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Cyber Physical Systems

Corso di sistemi wireless a.a.2011/2012

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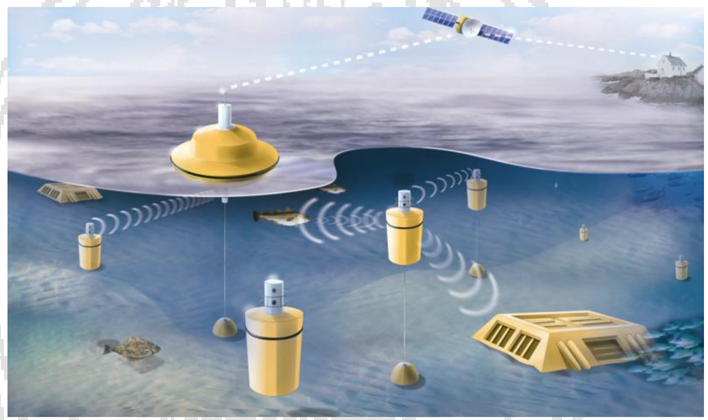
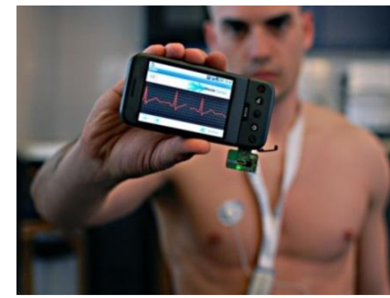
CBS – Cyber Physical Systems

- Come miliardi di sensori e computer miniaturizzati permetteranno di monitorare e controllare l'ambiente, i cambiamenti climatici e il consumo energetico delle citta'
- Un **cyber-physical system** (**CPS**) e' un sistema il cui funzionamento è basato su un coordinamento stretto tra elementi computazionali e oggetti fisici





Sensori fisici

Sensori ambientali

Sistemi embedded

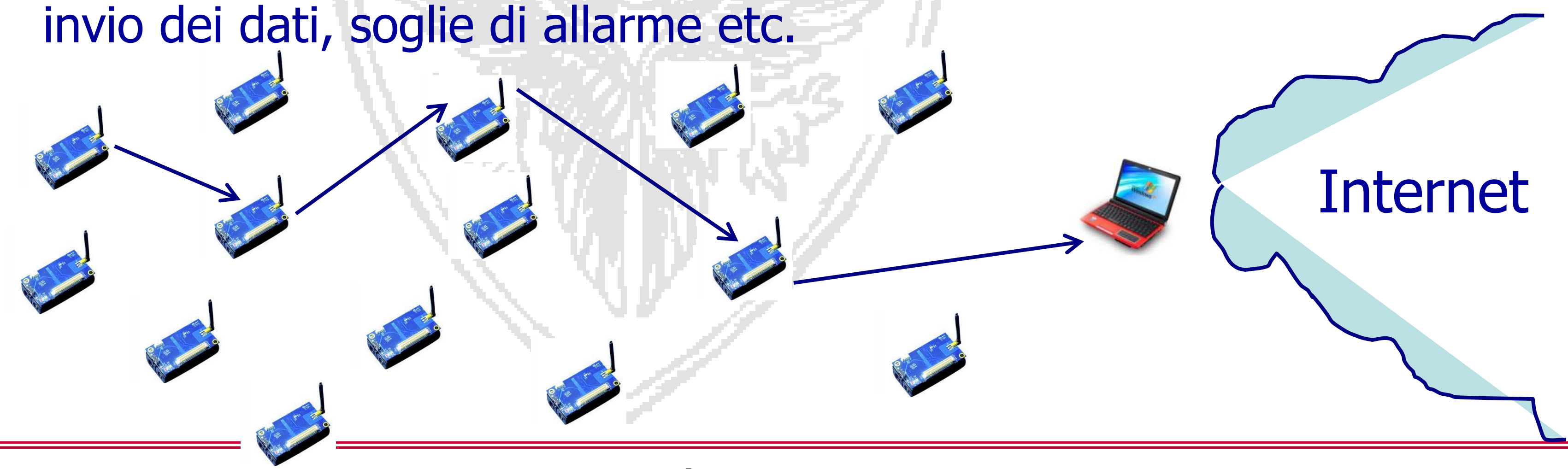
CPS: Osservazione del fenomeno

- Un cyber physical system prevede che gli oggetti fisici possano aver integrati elementi con capacità di calcolo, memorizzazione e comunicazione, che sono collegati in rete tra loro.

- Elemento base: nodo sensore, in grado di monitorare vari parametri di interesse del mondo che ci circonda
  - è in grado di monitorare i processi fisici.
  - tipici sensori integrati su un nodo: temperatura, umidità, luce, accelerometro, concentrazione di CO_2, polvere, presenza e prossimità, videocamera, inclinometro, cella di carico, barrette estensimetriche, livello di rumore, etc.
  - capacità di elaborazione, memorizzazione limitata. Risorse energetiche limitate

CPS: Comunicazioni dei dati

- Reti di sensori: i nodi sensori sono interconnessi
  - tipicamente tramite link radio
  - usando protocolli di comunicazione
  - inviano i dati su percorsi a più hop ad uno o più sink che svolgono il ruolo di gateway e inoltrano le informazioni verso un centro di raccolta ed analisi delle informazioni remoto
  - il sink comunica anche ai nodi sensori gli "interessi": le grandezze da monitorare, con quale frequenza, la frequenza di invio dei dati, soglie di allarme etc.



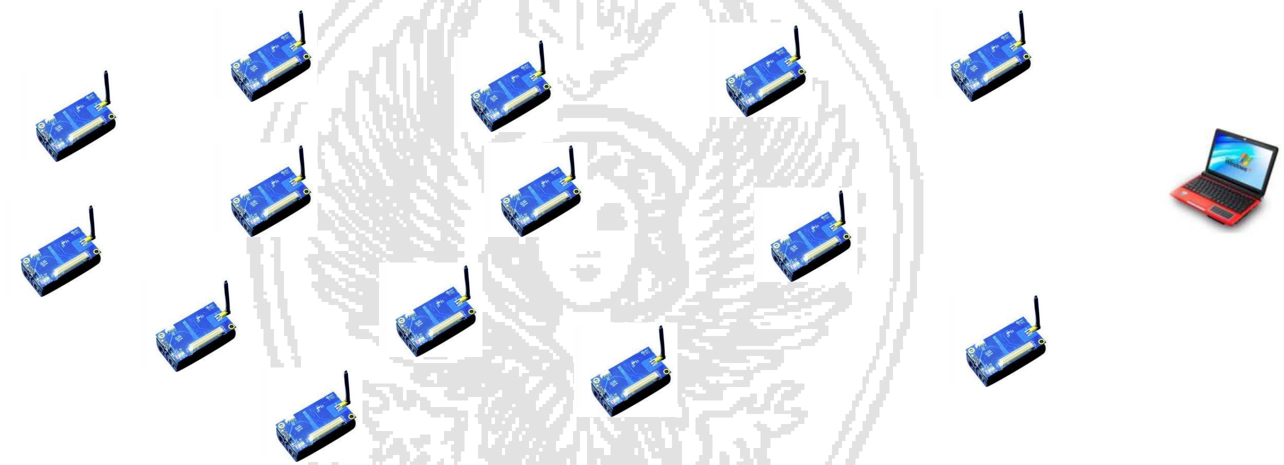
Problema del consumo energetico

- La comunicazione dell'informazione consuma energia
  - maggiore il raggio trasmissivo maggiore il consumo
  - maggiore l'informazione trasmessa maggiore il consumo
  - in ogni caso per sistemi long lasting è necessario evitare di mantenere attivo sempre il trasmettitore

