Energy in Wireless Sensor Networks

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Short resume of the presenter
Dr. Anne-Lena Kampen

- Received my PhD in Telematics from the Norwegian University of Science and Technology (NTNU) in 2017.
  - The research area for my PhD was Wireless Sensor Networks (WSN), and the research focus was energy efficiency and reliability related toward path recovery.
- Currently I am an associate professor at Western Norway University of Applied Sciences (HVL)
  - Main research area is Wireless Sensor Networks (WSN),
  - Main research focus is energy efficiency.
  - Also works on embedded machine learning in combination with WSN and to some extent underwater communication
  - Teaches in subject such as advanced network communication, network security, electronics and industrial data networks.
- Leave of absence from HVL from June 2018 until Mars 2020 to work for Norwegian Research Centre AS (NORCE).
  - Mainly working on smart sensor networks - embedded machine learning, and underwater communication.
- Prior to completing my PhD, I worked as a professor assistant at HVL from 2005, teaching network communication and electronics.
- Before I started at HVL, I worked at Nera Network from 1997 until 2005 where I
  - Development and performed research on advanced electronics.
  - Specifically, the research was focused on reducing the energy consumption of power amplifiers. In addition, I developed microwave modules for radio links.
- I received my Master of Science in Applied Physics from the University of Tromsø, The Arctic University of Norway, in 1995, where my dissertation concerned microwave techniques.

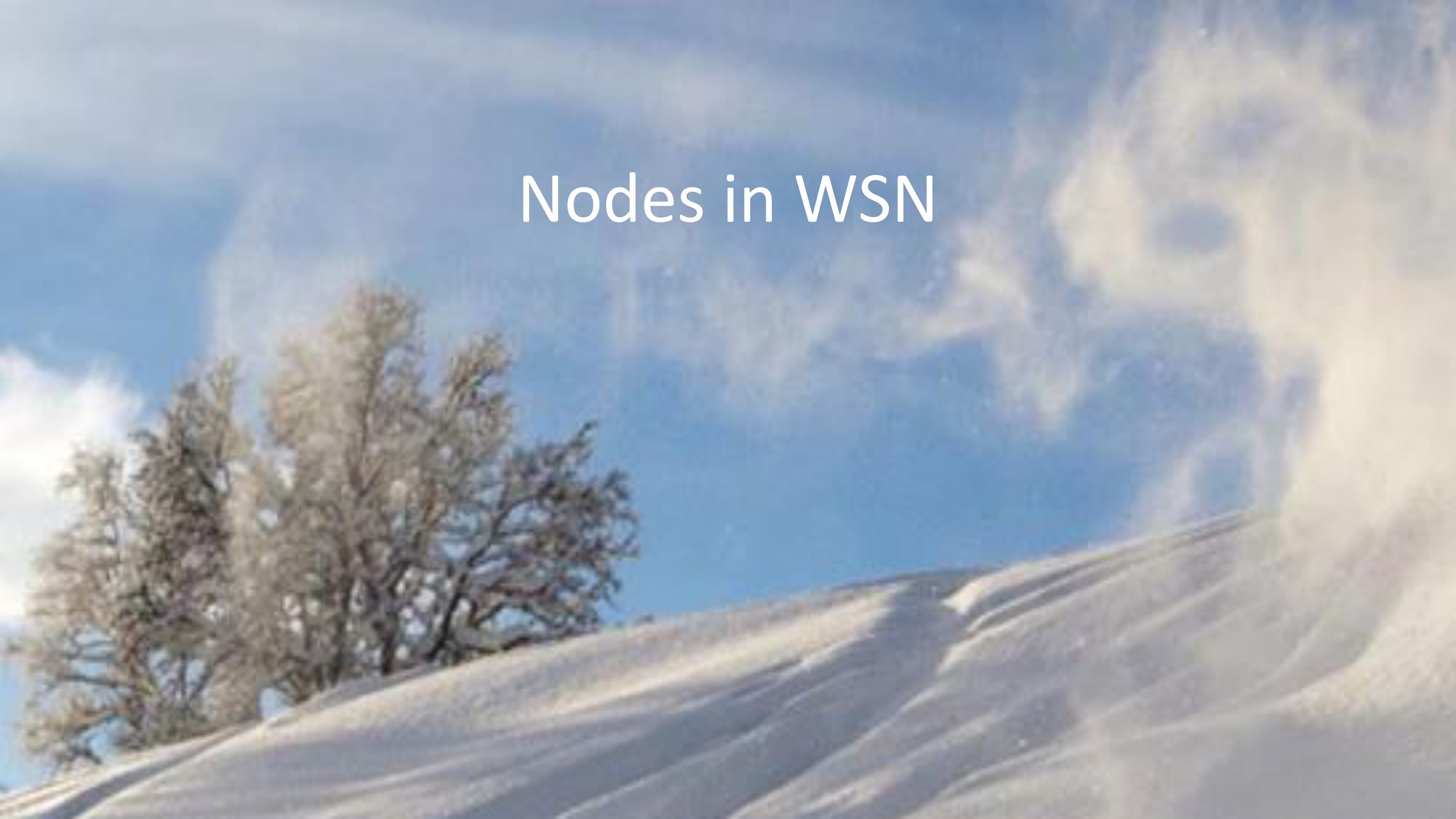
The topics of research interest of our workgroup and current projects we are working on

