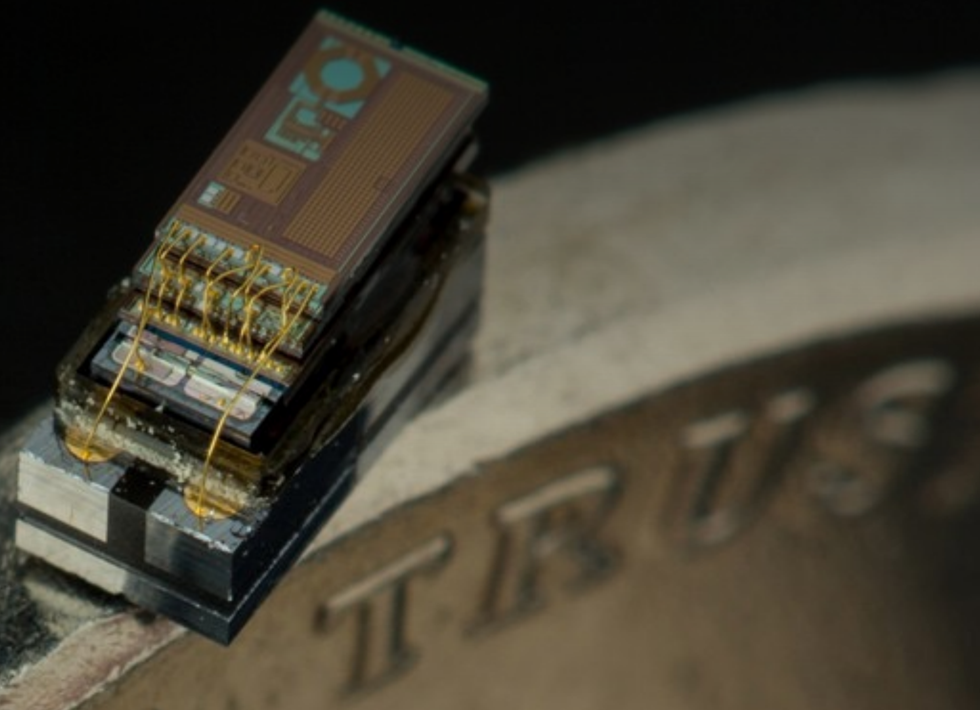
Constrained Networking

MAC Protocols



Geoff Merrett

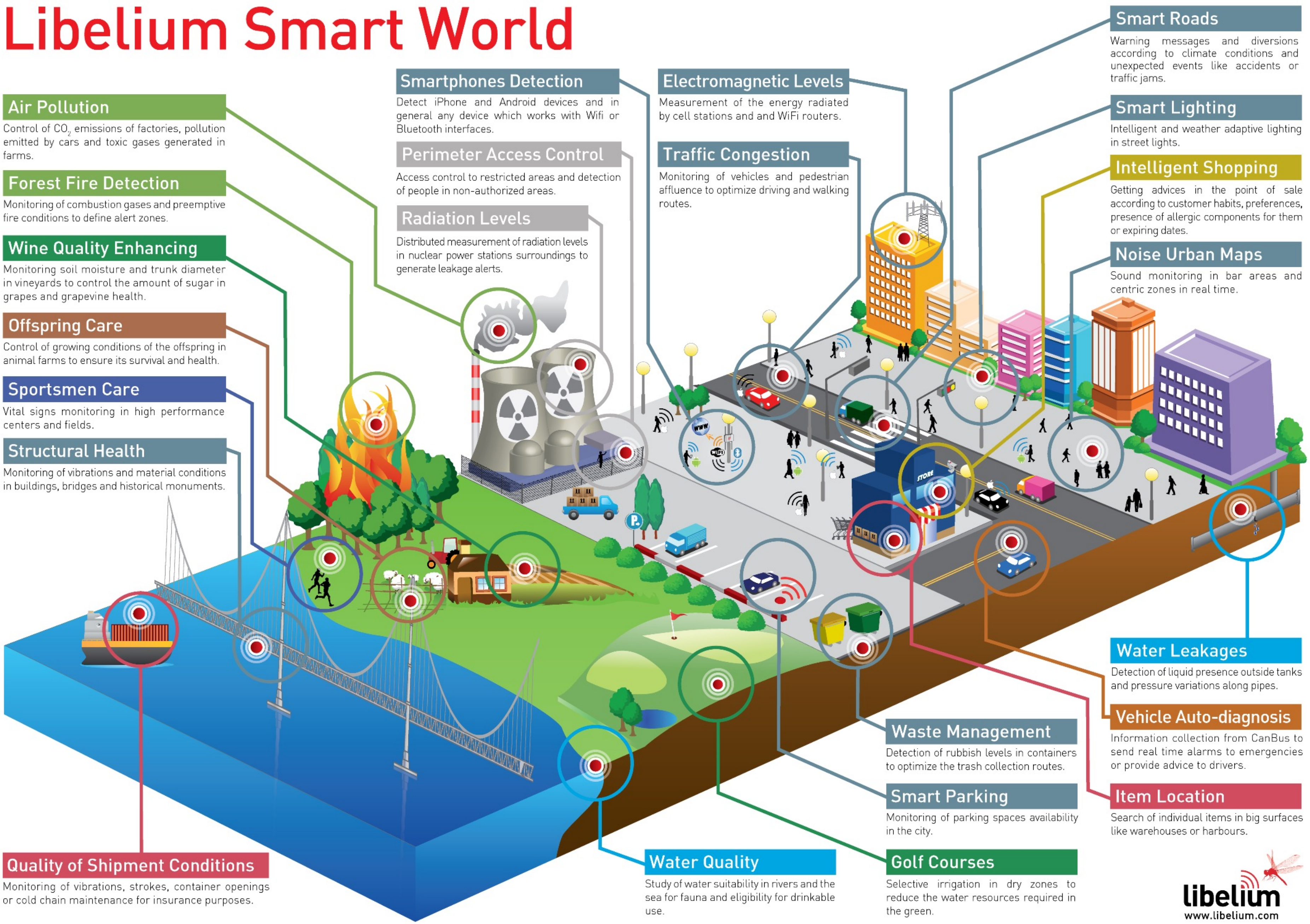
ELEC3227: Embedded Networked Systems

*Image: https://cdn-images-1.medium.com/max/2000/1*Pmbz0lEounzZL_xc1yt7Tw.jpeg [University of Michigan]*

Outline

- IoT (or WSN/Pervasive/Ubiquitous) networking requirements
- Power consumption
  - Of constrained and non-constrained devices
  - Reducing through low-power states and duty-cycled operation
  - Approximate models to evaluate the consumption of different approaches
- B-MAC (*Berkeley MAC*)
  - Asynchronous MAC protocol for constrained (computation/memory/power) devices
  - Low Power Listening (LPL)
  - Extensions and optimisations
  - This is just an example; there are lots of others (that perform better)!

- *Not the only part of the story, PHY, NET, TRANS etc also play a part!*



Libelium Smart World
Air Pollution
Control of CO_2 emissions of factories, pollution emitted by cars and toxic gases generated in farms.
Forest Fire Detection
Monitoring of combustion gases and preemptive fire conditions to define alert zones.
Wine Quality Enhancing
Monitoring soil moisture and trunk diameter in vineyards to control the amount of sugar in grapes and grapevine health.
Offspring Care
Control of growing conditions of the offspring in animal farms to ensure its survival and health.
Sportsmen Care
Vital signs monitoring in high performance centers and fields.
Structural Health
Monitoring of vibrations and material conditions in buildings, bridges and historical monuments.
Smartphones Detection
Detect iPhone and Android devices and in general any device which works with Wifi or Bluetooth interfaces.
Perimeter Access Control
Access control to restricted areas and detection of people in non-authorized areas.
Radiation Levels
Distributed measurement of radiation levels in nuclear power stations surroundings to generate leakage alerts.
Electromagnetic Levels
Measurement of the energy radiated by cell stations and and WiFi routers.
Traffic Congestion
Monitoring of vehicles and pedestrian affluence to optimize driving and walking routes.
Smart Roads
Warning messages and diversions according to climate conditions and unexpected events like accidents or traffic jams.
Smart Lighting
Intelligent and weather adaptive lighting in street lights.
Intelligent Shopping
Getting advices in the point of sale according to customer habits, preferences, presence of allergic components for them or expiring dates.
Noise Urban Maps
Sound monitoring in bar areas and centric zones in real time.
WWW
STORE
P
Water Leakages
Detection of liquid presence outside tanks and pressure variations along pipes.
Vehicle Auto-diagnosis
Information collection from CanBus to send real time alarms to emergencies or provide advice to drivers.
Waste Management
Detection of rubbish levels in containers to optimize the trash collection routes.
Smart Parking
Monitoring of parking spaces availability in the city.
Item Location
Search of individual items in big surfaces like warehouses or harbours.
Quality of Shipment Conditions
Monitoring of vibrations, strokes, container openings or cold chain maintenance for insurance purposes.
Water Quality
Study of water suitability in rivers and the sea for fauna and eligibility for drinkable use.
Golf Courses
Selective irrigation in dry zones to reduce the water resources required in the green.
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www.libelium.com