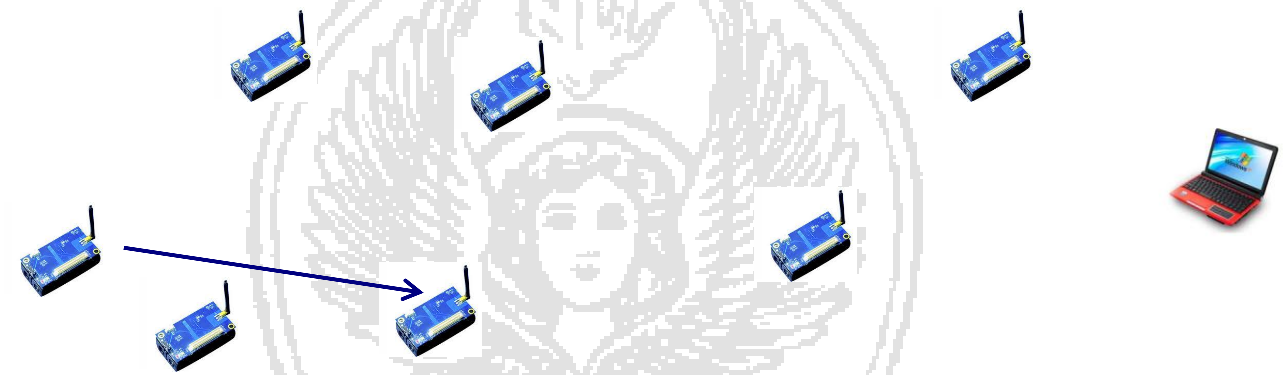
Stati del transceiver

$T_{ON}/(T_{ON}+T_{OFF})$= duty cycle

Reti di sensori con duty cycle



Reti di sensori con duty cycle



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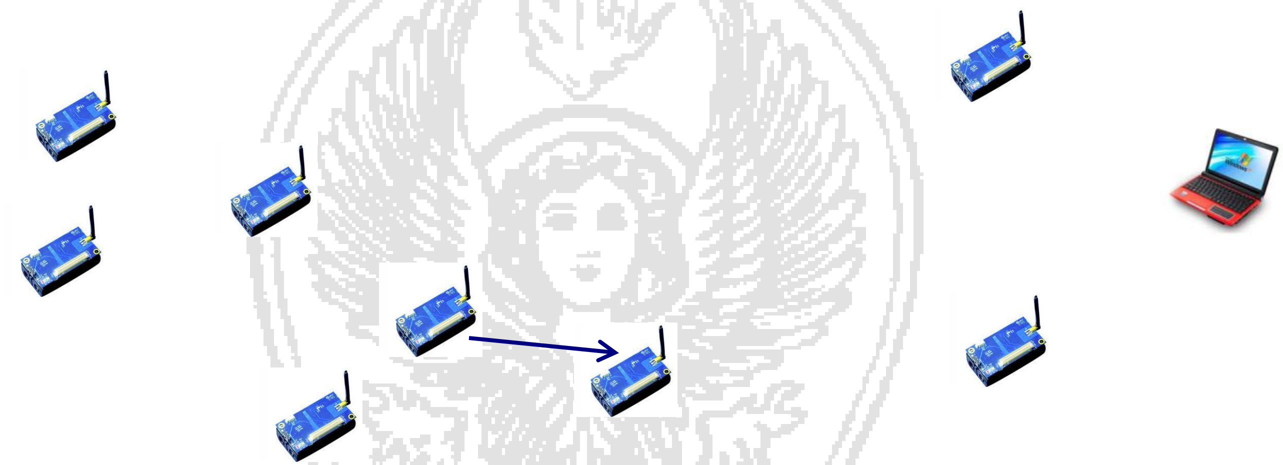
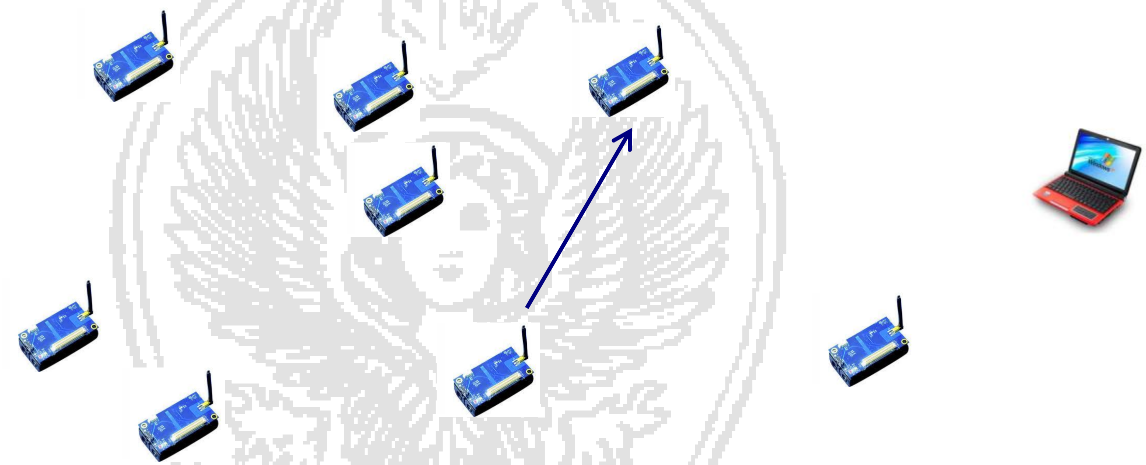


Reti di sensori con duty cycle



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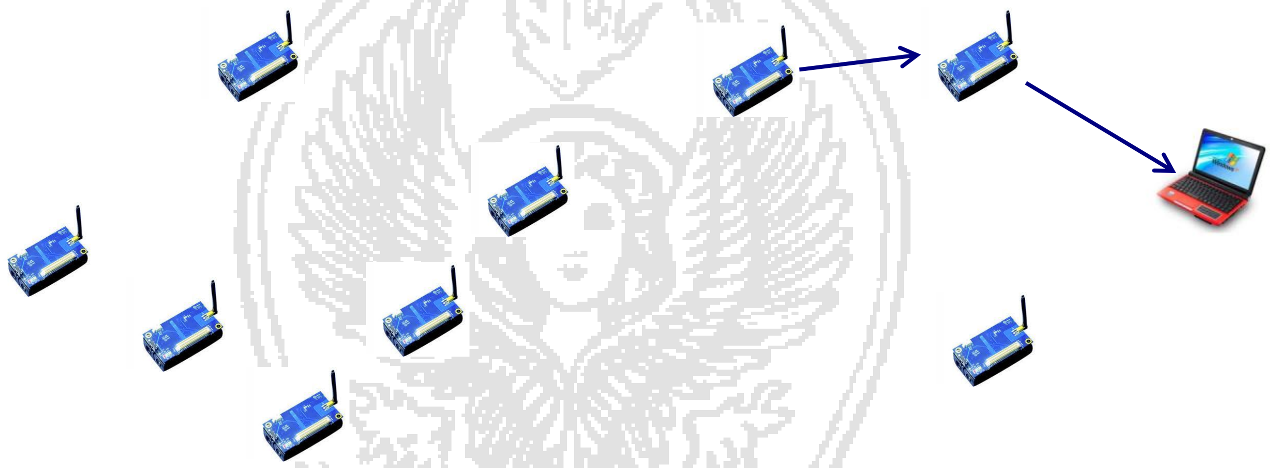