- Energy consumption in WSNs
- Industrial Internet of Things
  - Industry 4.0
  - Delay sensitive networks
  - Condition based maintenance
  - Industrial WSN
  - Cybernetics
- Underwater Internet of Things
  - Underwater networking

Energy in Wireless Sensor Networks
Outline of the presentation

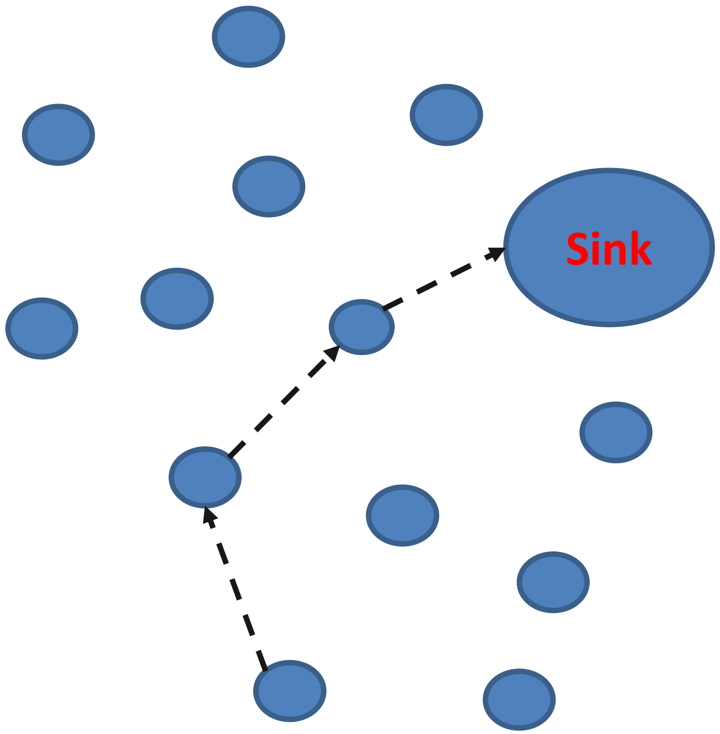
- Nodes in WSN
- What is the consequences of a depleted node?
- Which processes in a node consume energy?
- What is the probability that a network is partitioned when a node depletes?
- Energy conservation strategies at the different OSI-layers
  - Application, presentation, session, and transport layers
  - Physical layer
  - MAC layer
    - Discuss various approaches
    - Investigate impact of sleep state
    - Investigate the energy optimal distance between nodes using sleep protocol
  - Network layer
    - Discuss various approaches
    - Investigate various energy balancing approaches
- Investigate energy consumption in networks where nodes run machine learning (ML) algorithms
- Energy consumption in underwater WSNs
- Conclusion

