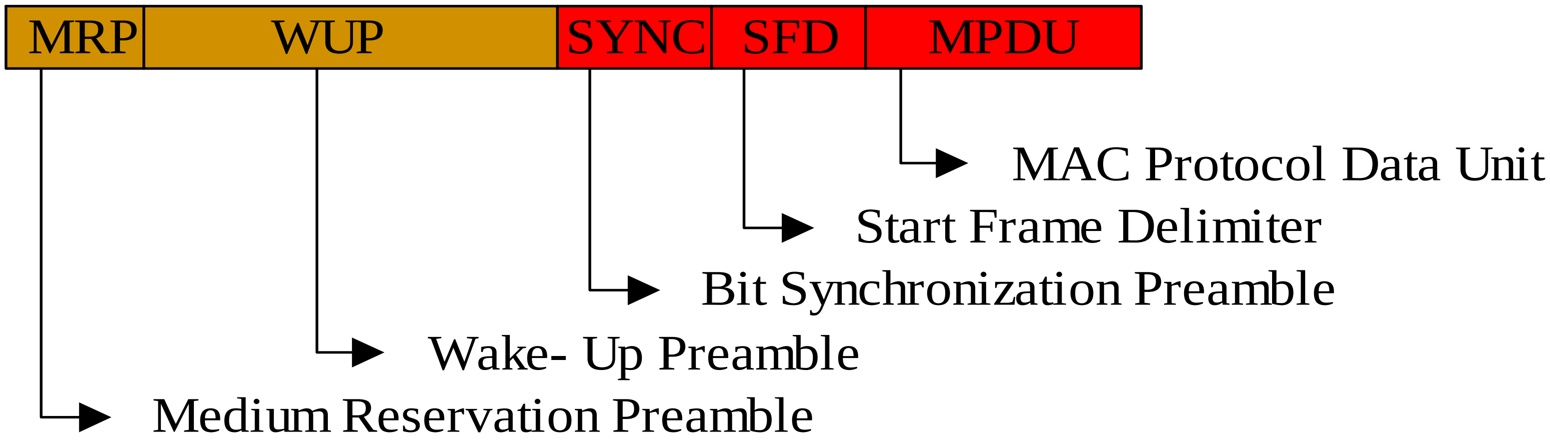
WiseMAC – Further Design Choices

- Medium reservation
  - To avoid collisions when using short preambles
- ‘More’ bit in data header
  - To allow the transport of traffic bursts
- Data frame repeated in preamble when preamble large
  - To reduce the frame error rate, mitigate overhearing, differentiate interferences from wake-up preambles
- Receive threshold above sensitivity
  - To avoid useless wake-ups caused by noise or weak signals (at the cost of the range)
- Carrier sensing range larger than interference range
  - To mitigate the hidden node effect (at the cost of the capacity)

Medium Reservation

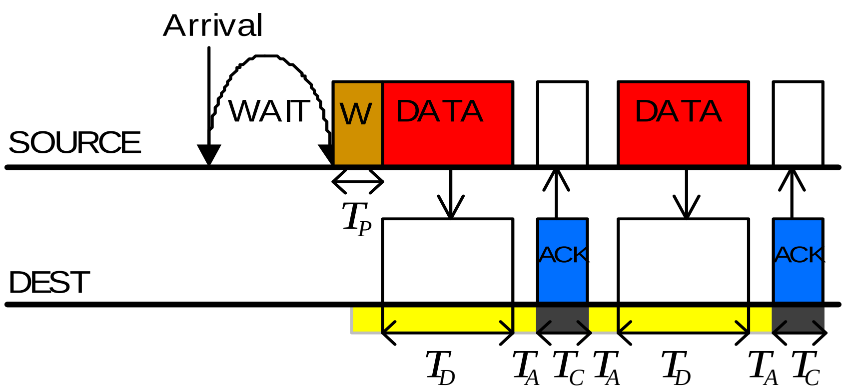


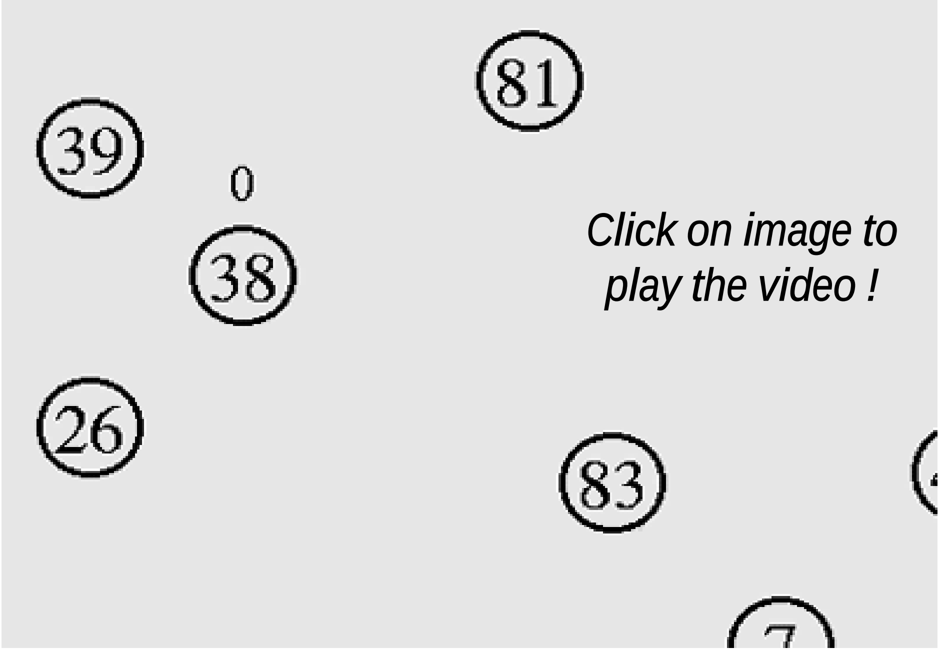
To avoid collisions between transmissions to the same node and at the same target sampling time



'More' Bit

- 'More' bit in data header indicates follow-up packets
- Allows the transport of busty traffic with low delays
- Cost of wake-up preamble shared among several packets