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Embedded Sensing Devices

MICAZ Mote

Image Credit GE Energy, ©2009 General Electric Company

Networking Power Consumption

Android Phone

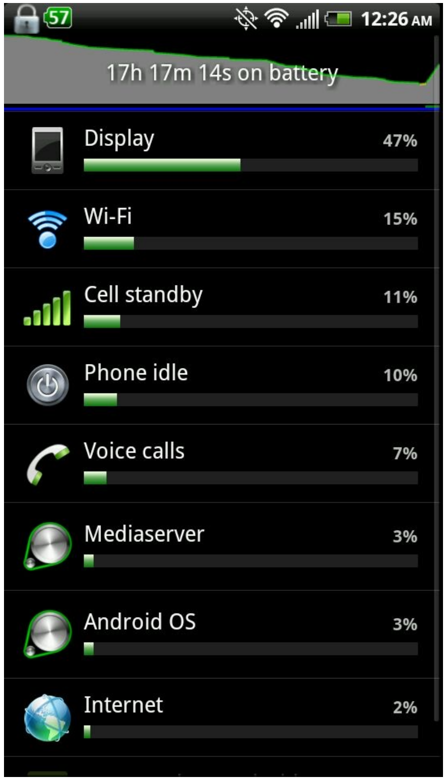


Image: http://droidlessons.com/how-to-check-battery-usage-on-android/

Windows 7 Laptop

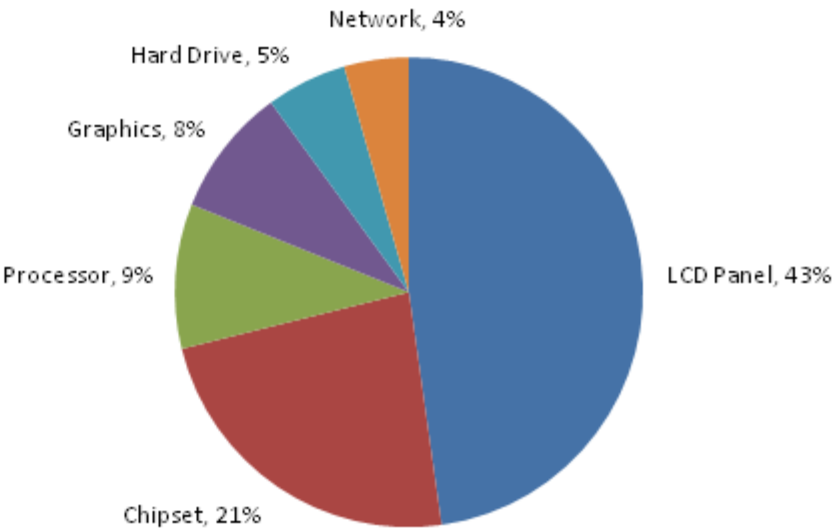
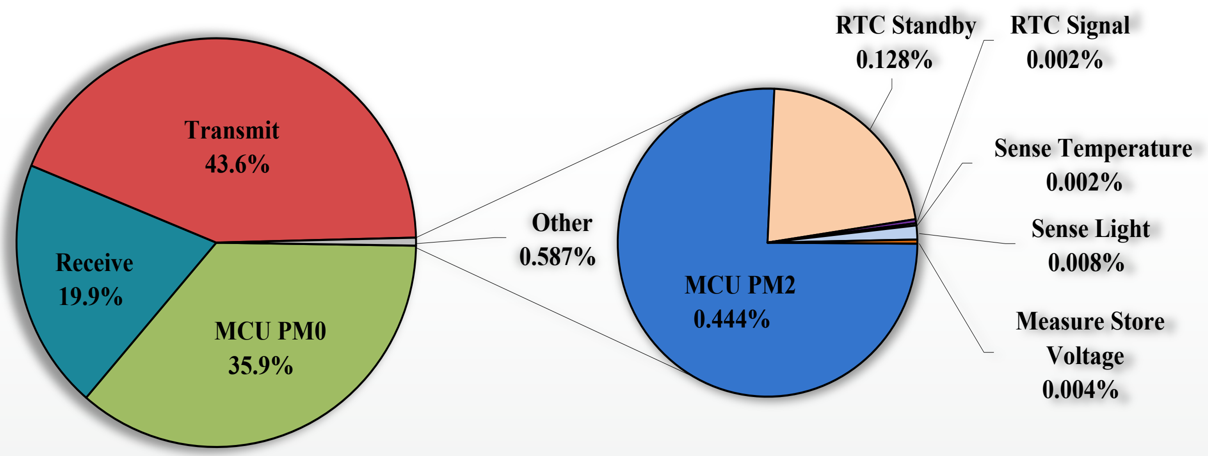


Image: http://blogs.msdn.com/b/e7/archive/2009/01/06/windows-7-energy-efficiency.aspx

Networking Power Consumption

- For example...



Merrett, G. V., Weddell, A. S., Lewis, A. P., Harris, N. R., Al-Hashimi, B. M. and White, N. M. (2008) An Empirical Energy Model for Supercapacitor Powered Wireless Sensor Nodes. In: *17th International IEEE Conference on Computer Communications and Networks*, 03-07 August 2008, St Thomas, Virgin Islands (USA).

IoT Applications

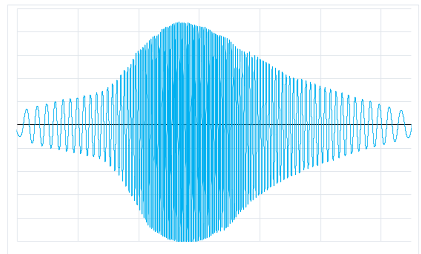
- Low-data rates
  - Typically not used to send multimedia data (*if do, usually locally pre-processed*)
  - Instead, occasional data from sensors
- Low through-put
  - Typically, might sample sensors and transmit data once every few minutes
- Latency less important
  - Typically ok if the data arrives a few seconds/minutes after it's generated
- Low power consumption is important
  - Need to operate from batteries for a LONG time, e.g. 10 years; why?

Power Sources

- We can recharge batteries!
  - So what's the problem?
- More nodes = batteries/wires/people
- Fit-and-forget/maintenance issues
  - Smart homes/grid/metering

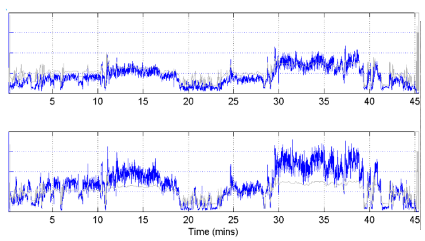
image: RS fabrications, http://www.rsfabrications.com/wp-content/uploads/2009/09/cimg2821.jpg
image: Kirk Martinez and Phil Basford, Glacsweb project, University of Southampton
image: Australian Transport Safety Bureau, http://www.atsb.gov.au/media/2489702/ro2010001.jpg
image: http://commons.wikimedia.org/wiki/File:Canary_Wharf_at_night,_from_Shadwell_cropped.jpg

Off on a tangent… *(not assessed)*



D. Balsamo et al. Hibernus++: a self-calibrating and adaptive system for transiently-powered embedded devices. IEEE TCAD, 1-13.

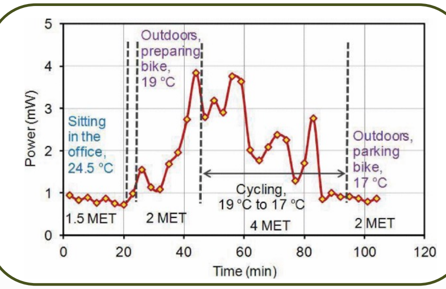
varies
temporally



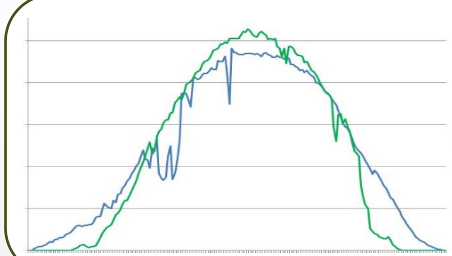
Beeby, S.P. et al. A comparison of power output from linear and non-linear kinetic energy harvesters using real vibration data. Smart Materials and Structures, 22, (7), 075022.

Power / Energy

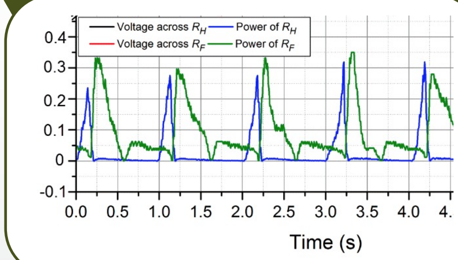
varies
spatially



V. Leonov, "Thermoelectric Energy Harvesting of Human Body Heat for Wearable Sensors," IEEE Sensors Journal, vol.13, no.6, pp.2284-91, June13



http://solar.rainham-kent.co.uk



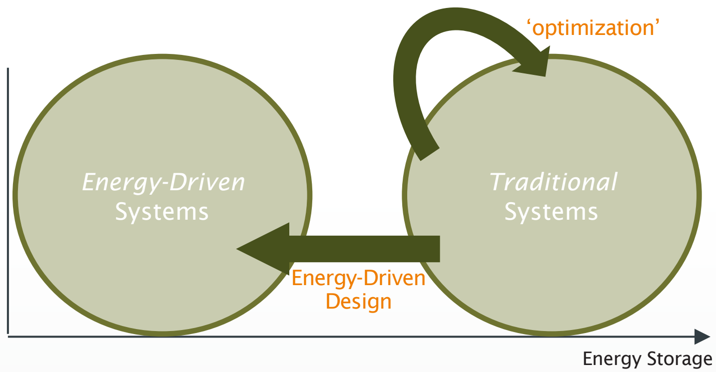
Zhao, J. et al. "A Shoe-Embedded Piezoelectric Energy Harvester for Wearable Sensors," Sensors 2014, 14, 12497-12510.

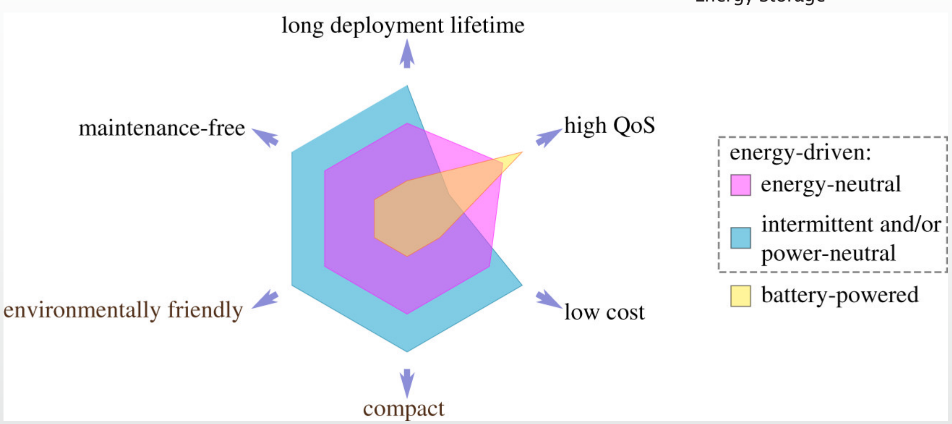
Highly variable supply + variable consumption!

S.W.C. Bing *et al.* Demo Abstract: An Energy-driven Wireless Bicycle Trip Counter with Zero Energy Storage. ACM SenSys '18.