Alternativa: wake up radio concept

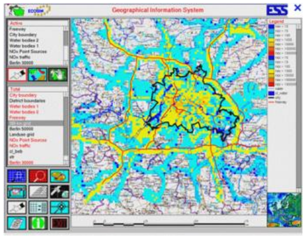
Osservazione & Comunicazione

- Allocazione di task ai sensori
- Cooperazione tra sensori per individuare eventi di interesse
- Awake/asleep schedule
- Comunicazione su un hop (protocolli di livello MAC e data link)
- Determinazione di percorsi da e verso il sink (tenendo conto dell'energia dei nodi, dell'affidabilità dei link, dello stato della coda etc.)
- Algoritmi per la fusione e aggregazione dei dati
- Protocolli per garantire la sicurezza dell'informazione scambiata

CPS – Elaborazione dell'informazione

- Processing dell'informazione per individuare eventi di interesse e correlazioni tra eventi e valori rilevati

- L'uso di tecniche di intelligenza artificiale
  - Data mining: scoperta di proprietà dei dati non note a priori
  - Machine learning: permette di predire l'evoluzione del sistema sulla base di tecniche di apprendimento automatico.



- CPS come:
  - Sistemi per il monitoraggio pervasivo del mondo che ci circonda
  - Sistemi che possono consentire di arricchire la conoscenza del mondo che ci circonda

CPS: Attuazione

- "Control loop"
  - In base all'individuazione di eventi ed alla comprensione dello stato del sistema possono essere fatti partire allarmi, richieste azioni (anche automatizzate- svolte da robot, AUV, etc.), possono essere controllati elettrodomestici e parametri ambientali (controllo dell'illuminazione/temperatura di una stanza, controllo di un sistema di irrigazione etc).
- Possono cambiare anche i parametri del sistema di monitoraggio (precisione/accuratezza dei dati da monitorare, grandezze di interesse, frequenza di campionamento delle grandezze da monitorare, frequenza con cui trasmettere dati, soglie di allarme etc)

Un esempio: gestione di una serra

- Agricoltura di precisione: Distributed robotic garden, MIT
  http://www.youtube.com/watch?v=BX2Zws94Oy0&feature=player_embedded
- Le piante di pomodori hanno un nodo sensore con sensore di umidità del suolo. Il sensore della pianta segnala la necessità di acqua.
- Navigazione automatica di un robot verso la pianta. I robot sanno innaffiare, raccogliere pomodori e mediante videocamera & image processing sanno riconoscere i pomodori maturi. Ricevono via wireless dagli utenti richiesta di raccogliere pomodori (e la quantità). Sanno coordinarsi in modo da svolgere richieste multiple in parallelo.

Robotic garden

- Multi-robot/multi-sensor system, Sensori e attuatori
- Algoritmi di task allocation per coordinare il team di robot, Navigation and path planning, Object recognition
- Controllo del movimento del robot
- Tiene conto di (e permette di aggiornare) modelli di crescita ideale delle piante

CPS: applicazioni

- Applicazioni:
  - Smart Grid & Energy efficient buildings;

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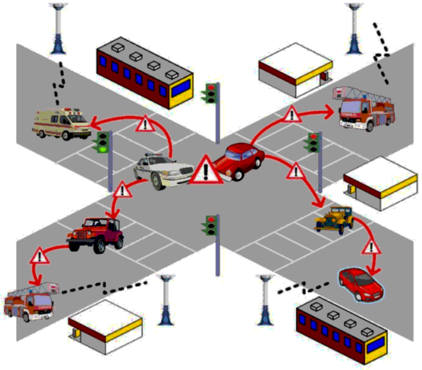
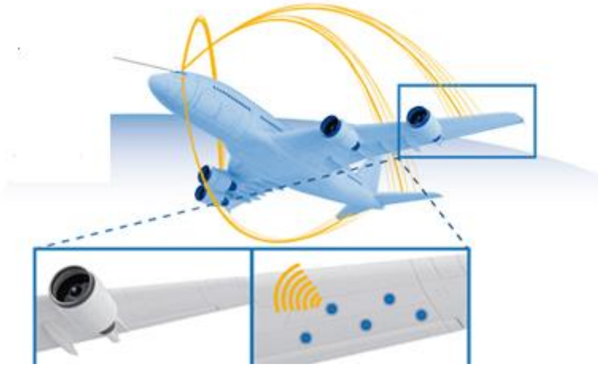
  - Smart Grid & Energy efficient buildings;
  - Advanced automotive systems;
  - Traffic control;
  - Critical infrastructure monitoring;
  - Environmental monitoring and control;
  - Water management;
  - Structural Health Monitoring;
  - Assisted Living&precision surgery;
  - Disaster Recovery & Early warning systems.