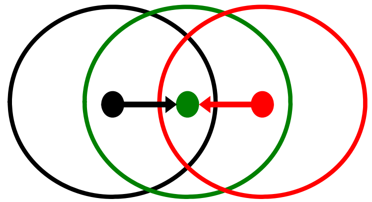


Preamble made of repeated packets

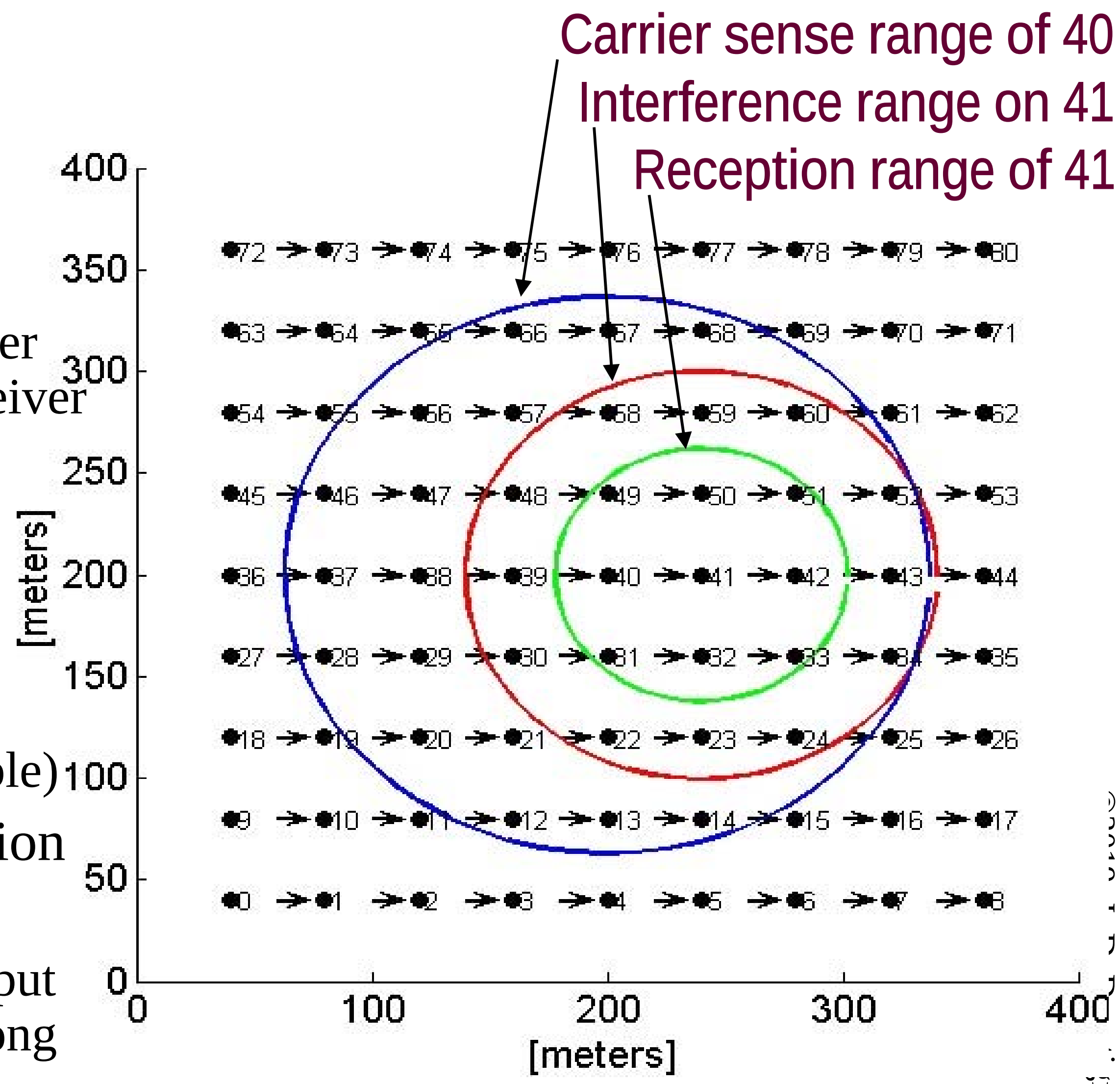
- Instead of having a preample made of a busy tone
- May be done by repeating
  - the data packet
  - A packet with only the address of the destination
- Modern radios impose a silence between 2 consecutive packets
  - Preamble sampling must be repeated twice
- Busy tone (carrier) is not always possible on some radios
  - Preamble is a multiple of packet size
    - Some degradation is one wants an efficient reservation preamble

Carrier Sensing Range Extension

- Hidden Node Effect

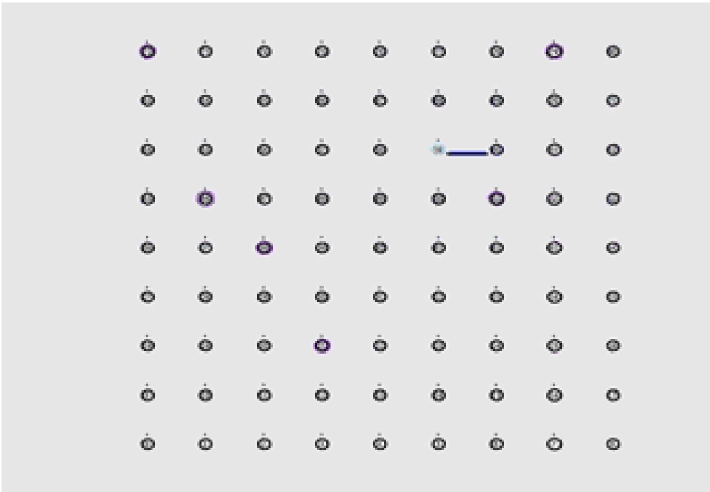


  - Hidden node is far from sender (not sensed), but close to receiver (interfering with reception).
- RTS-CTS
  - Not useful when data packets are small
  - Requires broadcast communication (long preamble)
- Carrier Sensing Range Extension
  - Mitigates hidden node effect
  - But reduces the max throughput (channel capacity shared among more nodes with CSMA)