Off on a tangent… *(not assessed)*

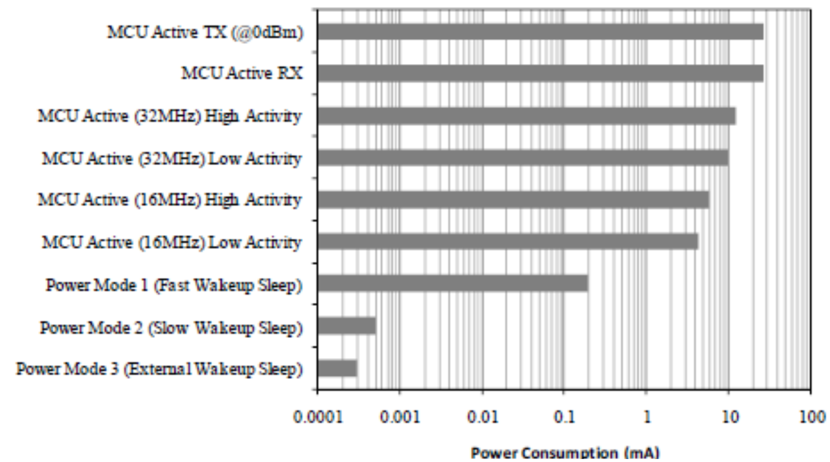
- Rethinking the design of EH systems





Typical Current Consumption

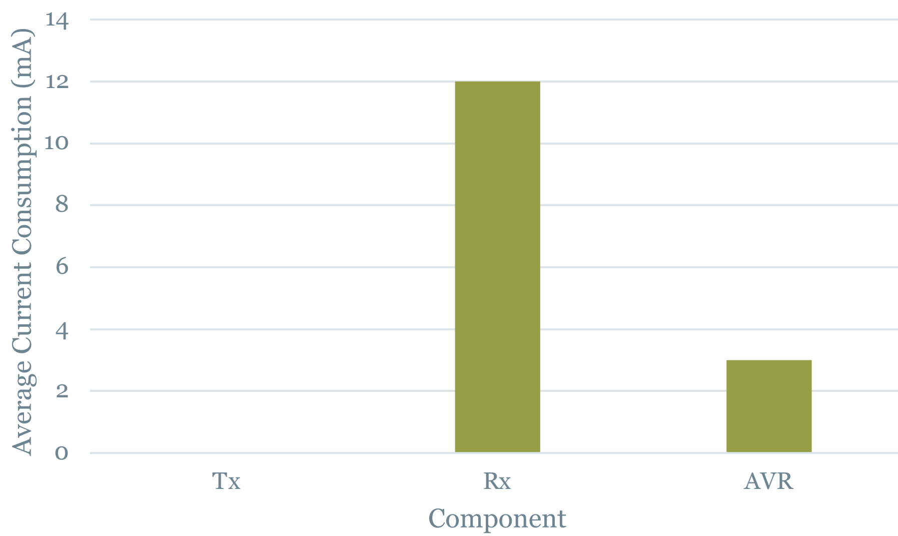
- Texas Instruments MSP430-RF2500
  - Low power MSP430 microcontroller
  - 2.4GHz IEEE 802.15.4 radio



- RFM12B-S2 + Il Matto
  - Transmit: 16-23 mA (depending on transmit power)
  - Receive: 12 mA
  - *or idle listening: 12 mA*
  - Sleep: 0.3 uA
  - AVR: 3mA @4MHz (active)

Typical Current Consumption

- Let's consider an example scenario (*with a simplistic model*):
  - We're using the RFM12B-S2 radio + the Il Matto AVR microcontroller
  - We want our node to transmit a packet once every 10 minutes (takes 10ms)
  - We may receive data from other nodes
- Using our 'traditional' network MAC protocols
  - Our radio will be always on, either transmitting or listening/receiving



note: graphs are based on a very simplistic model with lots of assumptions and a specific instance – just here to illustrate!

Typical Current Consumption

- So where are we wasting energy/power in the MAC?

- Collisions
  - All packets typically have to be retransmitted = energy waste
- Overhearing
  - You have to receive a packet before you can look at the destination address, and therefore know whether or not it was for you. If not, discard it = energy waste
- Overhead
  - E.g. control packets are always overhead, i.e. not actual data = energy waste
- Idle Listening
  - It typically consumes the same power to listen out for a packet as it does to actually receive one = energy waste

Duty Cycled Operation

- Duty-cycling is essential in low-power networking
  - We saw it in the Power-Save modes of IEEE 802.11 (WiFi)

- Most microcontrollers/microprocessors and radio have low-power states
  - Going into these turns off various functionality…
  - …but often significantly reduces power consumption

DC characteristic

symbol	parameter	Remark	minimum	typical	maximum	Unit
$I_{dd\_TX\_0}$	Supply current (TX mode, P_{out} = 0dBm)	315,433MHz band		15	17	mA
		868MHz band		16	18	
		915MHz band		17	19	
$I_{dd\_TX\_PMAX}$	Supply current (TX mode, P_{out} = P_{max})	315,433MHz band		22	24	mA
		868MHz band		23	25	
		915MHz band		24	26	
I_{dd_RX}	Supply current (RX mode)	315,433MHz band		11	13	mA
		868MHz band		12	14	
		915MHz band		13	15	
I_x	Idle current	Crystal oscillator on		0.62	1.2	mA
I_{pd}	Sleep mode current	All blocks off		0.3		uA

RFM12B-S2 Breakout Board

Table 10-1. Active Clock Domains and Wake-up Sources in the Different Sleep Modes.

	Active Clock Domains					Oscillators		Wake-up Sources							
Sleep Mode	clk_{CPU}	clk_{FLASH}	clk_{IO}	clk_{ADC}	clk_{ASY}	Main Clock Source	Timer Osc Enabled	INT2:0 and	TWI Address	Timer2	SPM/	ADC	WDT Interrupt	Other I/O	Software BOD Disable
Idle			X	X	X	X	X[2]	X	X	X	X	X	X	X	
ADCNRM				X	X	X	X[2]	X	X	X[2]	X	X	X		
Power-down								X	X				X		X
Power-save					X		X[2]	X	X	X			X		X
Standby[1]						X		X	X				X		X
Extended Standby					X[2]	X	X[2]	X	X	X			X		X

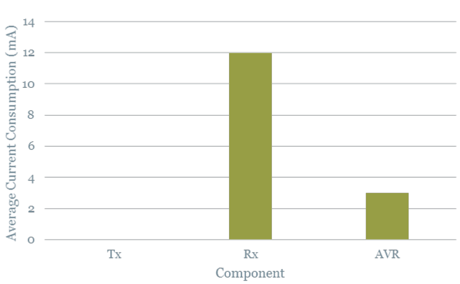
Table 28-7. T_A = -40°C to 85°C, V_{CC} = 1.8V to 5.5V (unless otherwise noted).

Symbol	Parameter	Condition	Min.	Typ. [2]	Max.	Units
I_{CC}	Power Supply Current [1]	Active 1MHz, V_{CC} = 2V		0.38	0.5	mA
		Active 4MHz, V_{CC} = 3V		1.8	2.7	
		Active 8MHz, V_{CC} = 5V		5.6	9.0	
		Idle 1MHz, V_{CC} = 2V		0.06	0.15	
		Idle 4MHz, V_{CC} = 3V		0.2	0.7	
		Idle 8MHz, V_{CC} = 5V		1.1	4.0	
	Power-save mode [3]	32kHz TOSC enabled, V_{CC} = 1.8V		0.5		µA
		32kHz TOSC enabled, V_{CC} = 3V		0.6		
	Power-down mode [3]	WDT enabled, V_{CC} = 3V		4.2	8.0	
		WDT disabled, V_{CC} = 3V		0.15	2.0	

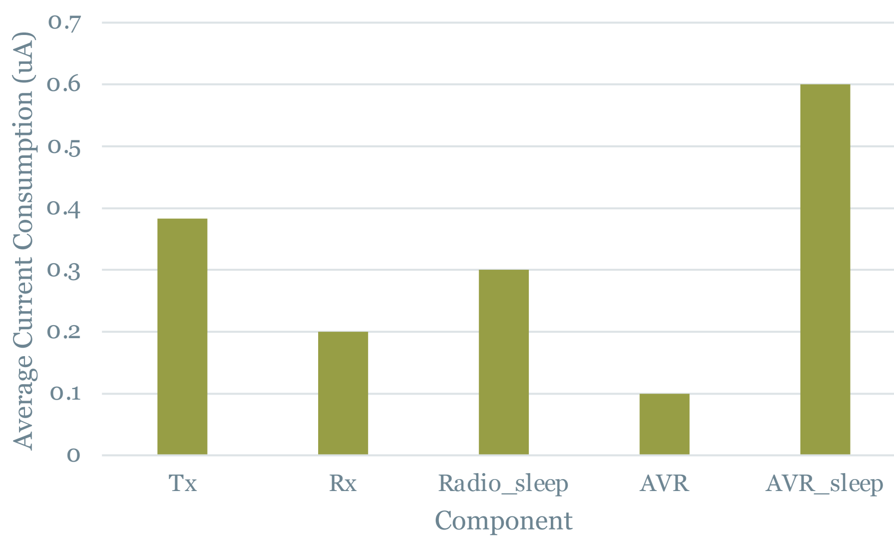
Duty Cycled Operation

- Returning to our example scenario:
  - We can try to save power by duty-cycling our operation
  - Why not copy IEEE 802.11's APSD mode, only trying to receive after we transmit?

note: graphs are based on a very simplistic model with lots of assumptions and a specific instance – just here to illustrate!



before…



…now

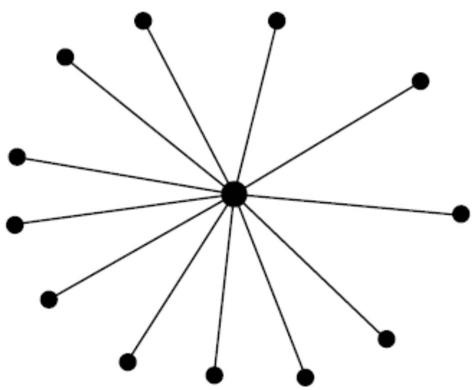
Duty Cycled Operation

- Uses a fraction of our target average current consumption!

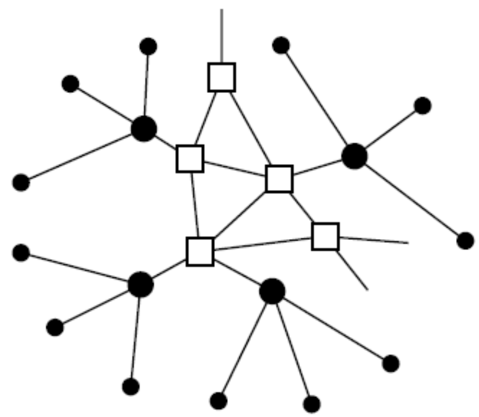
- What are the limitations of this approach?
  - Either the access point/base station needs to be always-on...
    - *In order to buffer packets (as we saw in 802.11's power-save mode)*
  - ...Or, all nodes need to be synchronised
    - *So that a receiver wakes up at the start of a transmission (and doesn't miss it altogether)*
    - *What happens if there are more than 2 nodes?*
  - Can only receive a packet once every 10 minutes!
    - *This is fine if you never need to receive (and so is used!)*

Typical Topologies

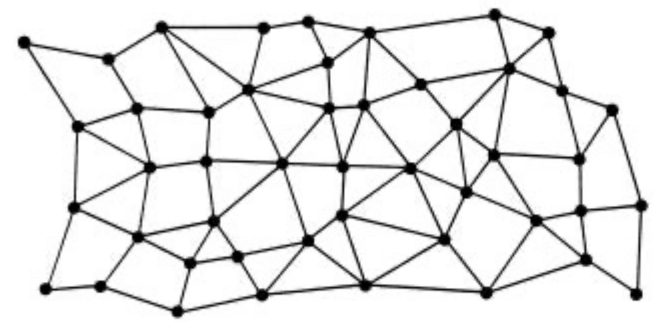
- These approaches work if you have a powered access point/base station
  - But in a true peer-to-peer network, the receiver needs to be low-power too