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  - Assisted Living&precision surgery;
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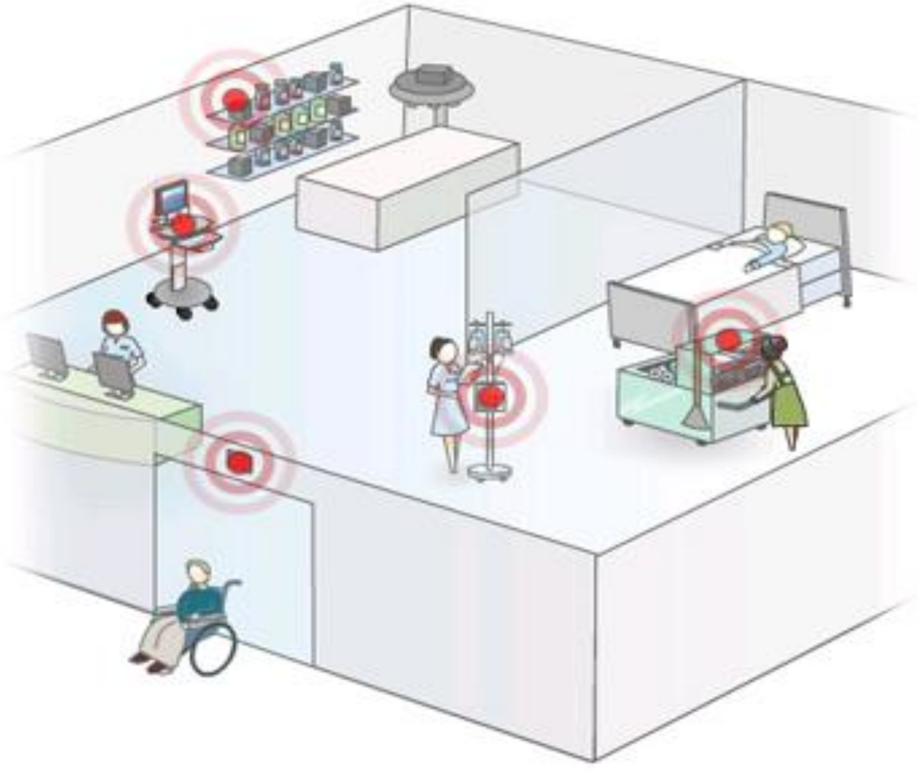
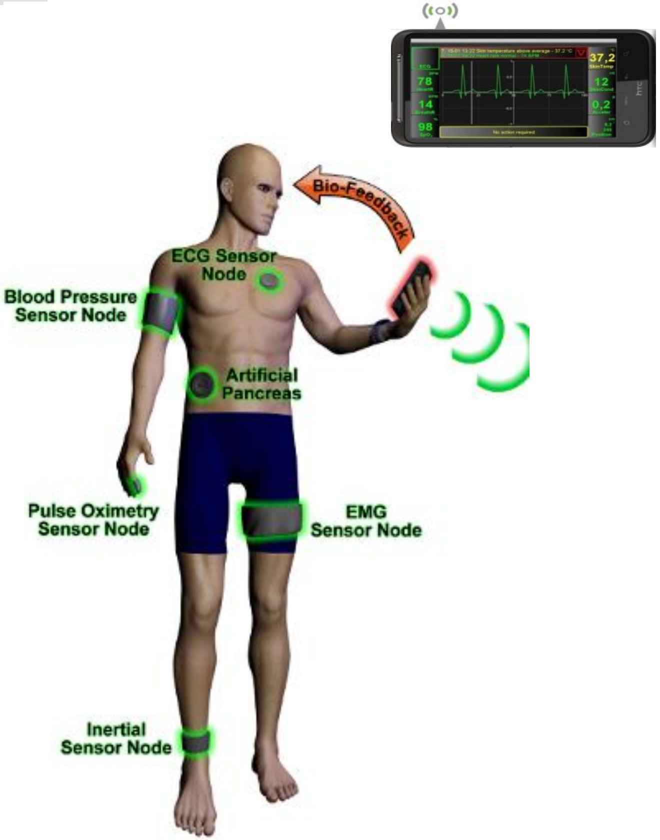
Applicazioni-Assisted Living

- Personal healthcare: monitoraggio di pazienti in ospedale o nelle proprie abitazioni mediante sensori fisici e ambientali





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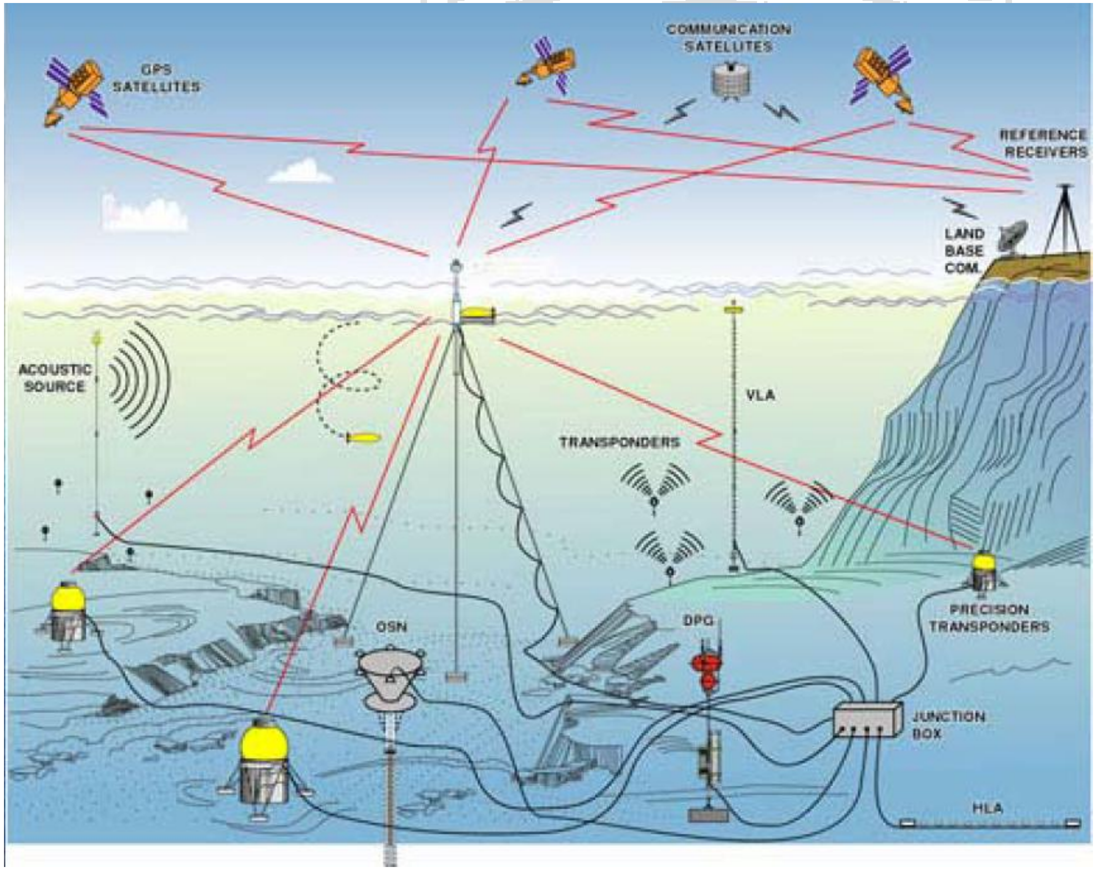
Applicazioni- Monitoraggio strutturale

- Green sensor networks: reti di sensori wireless basati su energie rinnovabili per il monitoraggio strutturale di edifici, strutture, monumenti, etc.

Applicazioni-Reti di sensori sottomarine

- Reti sottomarine di sensori wireless per monitoraggio terremoti, inquinamento, etc.



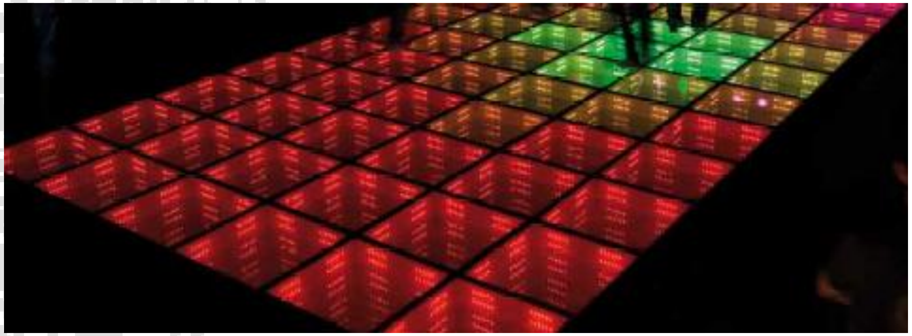
CPS: Big Challenges

- Basso impatto ambientale & Tempo di vita del sistema (Energy Neutral, Very long lasting systems)
  - Componenti e protocolli a basso consumo energetico
  - Energy harvesting dall'ambiente che ci circonda
- Sicurezza e affidabilità del sistema
  - in una situazione in cui gli ambienti di dispiegamento ed il basso costo dei dispositivi rendono probabile che possano accadere malfunzionamenti
- Adattività e proprietà self* del sistema
  - Adattività al contesto
  - Comprensione del sistema corretta e arricchita in corso d'opera
  - Nessuna manutenzione o ridotta manutenzione

Energy Harvesting

- **Energy Harvesting** è il processo per cui l'energia ambientale viene catturata, salvata e trasformata in energia elettrica direttamente utilizzabile.