Nodes in WSN



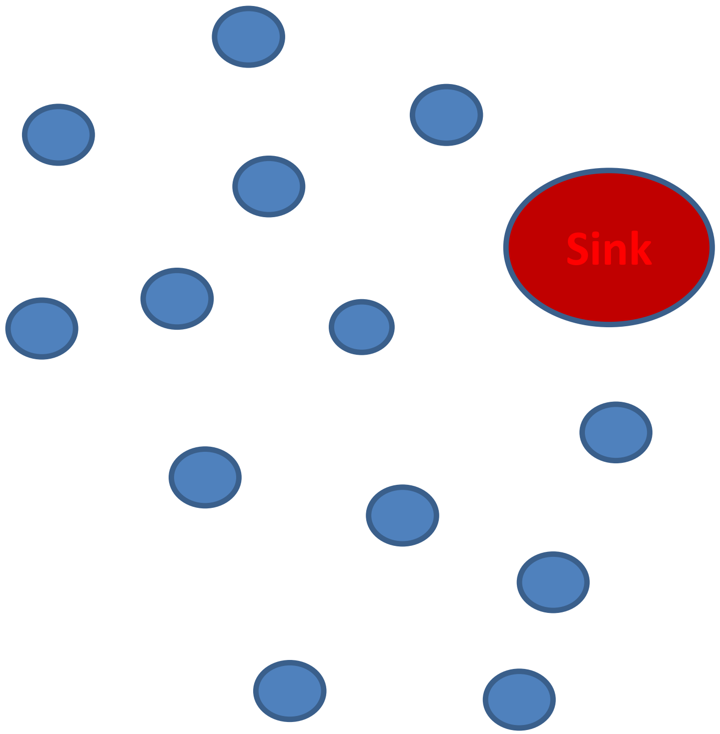
Nodes in WSNs

- Sensor nodes, or nodes for short
  - Data collection
  - Radio and antennae for wireless communication
  - Typically low cost devices with limited energy, memory, and microcontroller capacity
- Source nodes: Nodes that generate data
- During operation
  - The nodes cooperate to collect data at the sink
  - Data form remote nodes are forwarded hop-by-hop toward the sink
- Environmental variables that may be detected by a sensor
  - Temperature, vibration, moisture,
  - Proximity, ambient light
  - Sound (acoustic), acceleration, chemical substances (smoke), pressure..