Centralised/
Star Network



Hierarchical/
Decentralised Network



Distributed/
Peer-to-Peer Network

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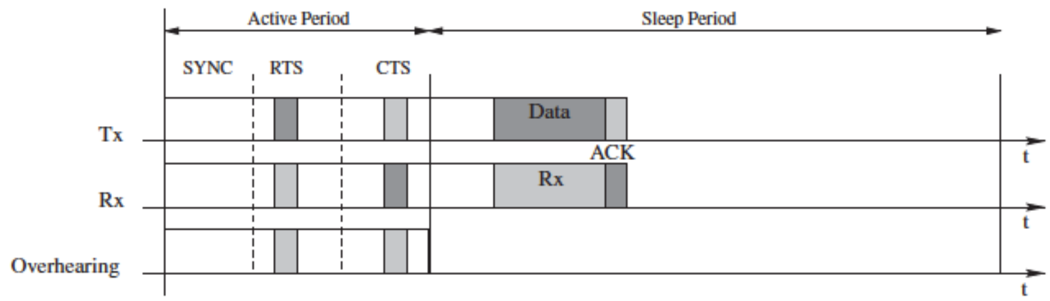
Reducing Idle-Listening

Synchronous MAC Protocols

- TDMA schemes
- Common Active Periods



Common Active Periods, from C. Cano, B. Bellalta, A. Sfairopoulou, M. Oliver, "Low energy operation in WSNs: A survey of preamble sampling MAC protocols," Computer Networks, 55(15), 2011, pp 3351-63

Asynchronous MAC Protocols

- Low-Power Listening (aka Preamble Sampling/Sender-Initiated)
- Receiver-Initiated

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Versatile Low Power Media Access for Wireless Sensor Networks

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ABSTRACT

We propose *B-MAC*, a carrier sense media access protocol for wireless sensor networks that provides a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization. To achieve low power operation, B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening. B-MAC supports on-the-fly reconfiguration and provides bidirectional interfaces for system services to optimize performance, whether it be for throughput, latency, or power conservation. We build an analytical model of a class of sensor network applications. We use the model to show the effect of changing B-MAC's parameters and predict the behavior of sensor network applications. By comparing B-MAC to conventional 802.11-inspired protocols, specifically S-MAC, we develop an experimental characterization of B-MAC over a wide range of network conditions. We show that B-MAC's flexibility results in better packet delivery rates, throughput, latency, and energy consumption than S-MAC. By deploying a real world monitoring application with multihop networking, we validate our protocol design and model. Our results illustrate the need for flexible protocols to effectively realize energy efficient sensor network applications.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Networks**]: Network Protocols; D.4.4 [**Operating Systems**]: Communications Management

General Terms

Performance, Design, Measurement, Experimentation

Keywords

Wireless Sensor Networks, Media Access Protocols, Energy Efficient Operation, Reconfigurable Protocols, Networking, Communication Interfaces.

1. INTRODUCTION

In wireless sensor network deployments, reliably reporting data while consuming the least amount of power is the ultimate goal. One such application that drives the design of low power media access control (MAC) protocols is environmental monitoring. Mainwaring et. al. [12] and the UCLA Center for Embedded Network Sensing [2, 6] have deployed wireless sensors for microclimate monitoring that operate at low duty cycles with multihop networking and reliable data reporting. They show that MAC mechanisms must support duty cycles of 1% while efficiently transferring various workloads and adapting to changing networking conditions. These workloads include periodic data reporting, bulk log transfer, and wirelessly reprogramming a node. In this paper we discuss the design of a MAC protocol motivated by monitoring applications.

Nodes in a wireless sensor network do not exist in isolation; rather they are embedded in the environment, causing network links to be unpredictable [16]. As the surrounding environment changes, nodes must adjust their operation to maintain connectivity. For example, RF performance may be hindered by a sudden rain storm or the opening and closing of doors in a building.

Woo [21] and Zhao [24] have studied the volatility in link quality in wireless sensor networks. Zhao shows the existence of "gray areas" where some nodes exceed 90% successful reception while neighboring nodes receive less than 50% of the packets. He shows that the gray area is rather large–one-third of the total communication range. Woo independently verified Zhao's gray area findings. In designing a reliable multihop routing protocol, Woo shows that effectively estimating link qualities is essential. Snooping on traffic over the broadcast medium is crucial for extracting information about the surrounding topology. By snooping, network protocols can prevent cycles, notify neighboring nodes of unreachable routes, improve collision avoidance, and provide link quality information. Since data must ultimately be reported out of the network, the media access protocol must be flexible to meet changing network protocol demands.

Not only are the networking conditions different, applications for wireless sensor networks have different demands than those designed for traditional ad-hoc wireless networks. Intanagonwiwat et. al. [8] show how 802.11 is inappropriate for low duty cycle sensor network data delivery. Idle listening in 802.11 consumes as much energy when the protocol is idle as it does when receiving data. Idle listening occurs when a node is active, but there is no meaningful activity on the channel resulting in wasted energy. is no activity. It is absolutely crucial that the MAC protocol support a duty cycling mechanism to eliminate idle listening.

For wireless sensor networks to gain acceptance in the scientific

e.g. B-MAC

Low-Power Listening

Joseph Polastre, Jason Hill, and David Culler. 2004. Versatile low power media access for wireless sensor networks. In Proceedings of the 2nd international conference on Embedded networked sensor systems (SenSys '04). ACM, New York, NY, USA, 95-107. http://web.stanford.edu/class/cs244e/papers/sensys04-bmac.pdf

B-MAC

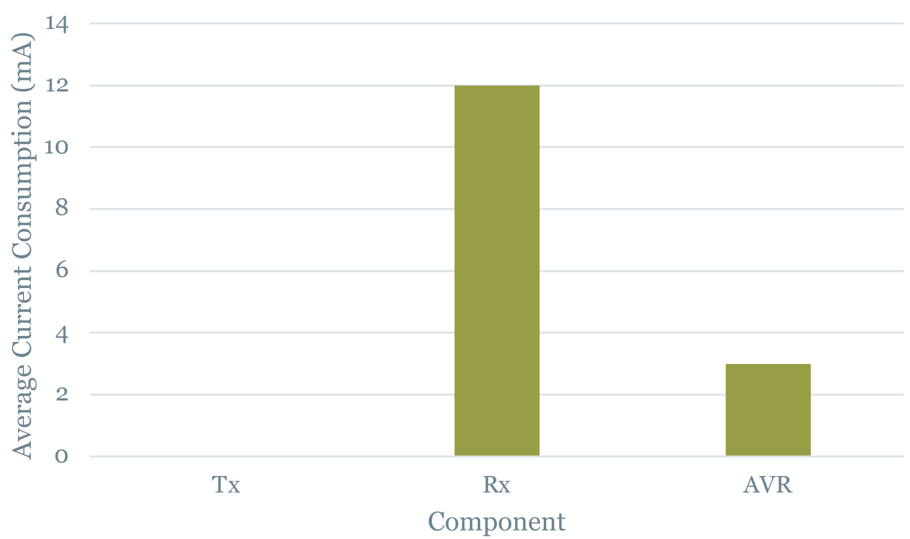
- A MAC protocol offering:
  - Low Power Operation
  - Effective Collision Avoidance
  - Simple Implementation, Small Code and RAM Size
  - Efficient Channel Utilization at Low and High Data Rates
  - Tolerant to Changing RF/Networking Conditions
  - Scalable to Large Numbers of Nodes

- Includes
  - Channel arbitration (CSMA-based)
  - Link-Layer Acknowledgments
  - Low Power Listening

Low Power Listening

- In our 'always-on' scenario, the receive consumption was significant, because the receiver had to stay on in case somebody tried to transmit to it.
  - This is a result of idle listening (it only actually received for 0.002% of the time)

note: graphs are based on a very simplistic model with lots of assumptions and a specific instance – just here to illustrate!



- In Low Power Listening (LPL), this overhead is transferred to the transmitter
  - Thus reducing idle listening

Low Power Listening

- Nodes are duty-cycled (over a period T_D)

Receiving

- Whenever it wakes up, a node turns on its radio and listens
  - If it detects activity on the channel, it stays awake to receive a packet;
  - If nothing is detected, it goes back to sleep.

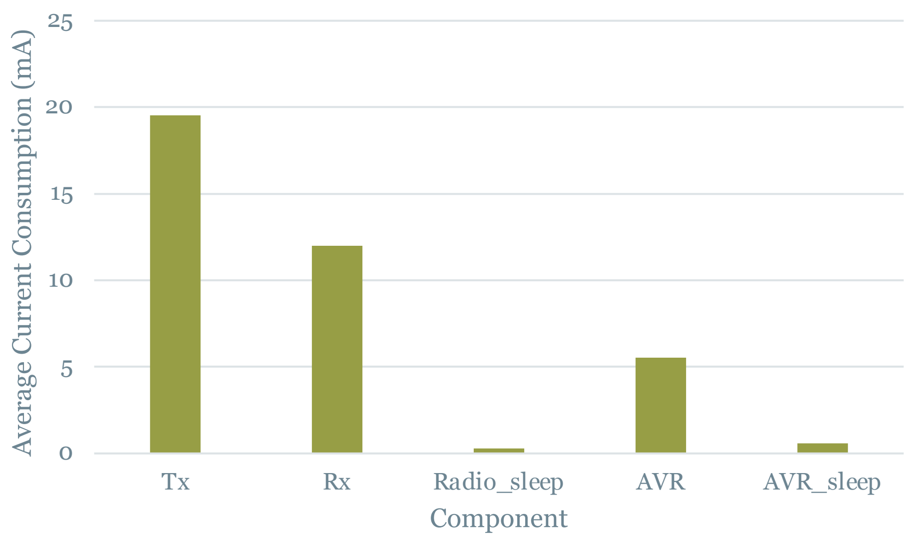
Transmitting

- To send, it transmits a 'long preamble', followed by the packet
  - This long preamble must be ≥ the duty-cycle period T_D

- *This gets rid of the need for synchronisation, hence an asynchronous MAC*

Low Power Listening

- Returning to our example scenario:
  - Using Low Power Listening
  - We still want our node to transmit a packet once every 10 minutes (takes 10ms)
  - We now transmit a long preamble for 500ms before transmitting data
  - We periodically listen for 5ms every 500ms (the same as the long preamble)



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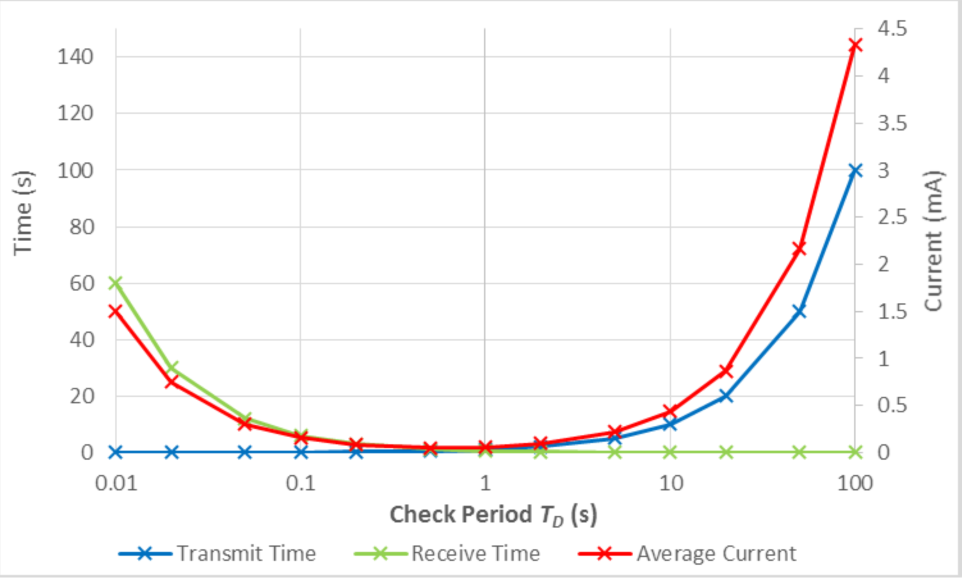
Low Power Listening