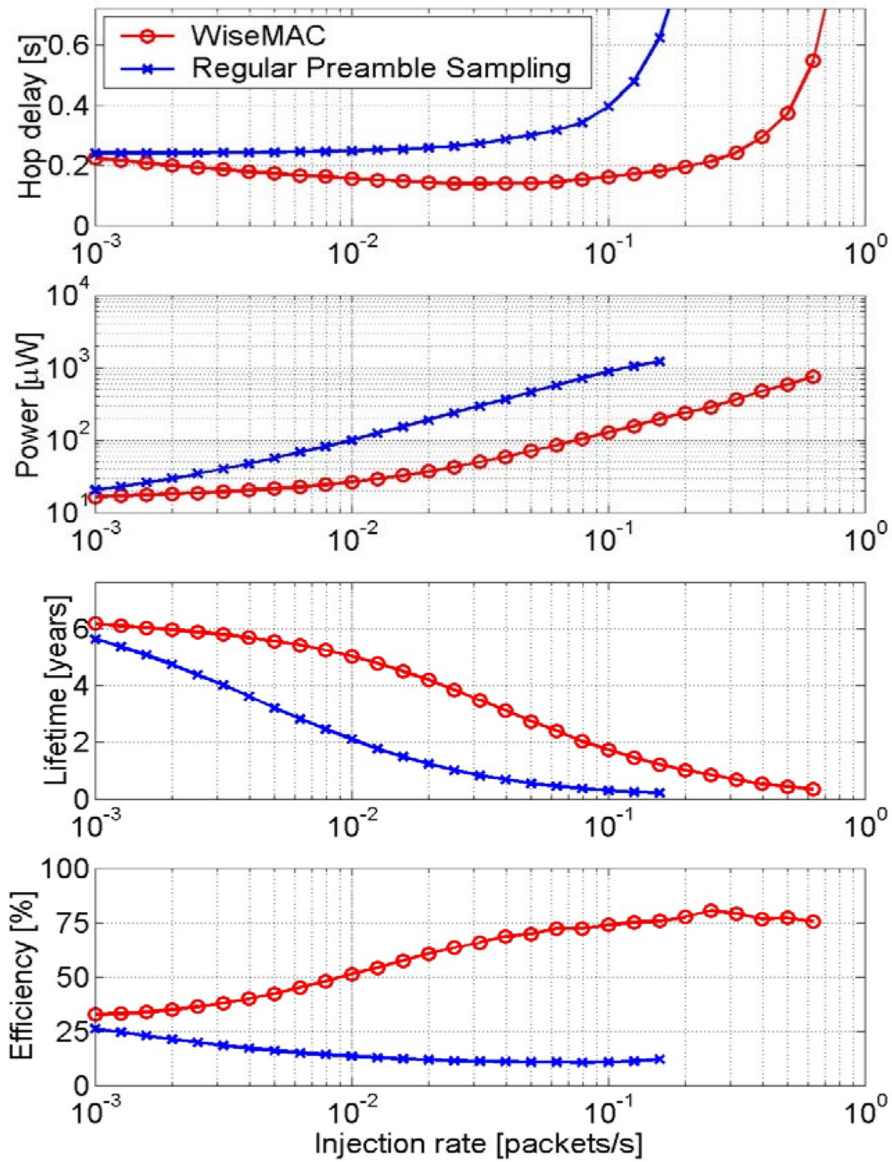


Performances

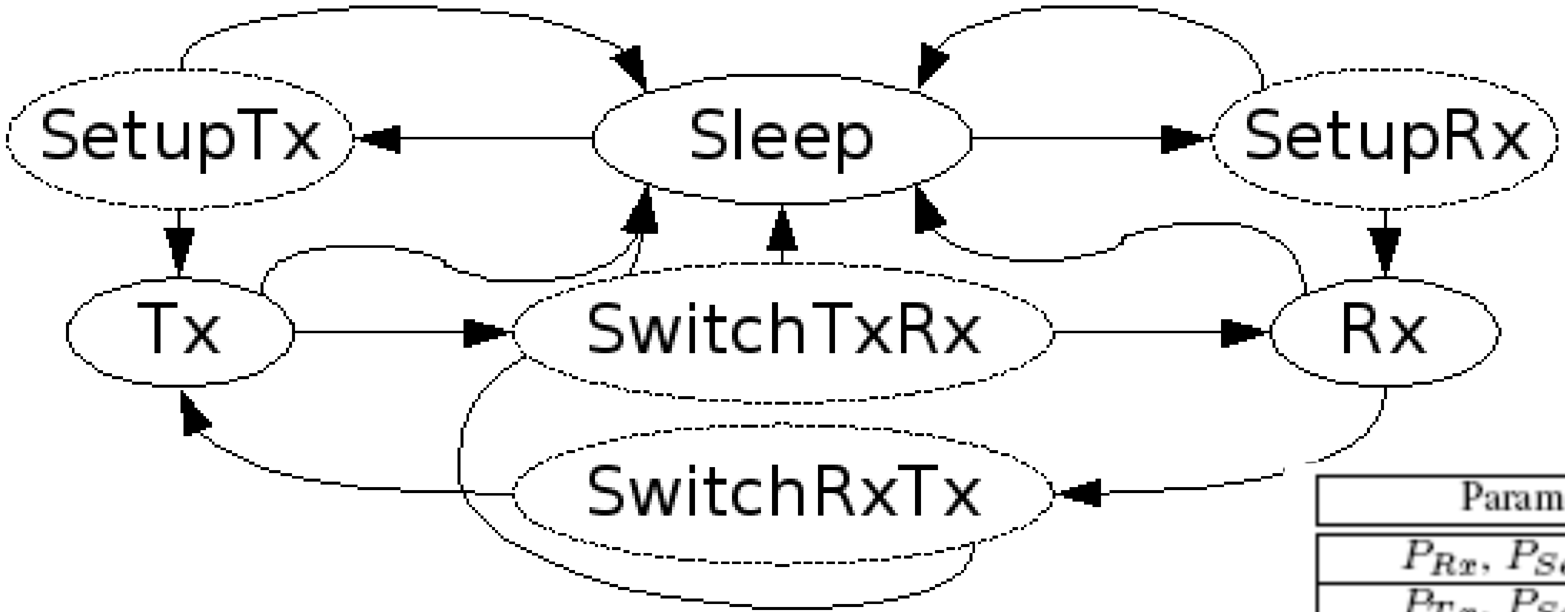
- Lattice Network



  - Traffic inserted in left-side nodes
  - Forwarded towards the right
  - Statistics collected on central node
  - Models infinitely large sensor net
- WiseMAC adaptive to the traffic
  - Ultra-low power consumption in low traffic conditions, high energy efficiency in high traffic condition



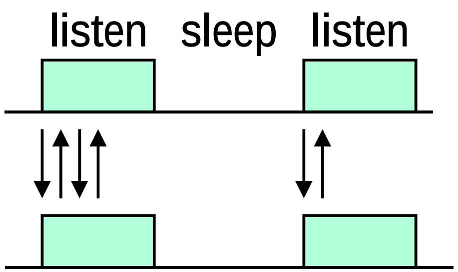
Radio state model

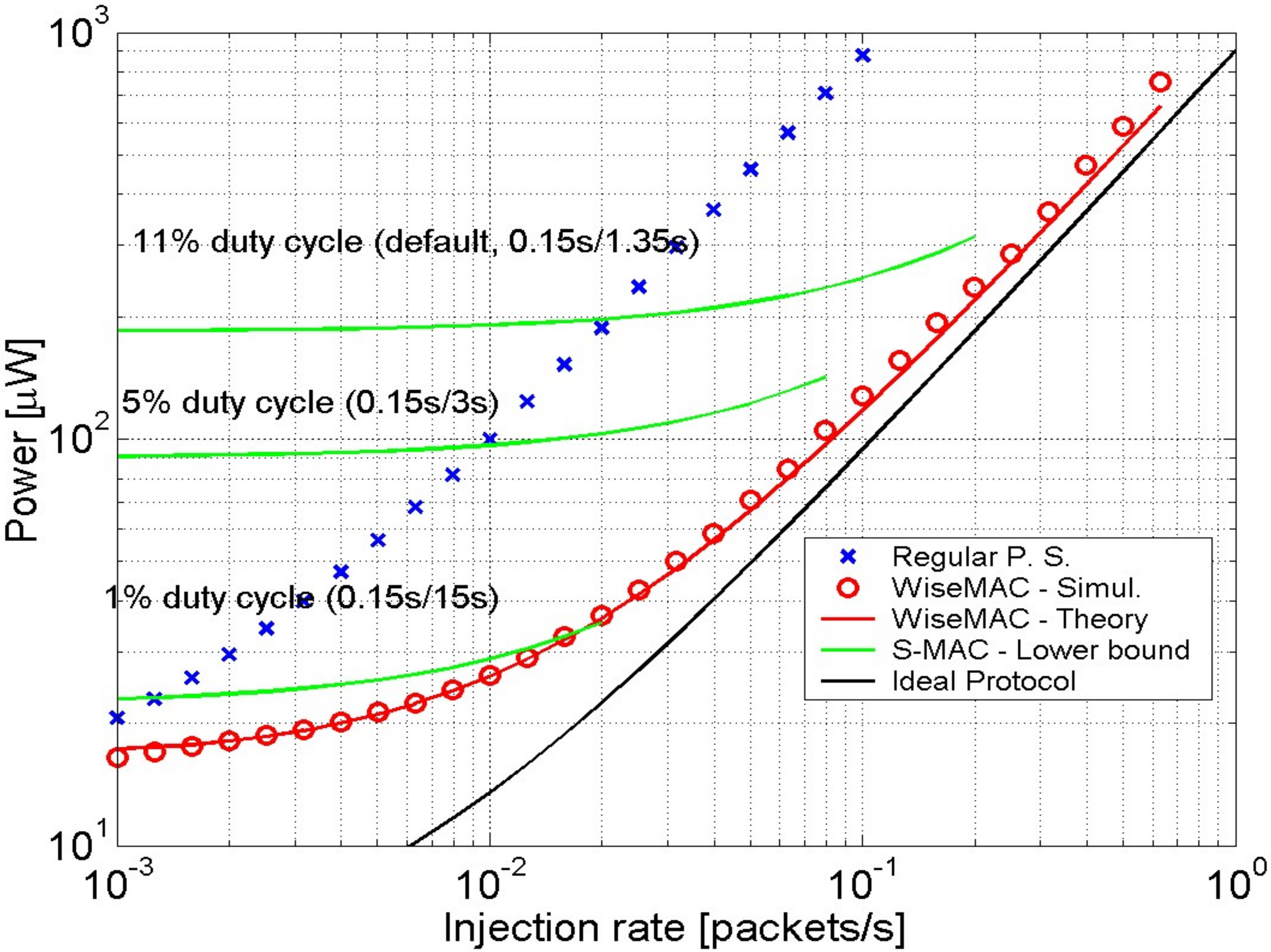


Parameter	Value
P_{Rx}, $P_{SetupRx}$	56.4 mW
P_{Tx}, $P_{SetupTx}$	25.5 mW
P_{Sleep}	0.06 mW
P_{SwTxRx}, P_{SwRxTx}	54.3 mW
T_{SwTxRx}	160 µs
$T_{SetupRx}$	192 µs
$T_{SetupTx}$	12 µs
T_{CCA}	128 µs
T_{Sync}	160 µs
Θ	$30 * 10^{-6}$
Bit rate	250 kbps

Comparison with S-MAC*

$$
\begin{aligned}
E_{WiseMAC} \approx\ & \frac{1}{\lambda}\left(\frac{P_{RX} T_{Se}}{T_{WU}} + P_{DOZE}\right) \\
& + P_{TX}\left(T_{MR} + T_P + T_M\right) \\
& + P_{RX}\left(\frac{T_P}{2} + T_M\right) \\
& + 7\frac{P_{RX}\left(T_{MR} + T_P + T_M\right)^2}{2T_{WU}}
\end{aligned}
$$





* S-MAC, Ye, Heidemann, Estrin, *INFOCOM* 2002.