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Cyber Physical Systems

- Strumento essenziale per la comprensione, il monitoraggio e controllo di fenomeni fisici complessi.
  - Elemento essenziale per lo studio dei cambiamenti climatici, il controllo dei consumi energetici e della produzione di energia, lo sviluppo di modelli per agricoltura di precisione, gestione delle risorse, produzione e vita sostenibili, la protezione dell'ambiente.
- Richiede competenze informatiche eterogenee (algoritmi, reti, sviluppo di sistemi distribuiti, sviluppo di architetture SW, programmazione embedded, elaborazione ed analisi dei dati, intelligenza artificiale, robotica) ed un approccio multidisciplinare ai problemi, grande creatività

What we can easily see is only a small percentage of what is possible.

Imagination is having the vision to see what is just below the surface; to picture that which is essential, but invisible to the eye.

Then to be or not to be is not the question; but to envision the future and set sail for your horizon.

http://reti.dsi.uniroma1.it/SENSES_lab/

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Protocolli MAC per reti di sensori

Sistemi Wireless, a.a. 2011/2012

Un. of Rome "La Sapienza"

Chiara Petrioli†

† *Department of Computer Science – University of Rome "Sapienza" – Italy*

S-MAC (Sensor MAC)

W. Ye, J. Heidemann, D. Estrin "An energy efficient MAC Protocol for Wireless Sensor Networks", IEEE Infocom 2002

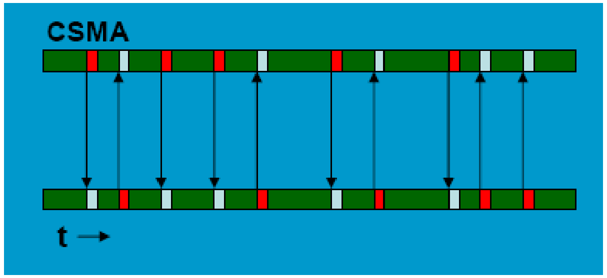
http://www.isi.edu/~johnh/PAPERS/Ye02a.pdf

Synchronized MAC based on duty cycle

Performance objectives

1) Energy efficiency

- Sources of energy waste
  - *collision*. When a transmitted packet is corrupted it has to be discarded, and the follow-on retransmissions increase energy consumption. Collision also increases latency as well.
  - *overhearing*, meaning that a node picks up packets that are destined to other nodes.
  - *control packet overhead*
  - *idle listening*, *i.e.*, listening to receive possible traffic that is not sent (major source of energy consumption).



2) End-to-end latency

3) Fairness

4) Network capacity/scalability (to density and traffic)

Nodes sleeping scheme

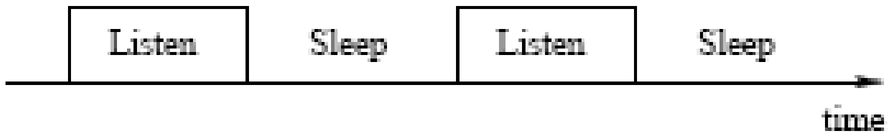


Fig. 1. Periodic listen and sleep.

- Nodes follow an awake/asleep schedule with a given duty cycle d
- In S-MAC nodes schedule are synchronized
  - all nodes transmit in the same slot and receive in the same slot if possible

Fig. 2. Neighboring nodes A and B have different schedules. They synchronize with nodes C and D respectively.

  - Periodic exhange of information is needed to resynch in case of clock drifts (in 0.5s the drift is a factor of 10^5 less-- if resynch every few tens seconds)

Choosing and maintaining schedules

- Before a node starts its periodic listen and sleep, it needs to choose a schedule and broadcast it to its immediate neighbors (schedule exchange).
  - at start up node x listens for some random time
    - ✓ if x receives a SYN from another node y it synchronize to its schedule (x is a *follower*). It waits for a random delay t_d and rebroadcast its schedule.
      - follower of the same synchronizer do not collide thanks to t_d
    - ✓ otherwise node x selects a random time t to sleep before waking again and send this to neighbors in a SYN (x is a *synchronizer*)
    - ✓ if a node receives a different schedule after it selects its own it adopts both schedule, broadcasting the new one
      - "border nodes" where two synch waves meet are the ones with multiple schedules
        - » they consume more energy
- Each node also maintains a *schedule table* that stores the schedules of all its known neighbors.

When a node has a packet to send

- It waits for the destination to be ON and sends the packet following CSMA/CA
  - performs carrier sense for a random interval
  - if no transmission within this interval the floor is taken (physical carrier sense) to transmit RTS/CTS
  - if the RTS/CTS is successful (virtual carrier sensing) DATA is sent which is followed by an ACK
  - NAVs are used for deciding for how long nodes should go to sleep before they can try to access again in case neighbors are transmitting
  - to better exploit the time needed to hanshake (RTS/CTS) bursts of packets are transmitted if more packets are in queue for the same destination

Maintaining synchronization

- Some initially exchanged SYN maybe lost e.g. due to collision, or new nodes maybe added
- Clock drifts

How do we keep nodes schedules up to date and synchronized?

- A node periodically sends a SYN.
- For nodes to receive SYN and DATA listen times are divided into two intervals

Maintaining synchronization

- Some initially exchanged SYN maybe lost e.g. due to collision, (
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How do we I ... and synchroni

- A node p
- For node ... times are divided in

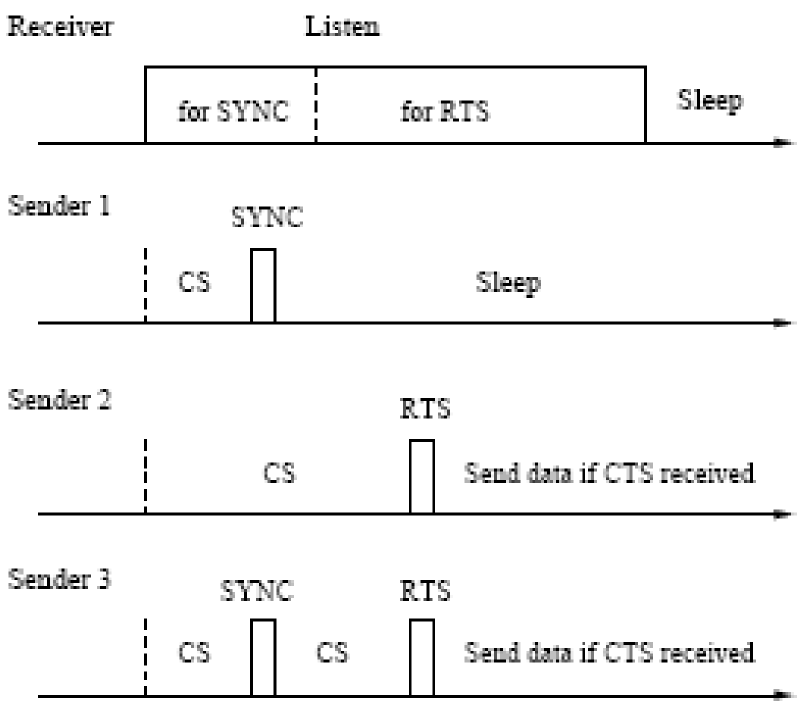


Fig. 3. Timing relationship between a receiver and different senders. CS stands for carrier sense.