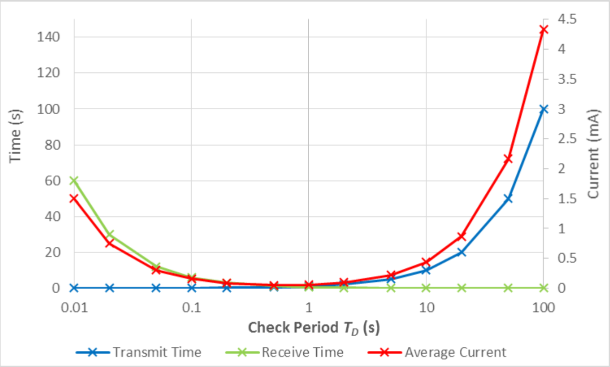
- The check period T_D significantly affects performance



note: graphs are based on a very simplistic model with lots of assumptions and a specific instance – just here to illustrate!

- For our specific scenario (i.e. the scenario and model parameters)
  - A check period of 0.5s appears to have the lowest power consumption

Low Power Listening



- In general…
- A longer period…
  - = longer preamble, hence transmit cost increases
  - = less frequent sampling of the channel (listening); hence 'quiescent' cost reduced
  - Suited to scenarios with very infrequent packet transfer
  - Too large tends to waste energy on transmissions (long preambles)
- A shorter period…
  - = shorter preamble, hence transmit cost decreases
  - = more frequent sampling of the channel (listening); hence 'quiescent' cost increased
  - Suited to scenarios with more frequent packet transfer
  - Too small tends to waste energy on idle listening
- But depends heavily on the application etc!

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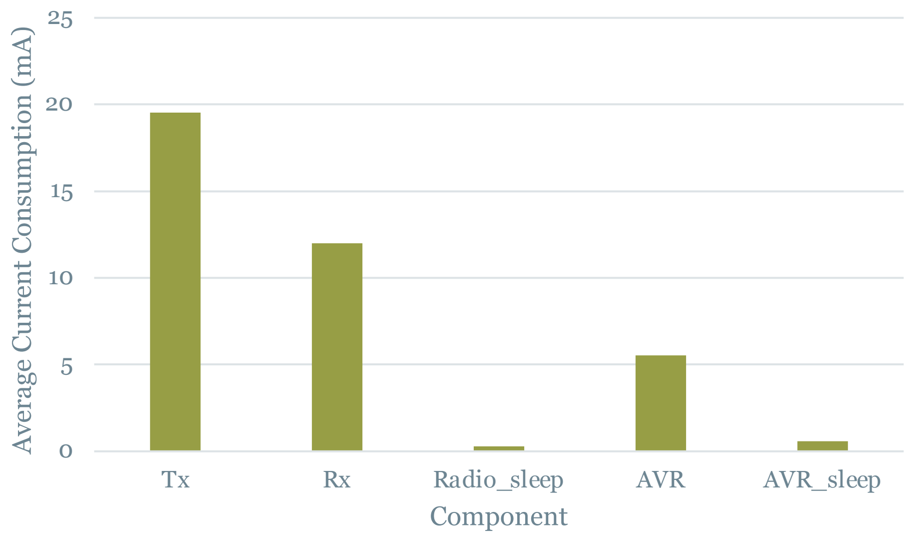
Low Power Listening

- Returning to our example scenario (transmitted 1 packet/10 minutes):

note: graphs are based on a very simplistic model with lots of assumptions and a specific instance – just here to illustrate!



- If we transmitted once every 100 minutes, what would happen to the graph?
- If we transmitted once every minute, what would happen to the graph?
- What effect might this have on our choice of check period T_D?

Low Power Listening

- What about packet latency?
  - Latency is the time it takes for a frame/packet to get from its source to destination

- Longer check periods increase latency
  - As it equals T_D for each hop
  - as T_D is the length of the long preamble, which must be transmitted first

- As always, the chosen parameters
  - Depend heavily on the application scenario and hardware/software
  - Are a trade-off between conflicting parameters

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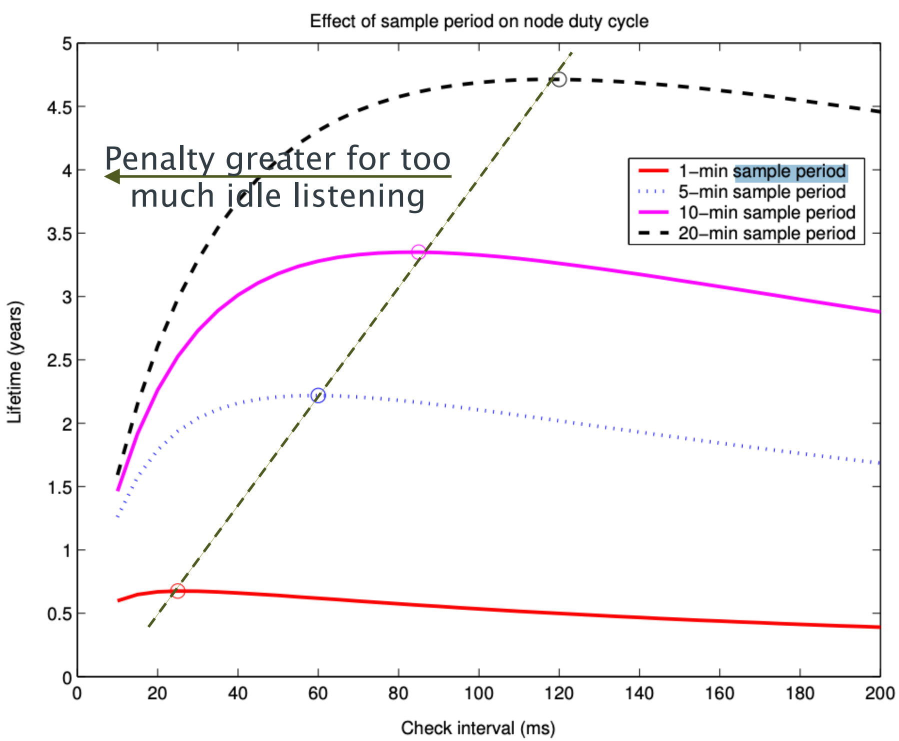
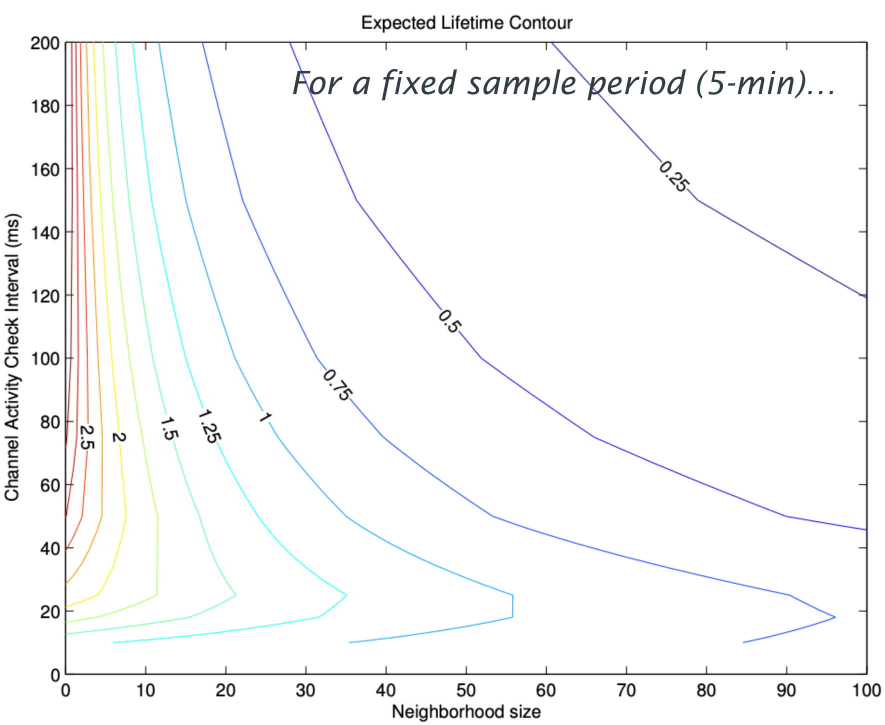
B-MAC Performance

- Check interval = duty cycle/check period
- Sample period = how often a frame is generated to transmit
- Neighborhood size = how many neighbors a node has *can affect by changing tx power*





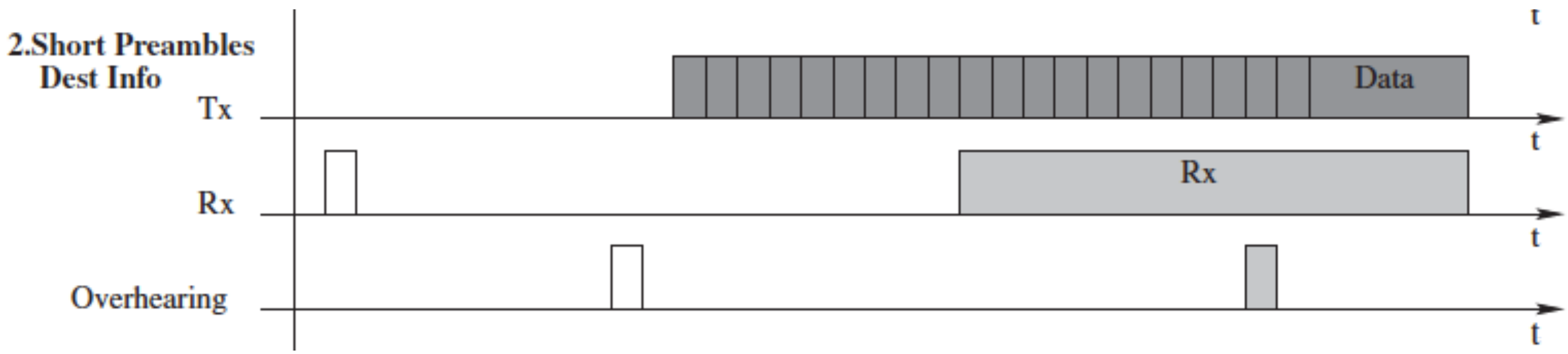
Joseph Polastre, Jason Hill, and David Culler. 2004. Versatile low power media access for wireless sensor networks. In Proceedings of the 2nd international conference on Embedded networked sensor systems (SenSys '04). ACM, New York, NY, USA, 95-107. http://web.stanford.edu/class/cs244e/papers/sensys04-bmac.pdf