SCP-MAC

- uses periodic Preamble Sampling
- neighbours are synchro-nized (SMAC technique)
- Adaptation to traffic with multihop optimization
- Collision mitigation

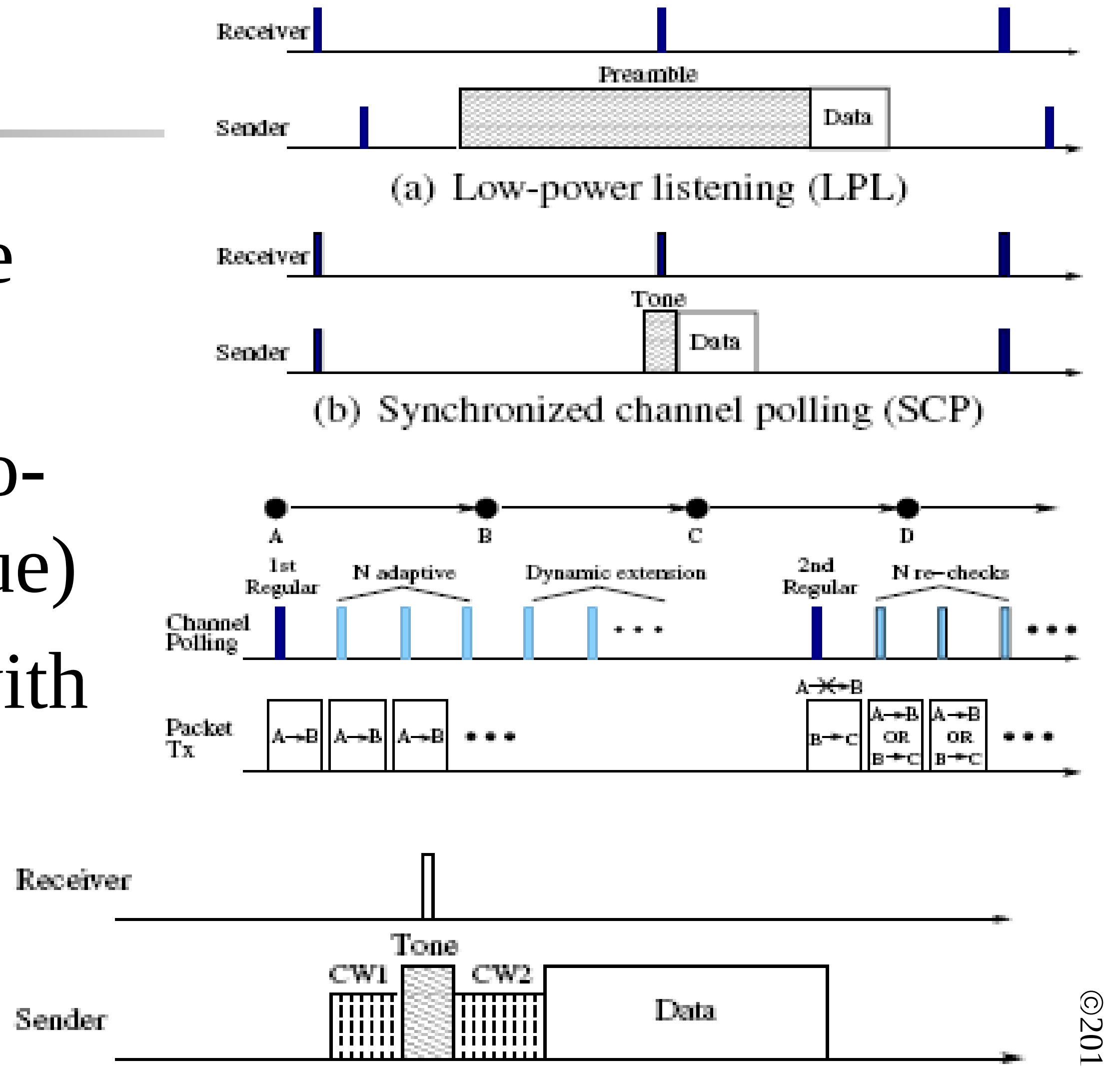
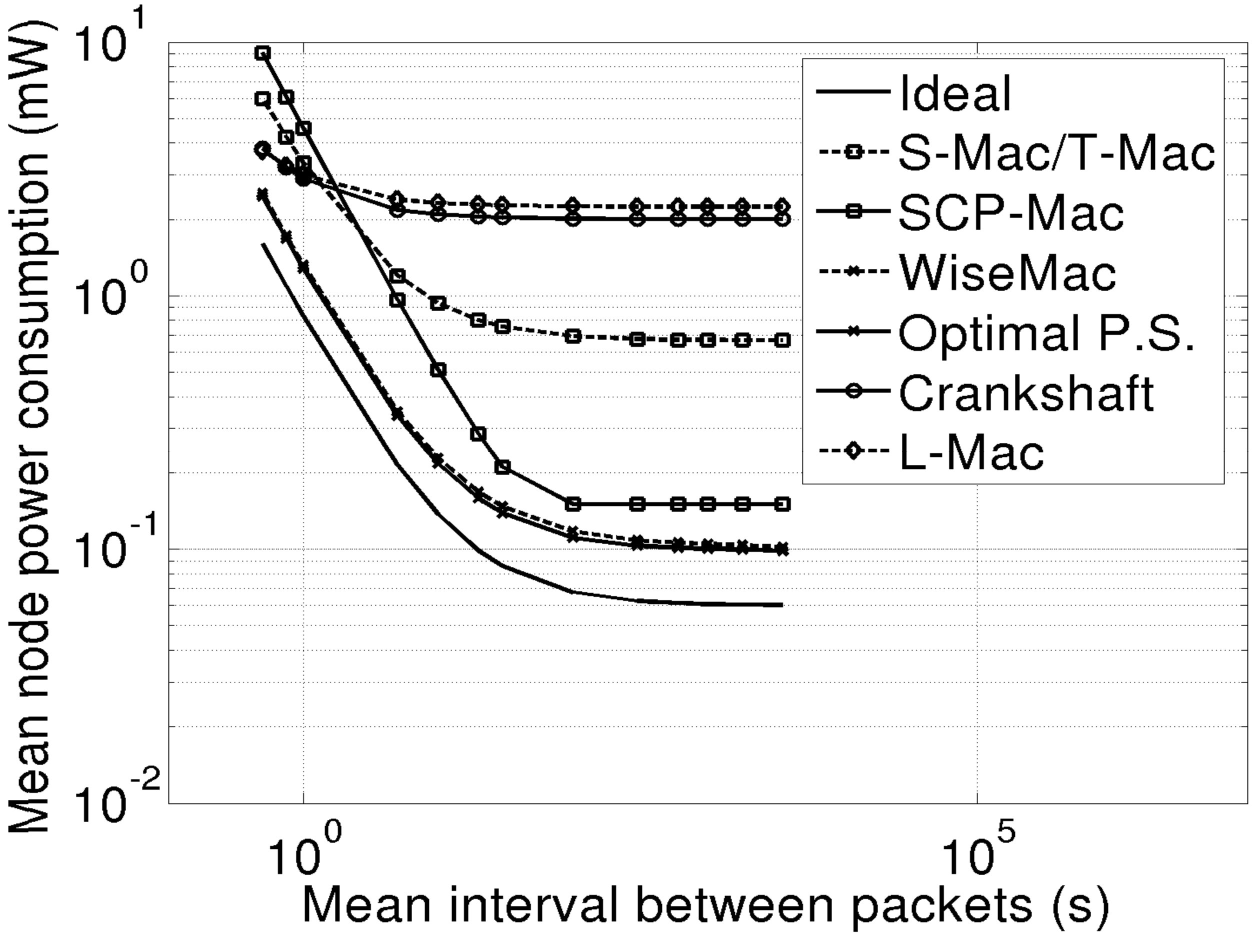


Figure 3. Two-phase contention in SCP-MAC.

Ye, W., et al. Ultra-low duty cycle MAC with scheduled channel polling. Proc. SenSys '06. pp. 321-334.

Comparisons

- each node sends and receives the same traffic
- all nodes are visible (10 nodes)

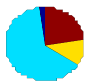


Comparison with 802.15.4

Forwarding a 32 bytes packet every 30 seconds in a multi-hop network.

Same weak-up period T_W = 250 ms, same hardware (XE1203 Radio).