Maintaining synchronization

How do we keep nodes schedules up to date and synchronized?

- A node periodically sends a SYN.
- For nodes to receive SYN and DATA listen times are divided into two intervals

New nodes in the network

- When a new node joins the network it listens for enough time to be able to become a follower of a node of which it receives the SYN (provided there is one)
- All nodes periodically transmit SYN even if they don't have followers

S-MAC: Limits

- Needs synchronization
  - even if clock drifts are not a major problem synchronization adds control overhead which may impair long lifetimes (e.g., in those applications where communication needs are sporadic)
- Throughput is reduced since only the active part of the frame is used for communication
  - all synchronized to the same time
  - SYN part control overhead
- Latency increases since when a node generates a packet it has to wait for the next hop relay on time before the packet can be forwarded.

T-MAC (Timeout MAC)

Tijs van Dam, Koen Langendoen “An adaptive energy efficient MAC Protocol for Wireless Sensor Networks”, ACM SenSys 2003

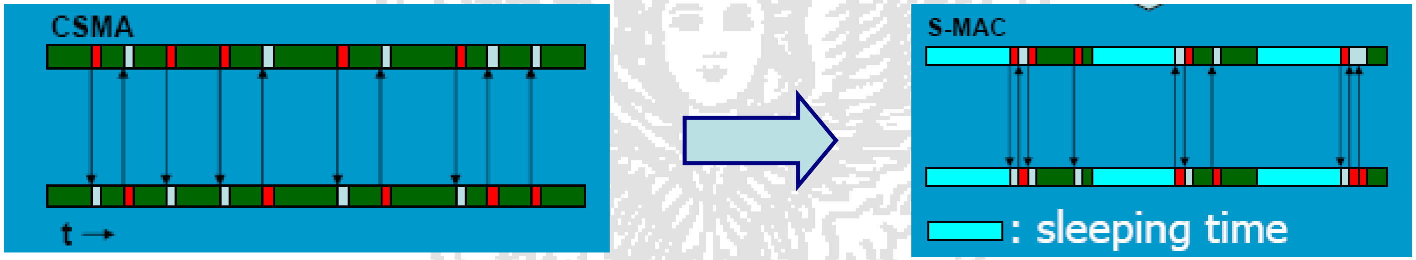
http://www.consensus.tudelft.nl/documents_papers/vanDam03.pdf

Synchronized MAC based on duty cycle

(STUDIO OPZIONALE)

T-MAC

- Observation: In SMAC there are two critical parameters (the active time and the frame time)
  - a long frame time increases latency
  - given an active time the longer the frame time the lower the energy consumption
  - the active time should be dimensioned based on traffic: for a frame time the higher the traffic, the longer the active time should be



  - In SMAC the two parameters are fixed
    - ✓ setting should depend on worst case
  - in TMAC the frame time is fixed but the active time is dynamically adapted

T-MAC: adaptive active times

- Adaptive active times

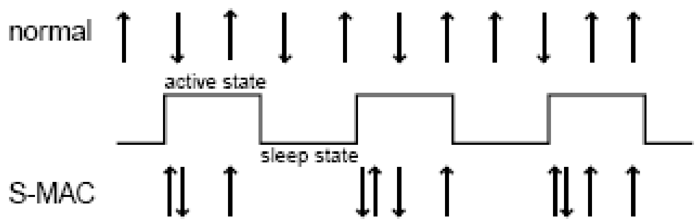


Figure 1: The S-MAC duty cycle; the arrows indicate transmitted and received messages; note that messages come closer together.

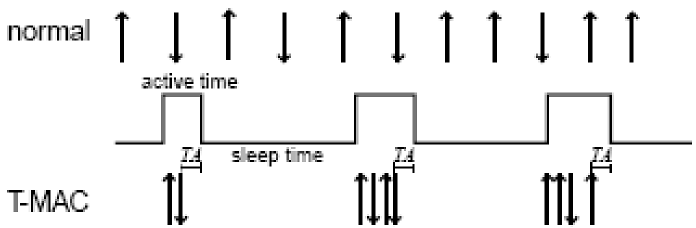
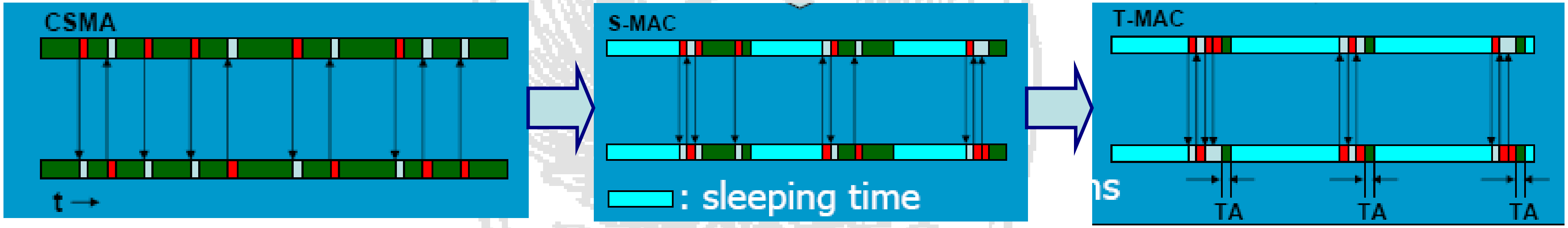


Figure 2: The basic T-MAC protocol scheme, with adaptive active times.