B-MAC

- *Are there any problems with this?*
- Collisions
  - *We may wish to add RTS/CTS to reduce collisions*
- Overhearing
  - Every node within range that detects a long preamble will remain on and listen for the packet, before finding out that it isn't the destination
- Control Packets
  - No need for synchronisation etc, so very little overhead
- Idle Listening
  - Idle listening heavily reduced, but wastes energy receiving a long preamble (even if it is the intended recipient: on average, a receiver has to listen to half of the preamble which contains no actual data)
- Latency and Channel Capacity
  - Each hop incurs a latency of $>T_D$, and poorly utilises the channel (as most of the transmission is a preamble containing no actual data)

Improving B-MAC

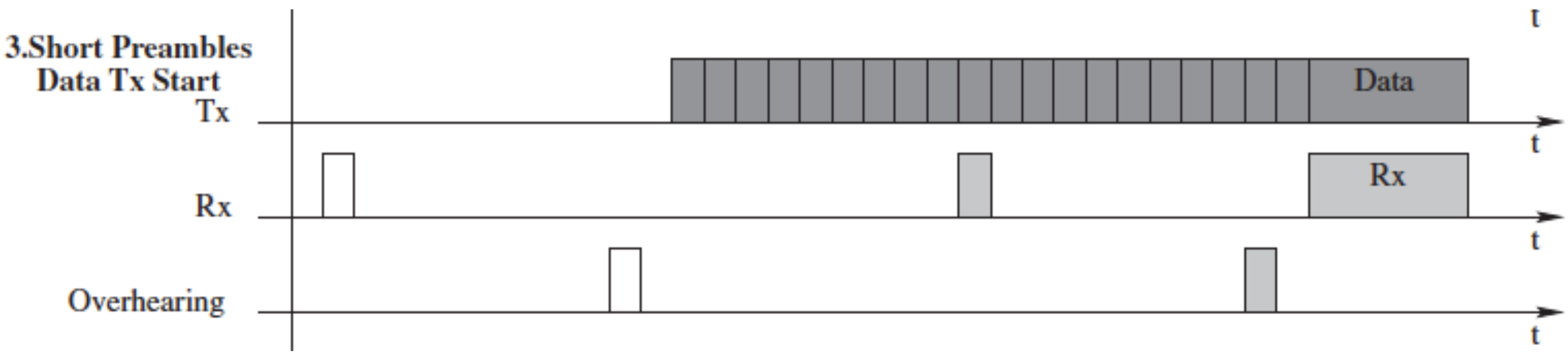
- We can better utilise the long-preamble to mitigate some of these issues:
  - Encode the destination address into the long preamble



C. Cano, B. Bellalta, A. Sfairopoulou, M. Oliver, "Low energy operation in WSNs: A survey of preamble sampling MAC protocols," Computer Networks, 55(15), 2011, pp 3351-63

Improving B-MAC

- We can better utilise the long-preamble to mitigate some of these issues:
  - Encode the destination address into the long preamble
  - Encode the time-until-data-transmission into the long preamble



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Improving B-MAC

- We can better utilise the long-preamble to mitigate some of these issues:
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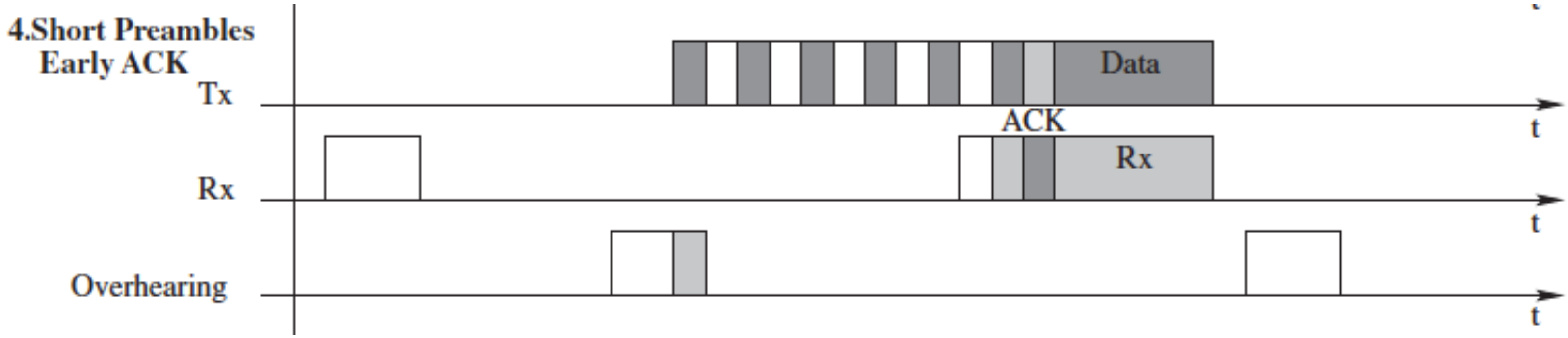
  - Allow the receiver to exit the long preamble prematurely



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Improving B-MAC

- We can better utilise the long-preamble to mitigate some of these issues:
  - Encode the destination address into the long preamble
  - Encode the time-until-data-transmission into the long preamble
  - Allow the receiver to exit the long preamble prematurely
  - Repeatedly transmit the data frame [ContikiMAC]
- Adaptively select a combination of the above, e.g.
  - Early-exit for unicast messages, but not for multi-cast/broadcast
  - Repeatedly transmit the data for short frames, but a preamble(s) for longer frames
- Can also semi-synchronise to reduce future overhead, e.g.
  - A transmitter knowing *approximately* when the receiver will next be listening
- Can also adapt the duty-cycle based on network conditions

C. Cano, B. Bellalta, A. Sfairopoulou, M. Oliver, "Low energy operation in WSNs: A survey of preamble sampling MAC protocols," Computer Networks, 55(15), 2011, pp 3351-63

Improving B-MAC

Table 2
List of preamble sampling MAC protocols.

Category	List of MAC protocols
Basic	Preamble sampling [14], LPL [15], B-MAC [12]
Short preamble burst	ENBMAC [17], BMAC+ [18], SpeckMAC-B [19], DPS-MAC [20], SyncWUF [21], SESP-MAC [22], TICER [23], CSMA-MPS [24], X-MAC [25], AS-MAC [26], Patterned Preamble MAC [27], AREA-MAC [28], 1-hopMAC [30], DPS-MAC' [31], CMAC [32], MX-MAC [33], Preamble sampling with state information [29], SpeckMAC-D [19], MH-MAC [34], MIX-MAC [35], TrawMAC [36], MFP-MAC [37], RA-MAC [38], SEESAW [39]
Taking advantage of sync. info.	WiseMAC [13], CSMA-MPS [24], SyncWUF [21], TrawMAC [36], AS-MAC' [40], SCP-MAC [41], MIX-MAC [35]
Adaptative duty cycle	WiseMAC more bit [13], Stay Awake Promise [43], BEAM [44], AS-MAC [26], AREA-MAC [28], AS-MAC'' [45], extension to B-MAC+ [46], BoostMAC [47], MaxMAC [48], LWT-MAC [49], SCP-MAC [41], AADCC and DDCC [50], ZeroCal [51], X-MAC [25], EA-ALPL [53], Preamble Sampling with State Information [29]

C. Cano, B. Bellalta, A. Sfairopoulou, M. Oliver, "Low energy operation in WSNs: A survey of preamble sampling MAC protocols," Computer Networks, 55(15), 2011, pp 3351-63

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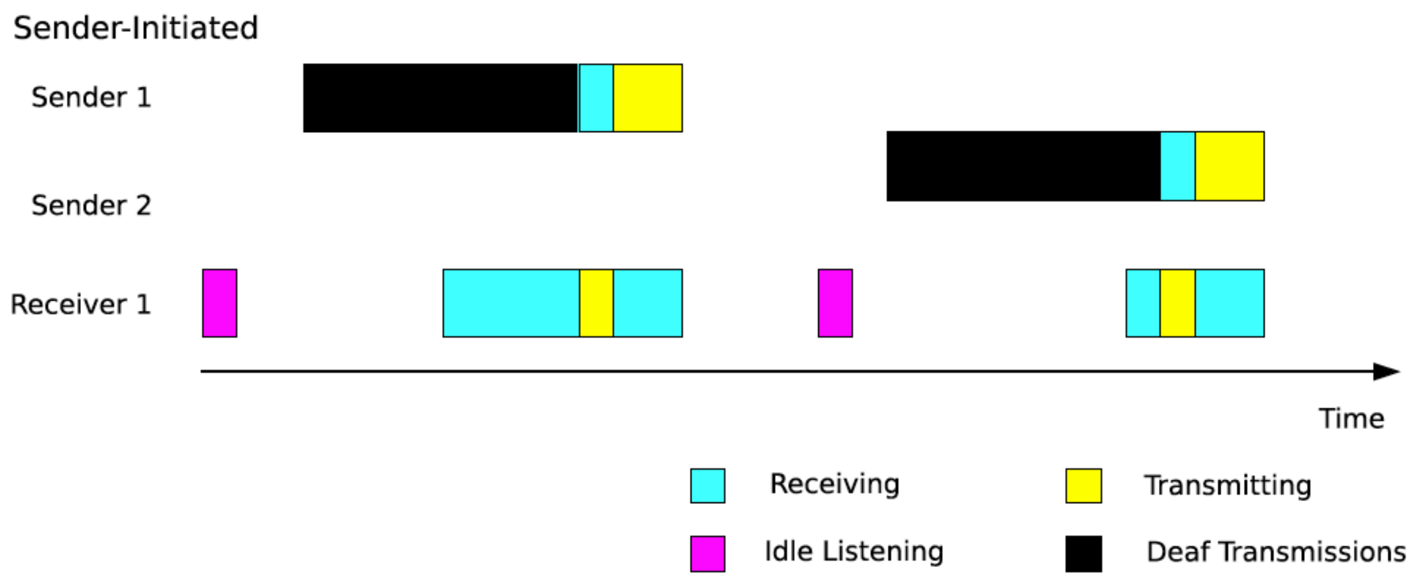
Receiver-Initiated MAC Protocols

Xenofon Fafoutis, Alessio Di Mauro, Madava D. Vithanage, Nicola Dragoni, "Receiver-initiated medium access control protocols for wireless sensor networks," Computer Networks, 76, 2015, Pages 55-74