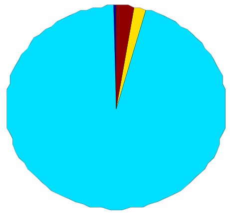
WiseMAC
(from CSEM)



Total 304 uW

- Doze
- Sampling
- Fwd Rx
- Fwd Tx

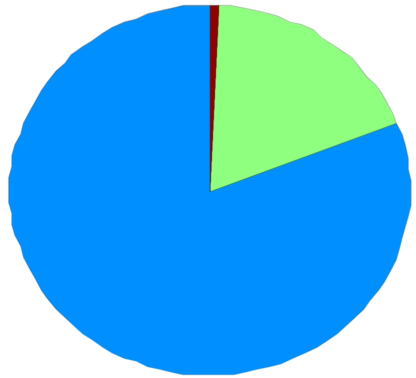
S-MAC
(from UCLA)



Total 2318 uW (x 7)

- Doze
- Periodic Listening
- Fwd Rx
- Fwd Tx

IEEE 802.15.4
ZigBee standard



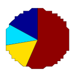
Total 7659 uW (x 25)

- Doze
- Tx Beacons
- Rx Beacons
- Fwd Rx Uplink
- Fwd Tx Uplink

Comparison using an IC that reduces receiving energy

Forwarding a 32 bytes packet every 30 seconds in a multi-hop network. *Same weak-up period T_W = 250 ms, same hardware (WiseNET SoC)*.

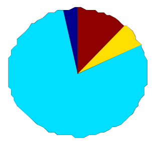
WiseMAC
(from CSEM)



Total 30 uW

Doze
Sampling
Fwd Rx
Fwd Tx

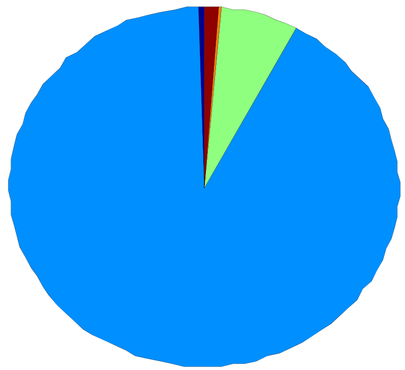
S-MAC
(from UCLA)



Total 139 uW (x 5)

Doze
Periodic Listening
Fwd Rx
Fwd Tx

IEEE 802.15.4 ZigBee standard

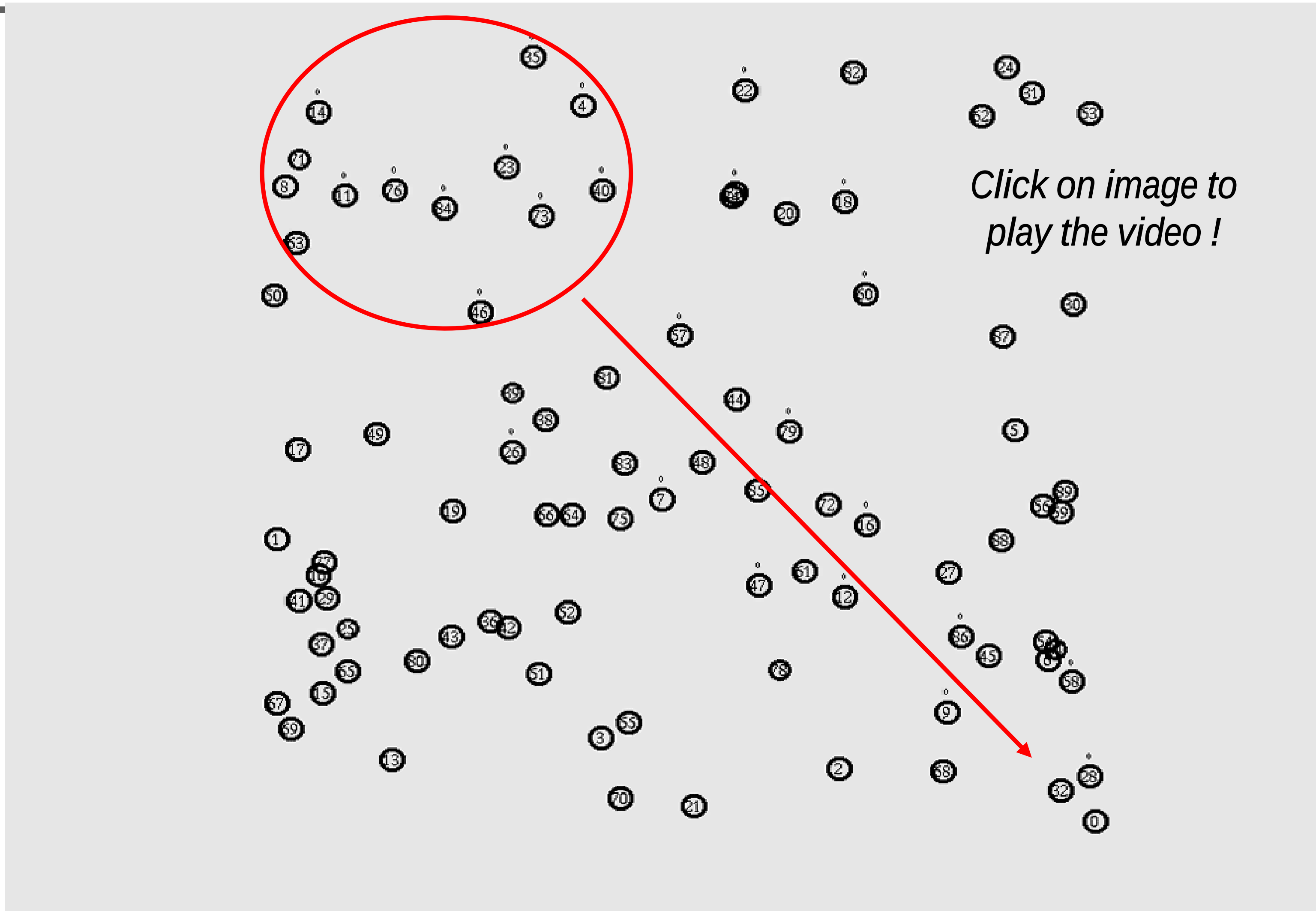


Total 1092 uW (x 36)

Doze
Tx Beacons
Rx Beacons
Fwd Rx Uplink
Fwd Tx Uplink

Event Detection in a Random Plane Network

- Transmission of initial report
- followed by the periodic transmission of measurements



First Conclusions

- WiseMAC is a single channel contention MAC protocol based on synchronized CSMA with preamble sampling
  - No setup-signaling. Self local synchronisation and re-synchronisation.
  - Adaptive to traffic: ultra-low power consumption in low traffic conditions and high energy efficiency in high traffic condition
  - Supports sporadic, periodic and bursty traffic
  - Provides years of autonomy with a single AA alkaline battery under traffic loads up to 1 message every 10 seconds
- “the WiseMAC protocol showed a remarkable consistent beha-vior across a wide range of operational conditions, always achieving the best, or second-best performance.” Langendoen 2010.
- A number of modifications of WiseMAC have been proposed
  - SyncWUF, CSMA-MPS, X-MAC, MX-MAC, …

LPL / PS practical issues

- Radios are not able to create preambles
  - Not a problem as preambles are only repeated packets
- Some radios go immediately into receive mode after sending -> Some silence between packets
  - Sample preamble twice with a delay > silence
- Noisy environment -> False wakeups (See M. Sha, et al., Energy-efficient LPL for wireless sensor networks in noisy environments. IPSN '13, pp.277-288)
  - Adjust level / sample medium twice / repeat packets
  - Adapt preamble (as in WiseMAC)

Broadcast in LPL

- Broadcasts are not acknowledged
- No possibility to get timing information
  - Thus always, long preamble

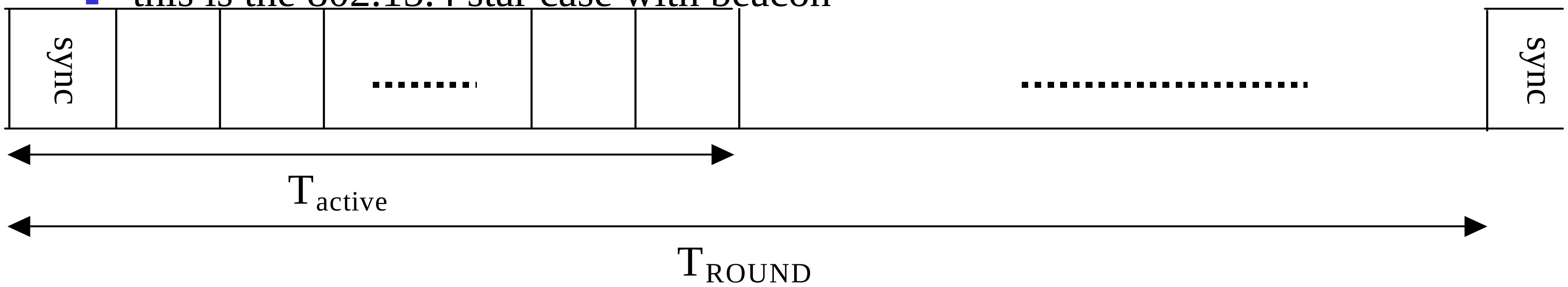
- How to reduce this overhead
  - Like with “more bit”
  - Send broadcast packets “back to back”

What about pure TDMA ?