T-MAC

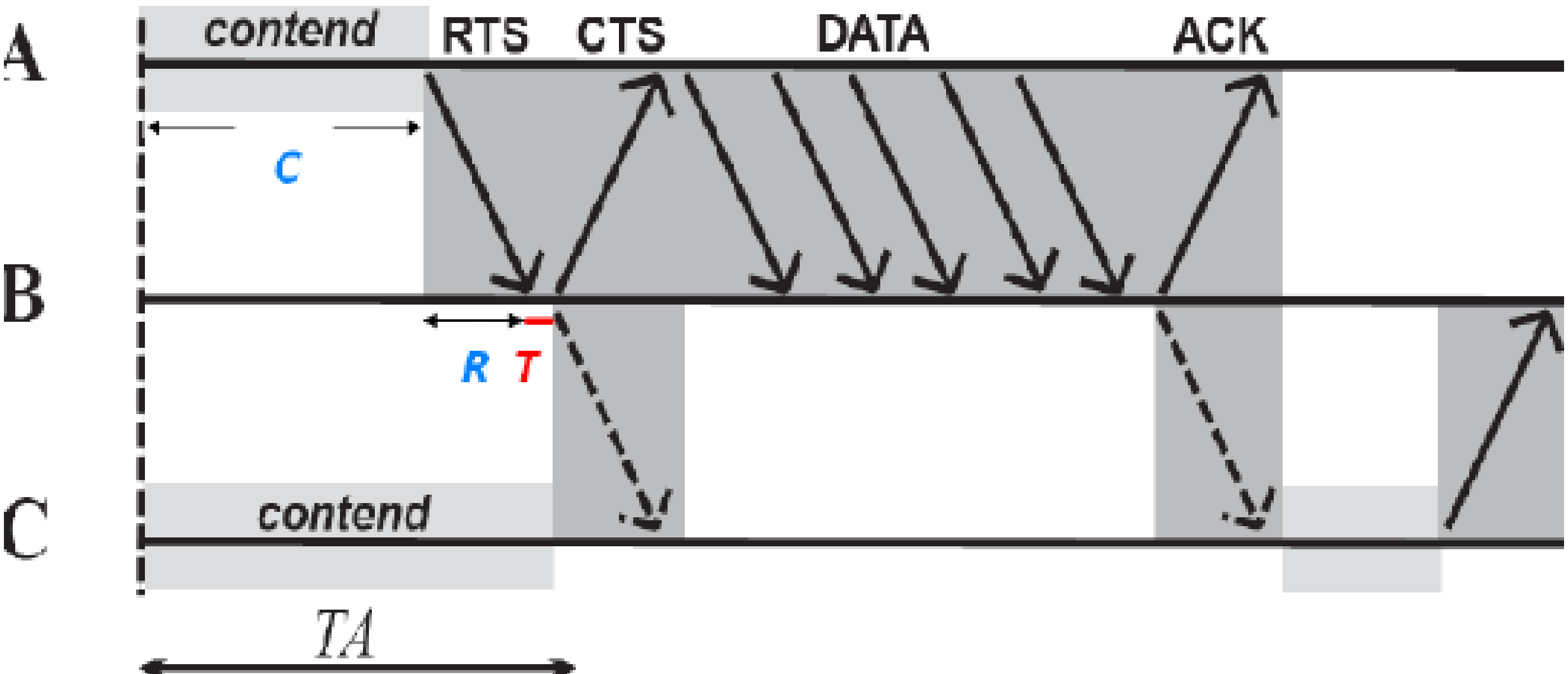
- Nodes synchronize their schedules using the SMAC virtual clustering approach.
- Within an active time CSMA/CA and back to back packet transmission in bursts are adopted
- Changes from S-MAC: if no transmission from neighbors for a time TA the active time is aborted and node goes to sleep



- TA timer is renewed if any data is received on the radio, communication (e.g, collision) is sensed on the radio, data are transmitted, RTS/CTS are exchanged by neighbors
  - ✓ A node should not go to sleep while its neighbors are still communicating since it maybe the receiver of a subsequent message

How to determine TA

Determining of TA



- TA > C+R+T (must be long enough to receive at least the start of the CTS packet)

T-MAC

- other changes from SMAC:
  - When a node sends an RTS but does not receive a CTS back this may be due to
    - ✓ 1) the RTS was not received due to collisions
    - ✓ 2) the receiving node cannot answer due to an RTS/CTS overheard
    - ✓ 3) the receiving node is sleeping

    In cases 1-2) reducing the active time would be wrong
    - " a node should retry by resending the RTS at least twice before giving up and going to sleep"
  - early sleep may degrade throughput (while decreasing idle listening and energy consumption)
    - ✓ mechanisms introduced to signal to nodes there is traffic for them at the beginning of the active time to prevent them from going to sleep
    - ✓ separate cases handled→ not clean solution

BMAC (Berkeley Media Access Control)

- Polastre, Hill, Culler "Versatile Low Power Media Access for Wireless Sensor Networks" , ACM SenSys 2004

http://www.polastre.com/papers/sensys04-bmac.pdf

- Asynchronous MAC

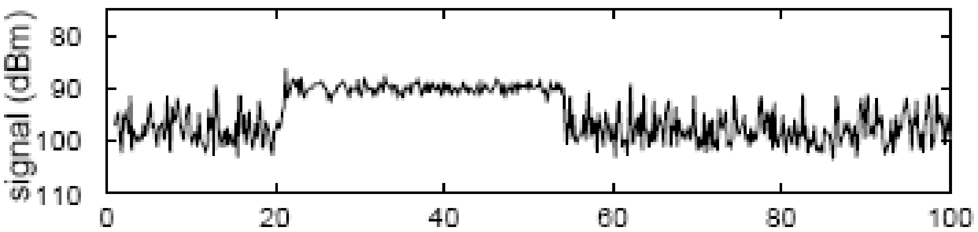
Targets

A MAC for wireless sensor networks

- Should have Low Power Operation
- Should perform effective Collision Avoidance
- Simple Implementation, Small Code and RAM Size
- Efficient Channel Utilization at Low and High Data Rates
- Reconfigurable by Network Protocols
- Tolerant to Changing RF/Networking Conditions
  - links can be dynamic
- Scalable to Large Numbers of Nodes

B-MAC

- For effective collision avoidance, a MAC protocol must be able to accurately determine if the channel is clear—Clear Channel Assessment or CCA
  - BMAC proposes a way to estimate the channel noise
    - ✓ samples taken at time (e.g., after transmission) when no transmission is assumed
    - ✓ exponential weighted moving average to estimate noise floor
  - and to determine whether the channel is free (taking some samples and checking whether any of the sample is significantly below the noise level)
    - ✓ Outlier approach
    - ✓ the proposed solution for channel assessment has been validated with experimental data



B-MAC & Low Power Listening

RECEIVER SIDE

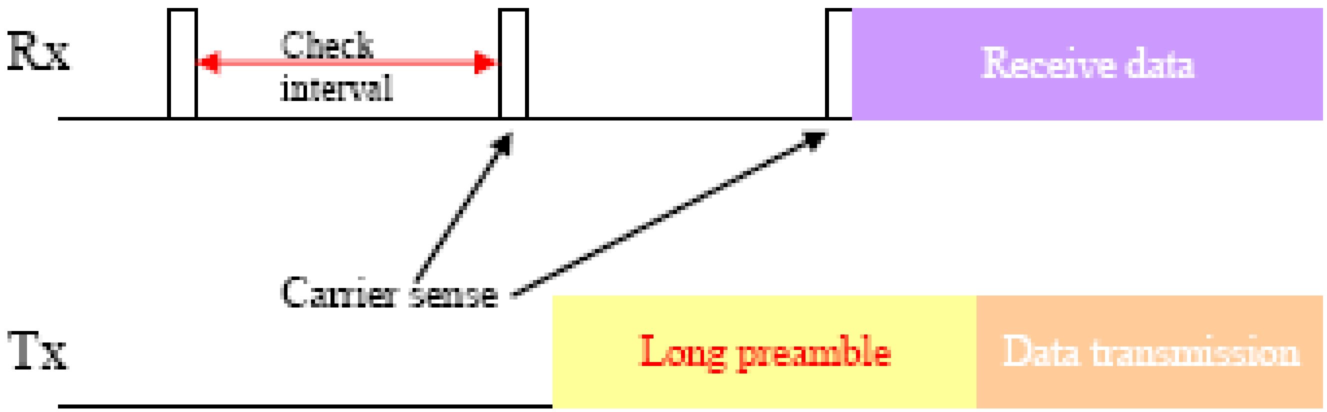
- B-MAC duty cycles the radio through periodic channel sampling (low power listening)
  - Each time the node wakes up, it turns on the radio and checks for activity. If activity is detected, the node powers up and stays awake for the time required to receive the incoming packet. After reception (or after a timeout expiration), the node returns to sleep. → CCA should not have false positives