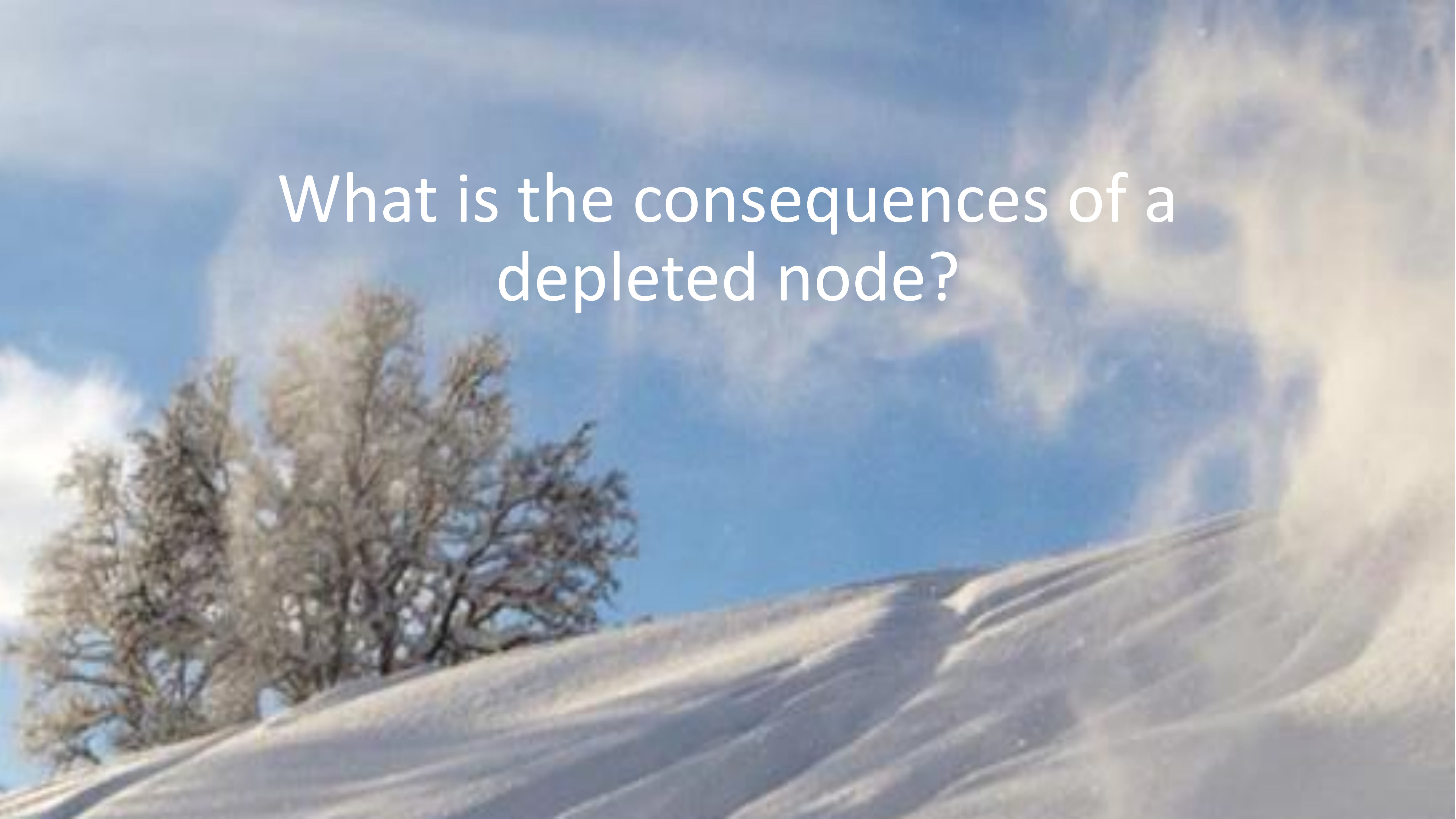


Nodes in WSNs

- **Sink**
  - Sensor data is gathered at the sink
    - Complete data set
    - Comprehensive knowledge of the monitored surroundings
  - May be a server, a cloud, powerful computer or similar
  - Connected to a power outlet

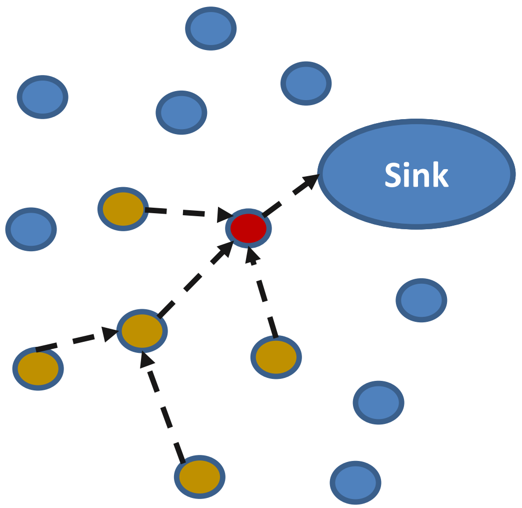


What is the consequences of a depleted node?