- we know that pure TDMA
  - Is very good from the safety point of view
  - Is not flexible
  - Does not scale
  - Does not support mobility
  - Hardly supports fluctuating links (because of desynchronisation)
- but
  - It is energy efficient
    - no collisions, nodes are turned on just the necessary time
  - It is the best choice in case of high loads
- Is that so ?

What about pure TDMA ? (2)

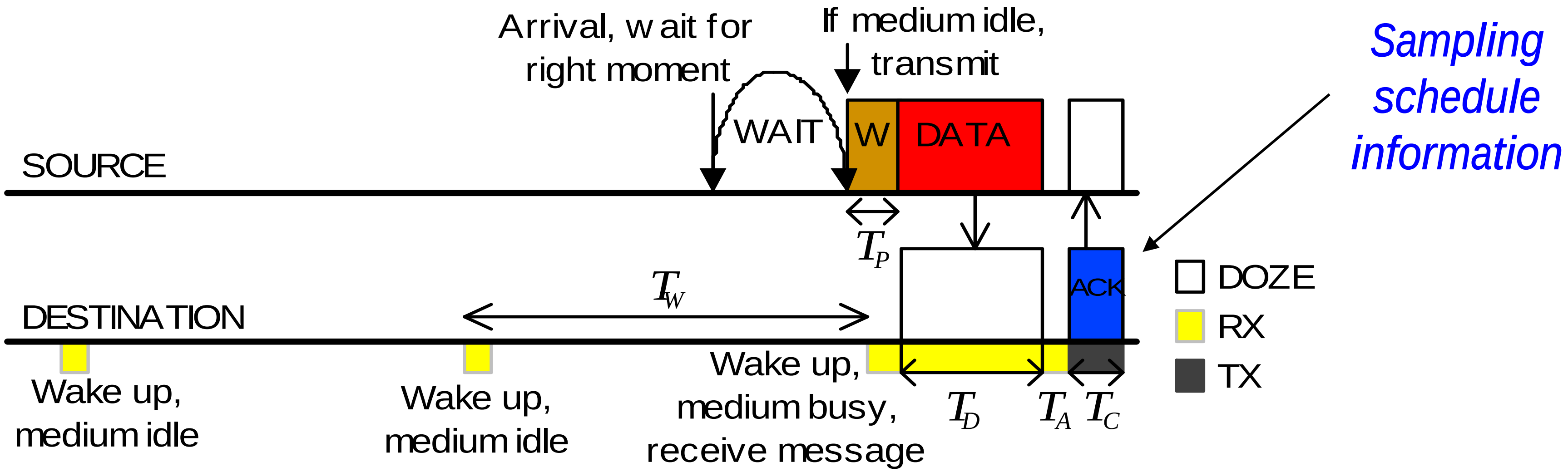
- simple case
  - all traffic has same period
    - this is the 802.15.4 star case with beacon



    - multihop network: each node receives 1 packet and transmits 1 packet per round
      - energy per round = $E_{rec} + E_{tx} + E_{rxsync} + \{E_{txsync} + 4\theta T_{ROUND} P_{tx} \} / N$
      - N number of participating nodes, θ clock drift
      - E_{txsync} (E_{rxsync}): energy to send (resp. receive) a sync. packet
      - E_{tx} (E_{rec}) : energy to send (resp. receive) a packet and receive (resp. send) ack
- adaptable case

What about pure TDMA ? (3)

- let us use a non TDMA protocol, Wisemac



  - assume same <u>low</u> traffic (1 msg sent and 1 msg receive par T_{round})
  - energy per round = $E_{rec} + E_{tx} + \{T_{ROUND} / T_W - 1\}E_{PS} + 4\theta T_{ROUND} P_{tx}$
  - as compared to $E_{rec} + E_{tx} + E_{rxsync} + \{E_{txsync} + 4\theta T_{ROUND} P_{tx}\} / N$

What about pure TDMA ? (4)

- adaptable case
  - TDMA rounds with slots assigned to links
  - a node need not emit at each round
  - one node sends a synchronisation message every K rounds
  - all nodes transmits 1 msg and receives 1 msg every L rounds
  - energy per L units = $E_{rec} + E_{tx} + L\ E_{rxsync}/K + \{L / T_{ROUND} - 1\}E_{PS} + 2\theta L\ P_{tx} + \{E_{txsync} + 4\theta K T_{ROUND}\ P_{tx}\} / N$
  - energy for Wisemac = $E_{rec} + E_{tx} + \{L / T_W - 1\}E_{PS} + 4\theta L\ P_{tx}$

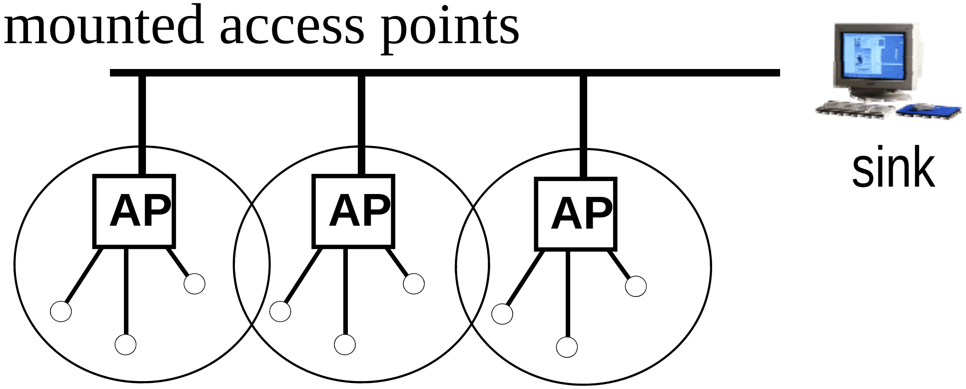
  - of course, this is only valid for low traffic conditions

What about pure TDMA ? (5)

- what about high traffic conditions ?
  - we need some margin between the slots for desync.
  - we need some margin for retries
  - we need some margin to accommodate the longest packet
- asynchronous protocols are also able to avoid collisions by suppressing arbitration is some cases
  - more bit (Wisemac)
  - TXOP (IEEE 802.11)

The special case of Infrastructure Based Wireless Sensor Network

- Sensor nodes communicate with access points
- Access points are connected to an infrastructure network
- Access points are energy unconstrained
- Topology is made of multiple star networks. Examples:
  - Temperature monitoring in an office building, using Ethernet infrastructure
  - Alarm system at home, using Powerline infrastructure
  - Solar powered or vehicle mounted access points



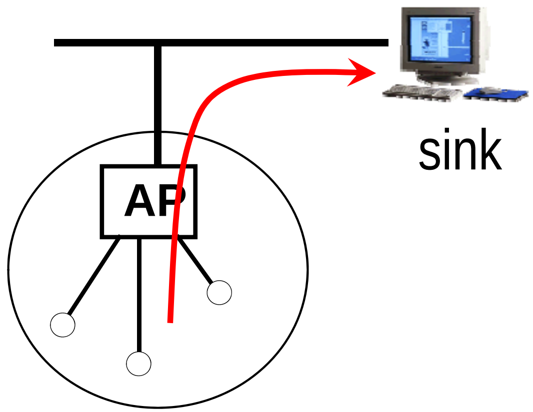
Can we design a better solution in star networks ?