TRANSMITTER SIDE

- The sender transmits a preamble, then the data
  - To reliably receive data, the preamble length is matched to the interval that the channel is checked for activity

B-MAC

Shifts most burden to the sender



<u>Challenge</u>

Check interval has to be short to ensure reasonable size preambles

XMAC

Buettner,Yee,Anderson, Han "X-MAC: A short preamble MAC protocol for duty cycled wireless sensor networks", http://www.cs.colorado.edu/department/publications/reports/docs/CU-CS-1008-06.pdf

ACM Sensys 2006

Starting point for XMAC

- A key advantage of asynchronous low power listening protocols such as BMAC is that sender and receiver can be completely decoupled in their duty cycles
  - no need for synchronization which requires periodic beaconing and exchange of information
- BMAC long preamble in low power listening however leads to performance degradation
  - the receiver has to wait for the full period until the preamble is finished before the data/ack exchange can begin, even if the receiver has woken up at the start of the preamble
    - ✓ increase in latency and energy consumption
  - overhearing problem
    - ✓ receivers who are not in the target of the sender also wake up during the long premable and have to stay on until the end of it to discover they are not the intended destination
      - Increase in energy consumption!
  - latency degradation
    - ✓ per hop latency lower bounded by preamble length

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XMAC

- Ideas
  - embed address info of the intended destination in the preamble
    - ✓ to avoid overhearing
  - use a *strobed preamble* : the preamble is a series of short preambles. Pauses between the short preambles allow the destination to send a fast ACK when up
    - ✓ reception of an early ACK makes the sender stop sending short preambles
      - the preamble is automatically set to the right size

XMAC

- Ideas
  - embed address info of the intended destination in the preamble
    - ✓ to a
  - use a *s* ... short preambl ... w the destinat
    - ✓ rece ... ing short prea
      - –

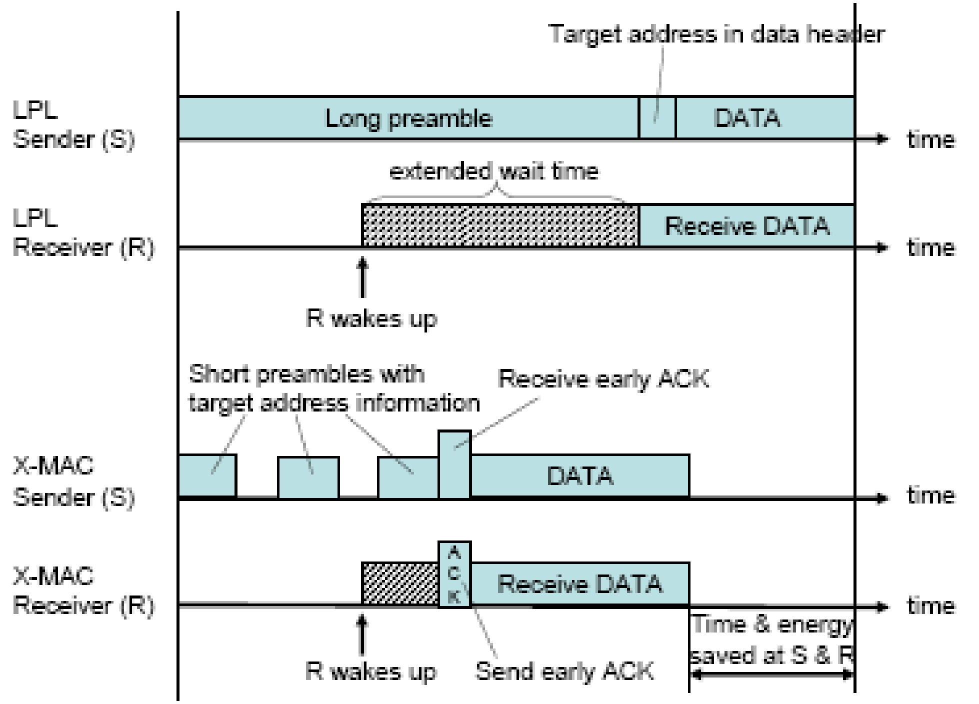


Figure 1. Comparison of the timelines between LPL's extended preamble and X-MAC's short preamble approach.

X-MAC additional contributions

- If two transmitter are trying to transmit to the same destination
  - with BMAC each has to transmit the long preamble
  - in XMAC: when a transmitter which is trying to send a packet to destination D overhears a preamble to D randomly selects a backoff
    - ✓ long enough to ensure that it will try to access the channel after the end of the current transmission
  - and then transmits its data to D without a preamble
- The nodes ON time must be long enough
  - longer than gaps in the strobed premables
  - longer than backoff lengths

To be sure that a transmitter will be able to find the destination ON

RI-MAC

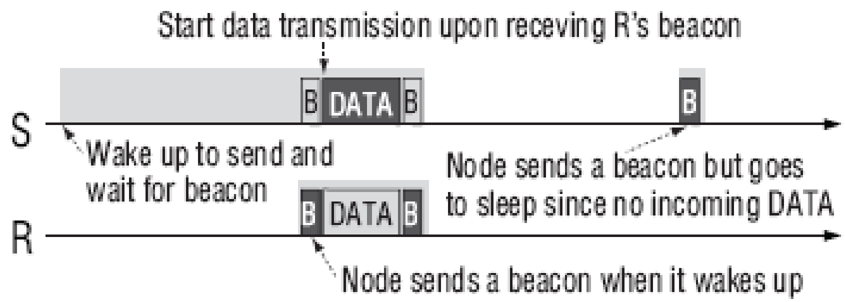
Y.Sun, O. Gurewits, D.B.Johnson "RI-MAC: A receiver initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks",

http://www.cs.rice.edu/~yanjun/research/sensys08.pdf

ACM SenSys 2008

Ri-MAC

- High overhead of LPL (due to long preambles) is critical in high load scenarios which may occur
- Solution: receiver initiated MAC (RI-MAC)
  - When a node wakes up if the medium is idle transmits a short beacon
  - A node with data to send stays up until it receives the destination beacon
    - ✓ When it receives the beacon it sends the data which is acknowledged by a new beacon



Overview of RI-MAC. Each node periodically wakes up and broadcasts a beacon. When node *S* wants to send a DATA frame to node *R*, it stays active silently and starts DATA transmission upon receiving a beacon from *R*. Node *S* later wakes up but goes to sleep after transmitting a beacon frame

RI-MAC

- Node x wakes up
  - It sense the channel
    - ✓ Clear medium –> transmit beacon
    - ✓ Busy medium → backoff and try again
- If it receives a data packet for it
  - It ACKs it piggybacking the ACK in a beacon
  - Dwell time: time the node remain active aftre a data packet reception (for possible other data)
- If node x does not receive any data after a short time following the beacon transmission it goes back to sleep
  - For a time associated to the first (short) backoff window
- Beacon contain also a BW (backoff windos) estimate
  - exponential increase in BW managed by the receiver in case of collisions

A-MAC

P. Butta, S. Dawson-Haggerty, Y. Chen, C Liang, A. Terzis "Design and evaluation of a Versatile and Efficient receiver Initiated Link Layer for Low Power Wireless", ACM SenSys 2010