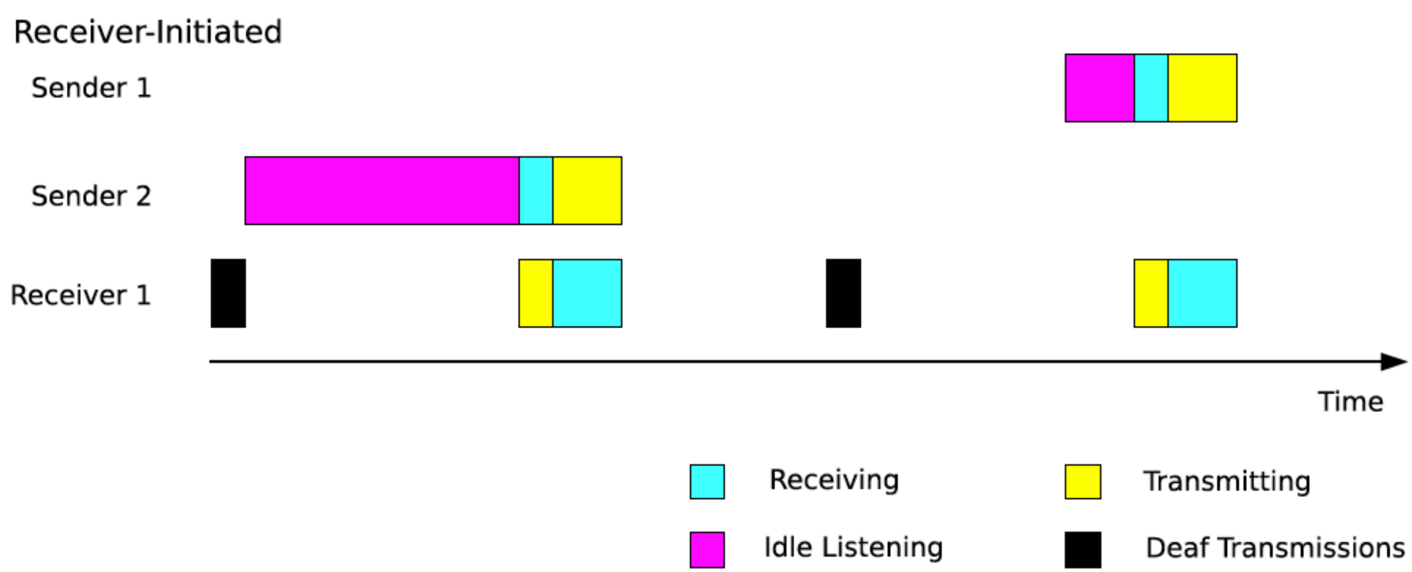
Receiver-Initiated Protocols

- Regardless of improvements, LPL approaches fundamentally shift the receive cost to the transmitter; transmitting occupies the channel



Receiver-Initiated Protocols

- In receiver-initiated protocols, a sender listens to the channel for an extended period (instead of transmitting). This doesn't occupy the channel
- Every device periodically wakes up and transmits a beacon, and then listens for a reply if a device wishes to send data to it.



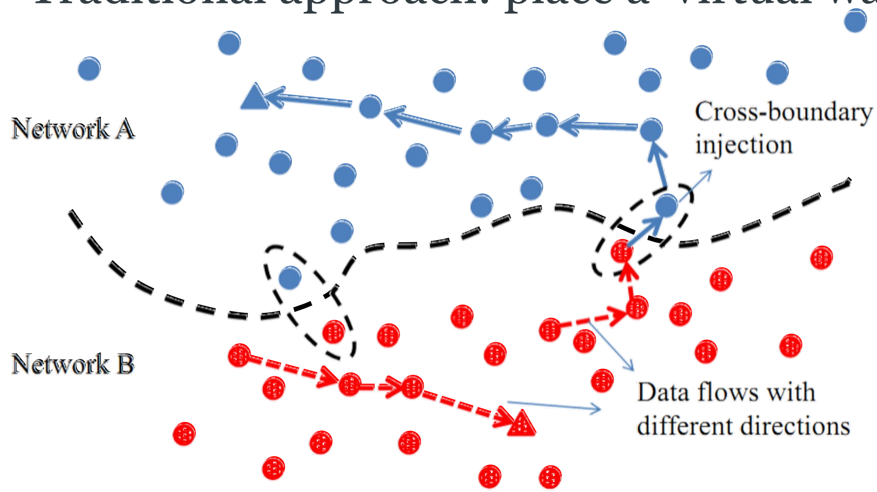
Receiver-Initiated Challenges

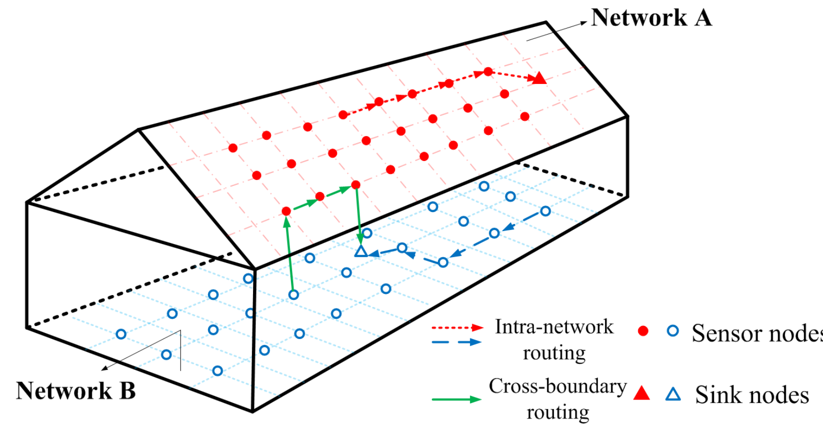
Challenge	Technique	Protocols
Idle listening	Wake-up prediction	EM-MAC, FERI-MAC, HKMAC, Pseudo, PR-MAC, PW-MAC, RICER, RW-MAC, SRI-MAC, WideMAC
	Beacon acknowledgment	A-MAC
	Duty cycle of listening	EE-RI-MAC, QAEE-MAC
	Cross-layer interaction	OC-MAC, ODMAC, REA-MAC, RICER
	Beacon period adaptation	FERI-MAC, HKMAC, IRDT, SARI-MAC
	Indirect	IRDT, ODMAC
Collision avoidance	Random backoff	A-MAC, AQ-MAC, DCM, ERI-MAC, EM-MAC, IRDT, OC-MAC, ODMAC, RC-MAC, RI-MAC, RICER, SRI-MAC, QAEE-MAC, WideMAC, YA-MAC
	Cooperation	FERI-MAC, OC-MAC, ODMAC
	Data aggregation	AQ-MAC, ERI-MAC, IRDT
	Beacon period adaptation	IRDT, SARI-MAC
	Time-slot reservation	SARI-MAC, SWI-RI-MAC
	Staggering	RW-MAC
	Multi-channel extensions	DCM, EM-MAC
	CCA Extension	Asym-Mac
Adaptive duty cycling	Traffic based	CyMAC, SARI-MAC
	Energy based	ERI-MAC, ODMAC
	Distance based	Stair
Quality of service	Frame reordering	AQ-MAC, CyMac, QAEE-MAC
Broadcast	Synchronization	DCM, SWI-RI-MAC, YA-MAC
	Multiple unicasts	ADB, RWB
Asymmetric Links	Mode change	Asym-Mac
Security	Authentication	RAP

Xenofon Fafoutis, Alessio Di Mauro, Madava D. Vithanage, Nicola Dragoni, "Receiver-initiated medium access control protocols for wireless sensor networks," Computer Networks, 76, 2015, Pages 55-74

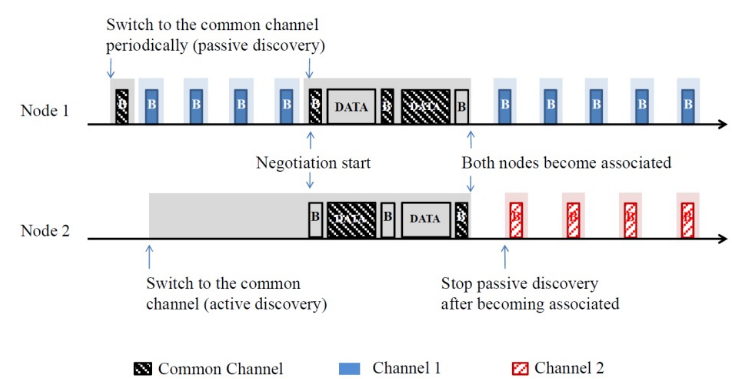
And finally… *(not assessed)*

- Traditional approach: place a 'virtual wall' around the WSN



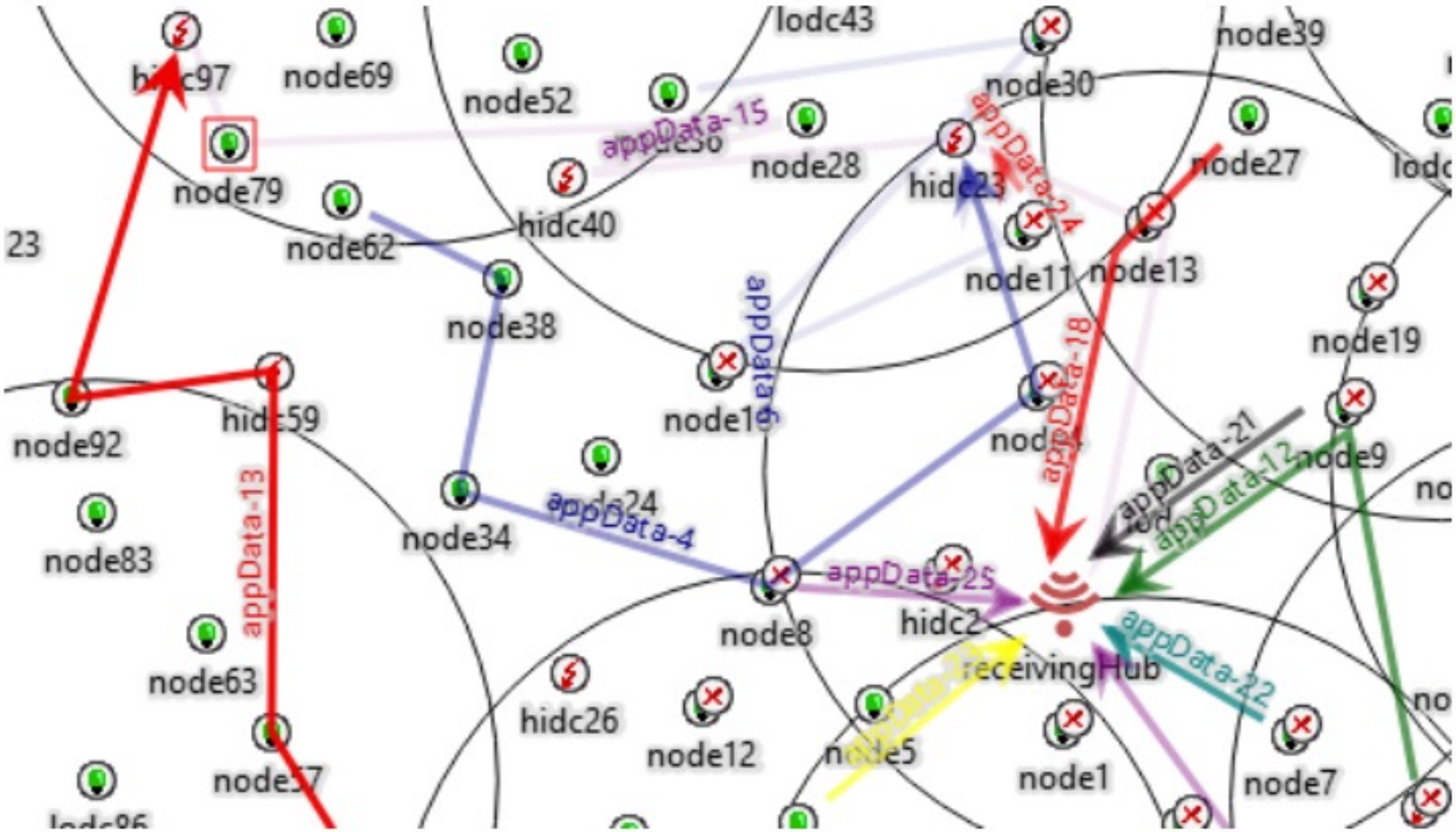


- Opportunistic Direct Interconnect: break this wall…
  - MAC protocol
  - Practical validation
  - NET/APP implications
  - Agent-based negotiation