- To save energy, the radio of sensor nodes must be turned off when not communicating.
- MAC protocol should minimize idle listening, overhearing and collisions.

  How to wake-up sensor nodes for receiving traffic ?
- Base station is energy unconstrained ➔
  - May listen to the channel all the time.
  - May transmit any amount of data and signaling traffic.

How to exploit the unlimited energy at the base station to save energy at the sensor node ?

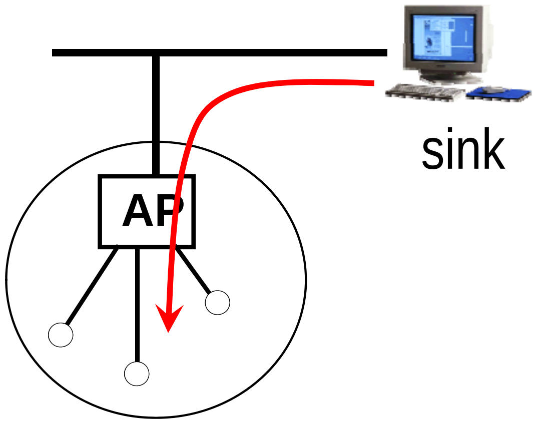
Low Power MAC Protocol for Uplink



- Kind of traffic: Periodic measurements, event detection reports
- Challenge: Minimize collisions
- Base station can listen all the time
- Traffic is far from congestion

Non persistent CSMA

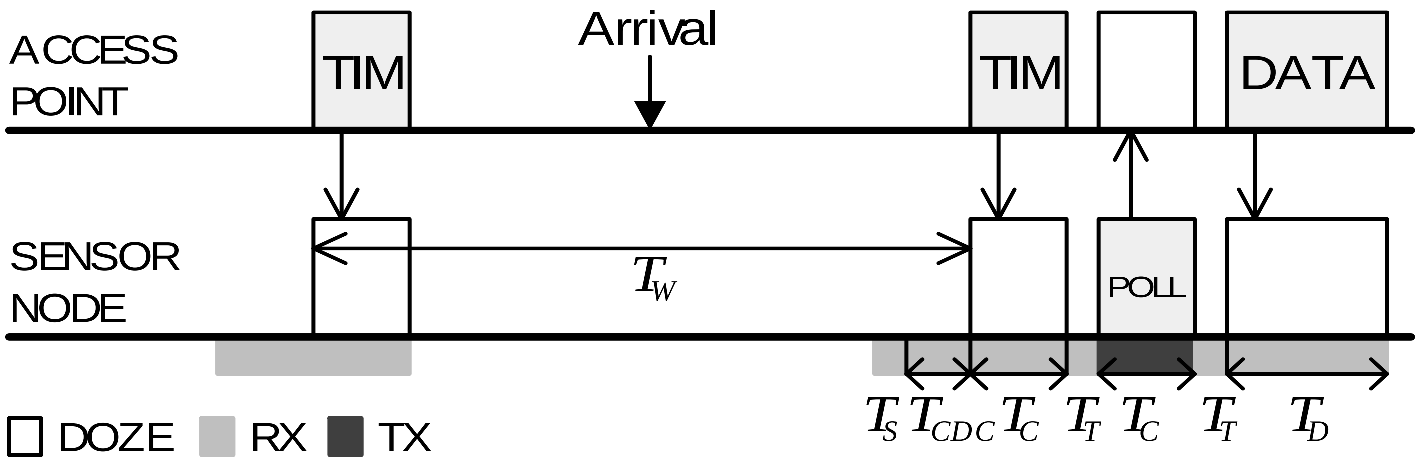
Low Power MAC Protocols for Downlink



- Kind of traffic: Queries, configuration commands.
- Challenge: Minimize idle listening and overhearing.
- MAC Protocols under consideration:
  - WiseMAC (Wireless Sensor MAC)
  - PTIP (Periodic Terminal Initiated Polling)
  - PSM (IEEE 802.11 and IEEE 802.15.4 Power Save Mode)

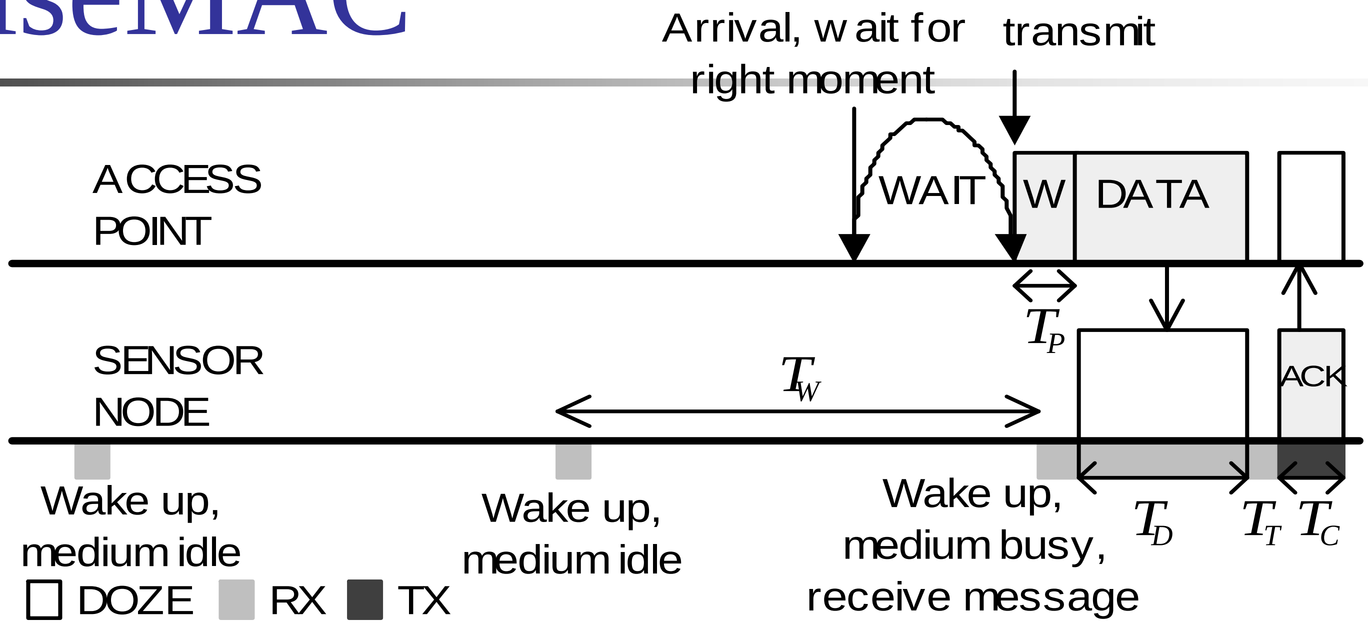
Original contributions

PSM



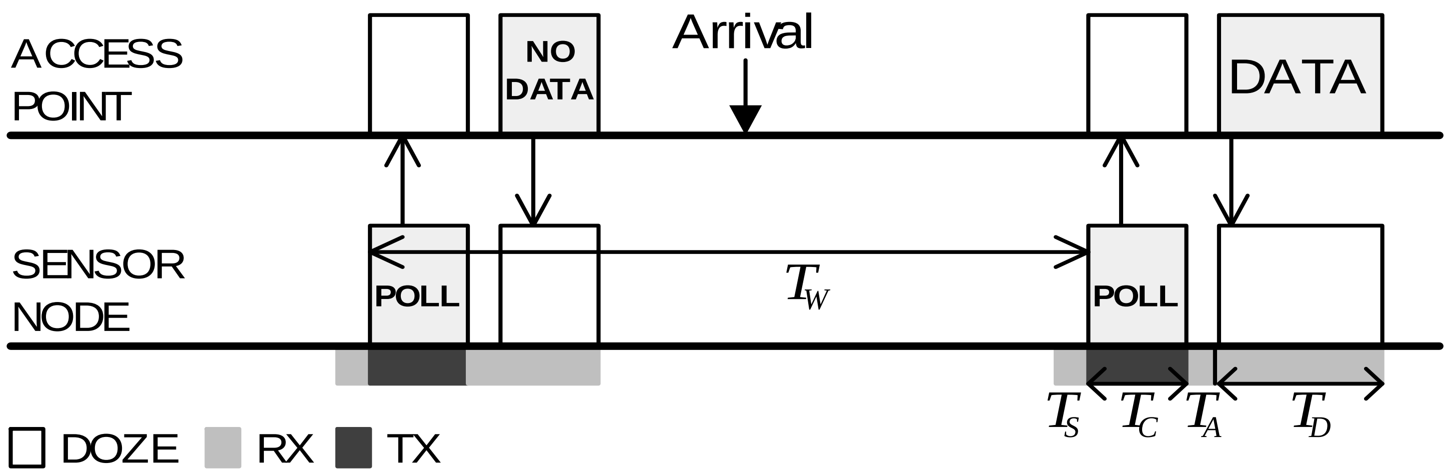
- Sensor nodes regularly wake-up to receive the traffic indication map.
- If a sensor node finds its address in the TIM, it polls the base station to receive the data packet(s).