And finally... *(not assessed)*

- Networking in Intermittently Powered Networks



Longman, El-Hajjar, Cetinkaya, Merrett, “Mesh networking for intermittently-powered devices: Architecture and challenges,” IEEE Network, 36 (3), 122-8.
Longman, El-Hajjar, Merrett, “Multihop Networking for Intermittent Devices,” ENSsys 2022, Boston, USA
Longman, Cetinkaya, El-Hajjar, Merrett, “Wake-up radio-enabled intermittently-powered devices for mesh networking: A power analysis,” IEEE Consumer Comms & Net. Conf., Jan 2021
Longman, El-Hajjar, Merrett, “Intermittent opportunistic routing components for the INET framework,” OMNeT++ Community Summit 2021

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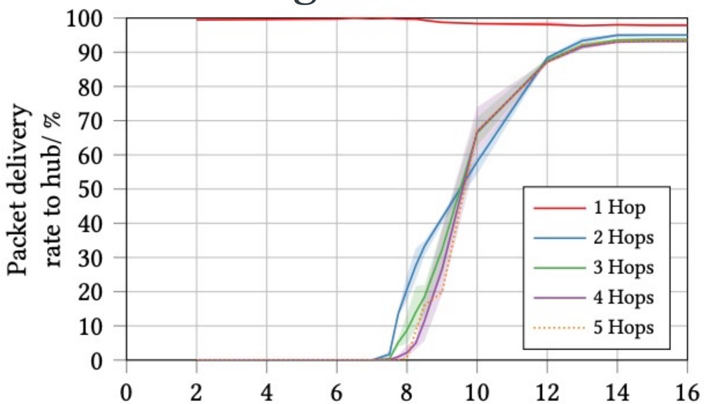
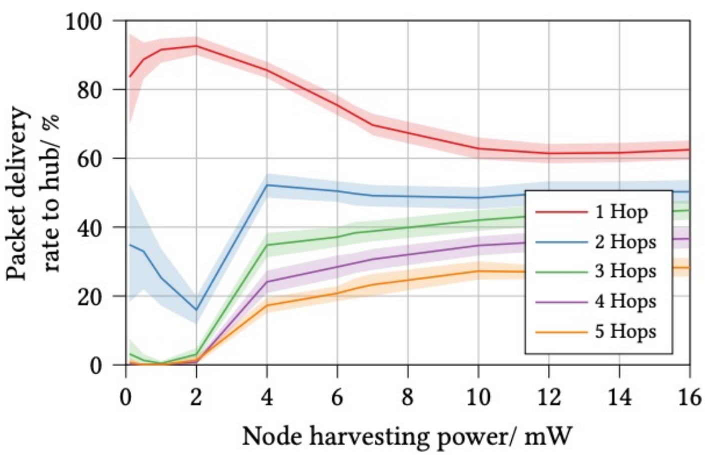
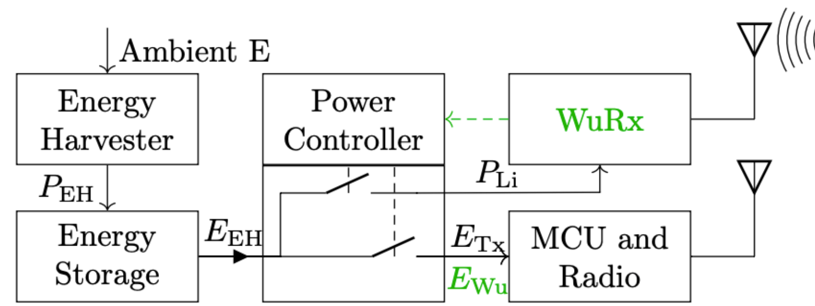
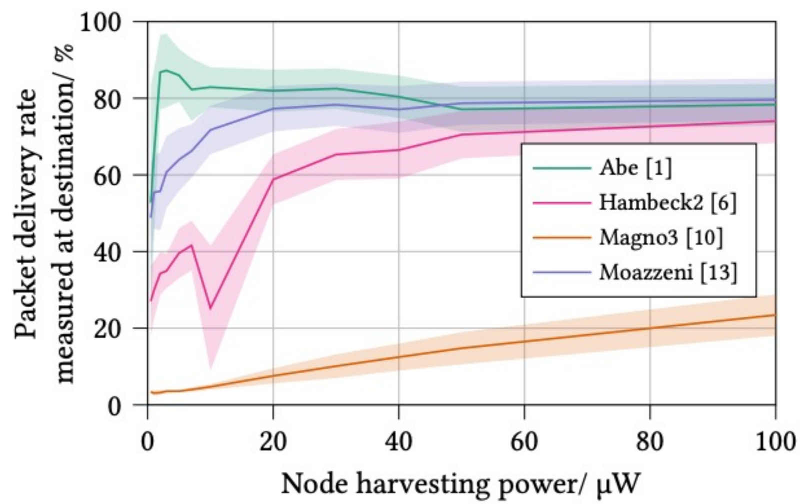
And finally… *(not assessed)*

- Networking Protocols for Intermittently Powered Networks









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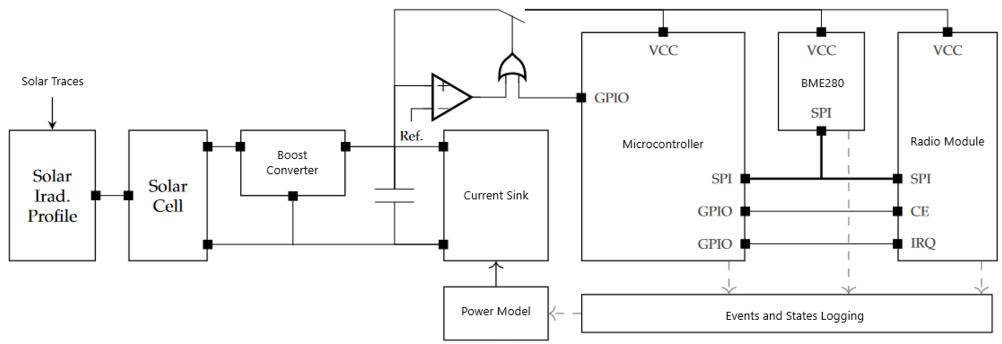
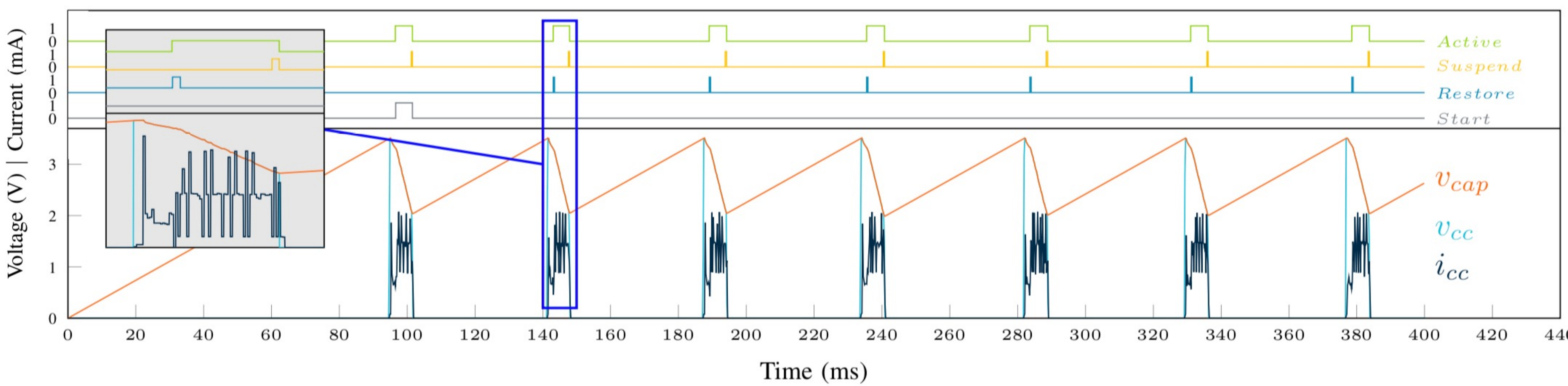
And finally… *(not assessed)*

Download: www.arm.ecs.soton.ac.uk/technologies/fused

FUSED: Virtual prototyping of complete EH systems

- Ambient energy environment
- Energy harvesters
- Power management circuitry
- On/off-chip peripherals





Energy-aware HW/SW Co-modeling of Batteryless Wireless Sensor Nodes
Wong *et al.*, ENSsys 2020

Past Exam Questions

- ELEC3227, 2019-20

The following are sources of inefficiency/energy wastage in the Data Link Layer: overhearing; idle listening; control overheads; and collisions.

(i) Define each of these terms.

(ii) Explain how the X-MAC *[extension to B-MAC]* protocol reduces these sources of inefficiency.

Past Exam Questions

- ELEC3227, 2022-23

Suggest and discuss a modification that could be made to the ALOHA MAC protocol to reduce the average power consumption at the MAC sublayer for

(i) transmitting frames, and

(ii) receiving frames.

Your answer should explain the effect of each modification on:

1) average power consumption,

2) frame latency, and

3) throughput.

Past Exam Questions

- ELEC3227, 2020-21

A radio consumes 50mW, 45mW, and 0mW in transmit, receive/listen, and sleep states respectively. It takes 10ms for a frame to be transmitted or received. Choose a MAC and flow-control protocol of your choice. You can ignore the power consumption of the microcontroller and sensors etc.

(i) Derive an expression to approximate the average energy consumption of the device. Justify any assumptions that you make.

(ii) Estimate how long you might expect a device to last for, when powered from a 150mAh 1.5V coin cell. Justify any assumptions that you make. Explain whether you think your answer is realistic.

Questions?