WiseMAC



- Sensor nodes sample the medium to detect a wake-up preamble.
- Access points send wake-up preamble in front of data packets.
- APs learn the sampling schedule of sensor nodes (through ACK messages) & send messages at the right time, with a wake up preamble of minimized size.

PTIP



- *Sensor nodes periodically poll the access point to check for potential data packet(s).*

Performance Evaluation - Metrics

- Performance metrics:
  - Average power consumption P, and transmission delay D
- Protocol parameter:
  - Wake-up period T_W
- System parameters:
  - Power consumption in DOZE, RX and TX modes P_Z , P_R , P_T
  - Setup and turn-around time T_S , T_T
  - Quartz drift rate θ

Analytical Expressions

$$P_{WiseMAC} = P_Z + \frac{\hat{P}_R(T_S + 1/B)}{T_W} + \frac{\hat{P}_R(T_P/2 + T_D + T_T) + \hat{P}_T T_C}{L} + \hat{P}_R(N-1)\frac{(T_P + T_D)^2}{2LT_W}$$

$$D_{WiseMAC} = T_W/2 + T_P + T_D$$

$1/\lambda << T_D + T_T + T_C$ *(queuing negligible)*

$$P_{PTIP} = P_Z + e^{-\frac{T_W}{L}} \frac{\hat{P}_T T_C + \hat{P}_R(T_S + T_T + T_C)}{T_W} + \frac{\hat{P}_T T_C + \hat{P}_R(T_S + T_T + T_D)}{L}$$

$$D_{PTIP} = T_W/2 + T_T + T_D$$

$T_W << NT_C$ *(collisions negligible)*

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

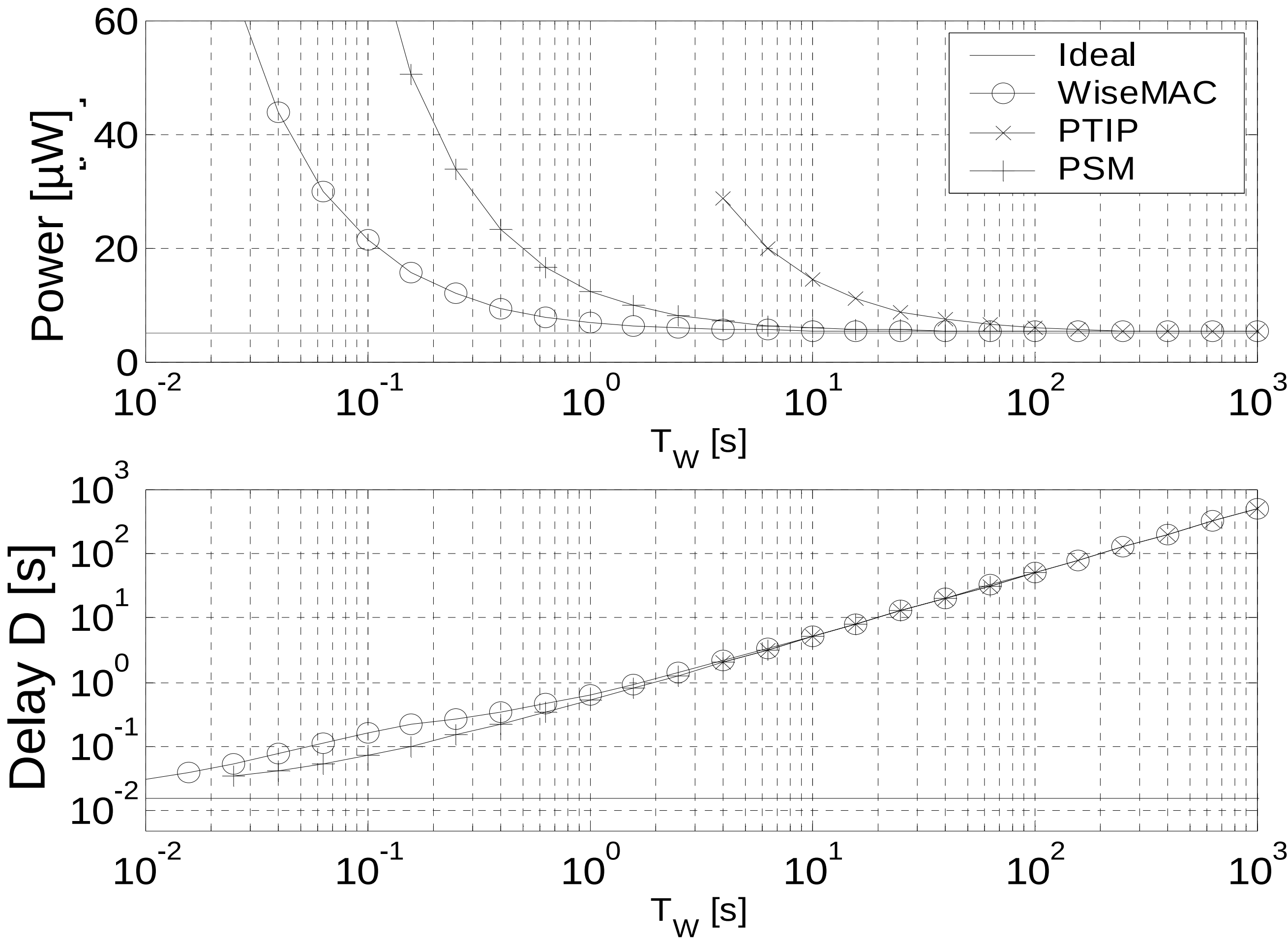
$$D_{PSM} = T_W/2 + 2T_C + 2T_T + T_D$$

$T_W \le 1/\lambda$ *(collisions negligible)*

Performance Evaluation - Results

- N=10,
- L=1000 s
- Data: 50 bytes
- Control: 10 bytes

- CSEM WiseNET® low power radio:
- P_R =1.8 mW
- P_T =27 mW



Conclusions on infrastructure (star) case

- In low traffic conditions, WiseMAC is significantly more energy efficient than PSM.

- When high latencies can be tolerated by an application, the very simple PTIP protocol becomes energy efficient.

Conclusions

- Protocols that were created for wireline comm. are not suited
- It is possible to achieve at the same time
  - Very low power consumption and low latency
- Pure TDMA may not be the solution because asynchronous solutions give similar results without the synchronisation pb.
- In WSN, communication is often the largest source of consumption
- One solution may be to switch between protocols depending on the traffic (having different modes)

- Routing has a large impact on consumption and latency

Choice

Criterion	Comments
Traffic model (deadline, period, inter arrival, ...)	Load evaluation for elimination or ranking.
Temporal guarantees	YES/NO ? Under which conditions ?
Reliability constraints	allows to reject solutions without retries
Maximum distance between nodes	allows to reject single hop solutions
Mobility or Immobility	allows to reject solutions based on long associations
Coexistence with other systems	allows to reject solutions that need planning
Dependence on Infrastructure or not	Allows to reject protocols that rely on this when this is not available
Single, Multiple sinks or Other patterns	Allows to reject protocols that do not support multiple sinks when this is needed by application
Energy constraints	If the constraint is on all nodes, this eliminates solutions with special coordination roles
Position referenced nodes	Allows reject protocols that need it when this is not available on the nodes
Simplicity	Ranking criterion

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