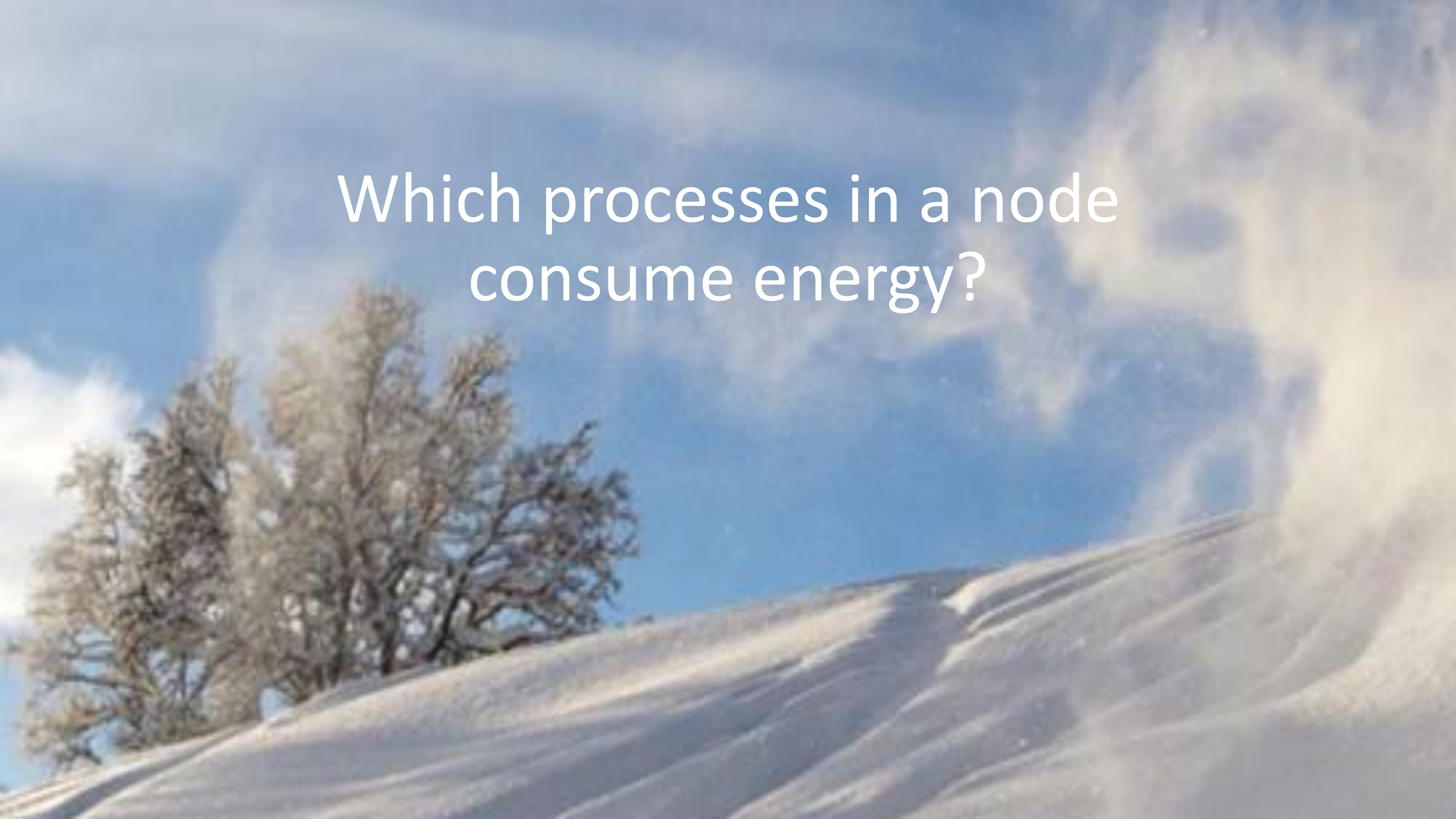


What is the consequences of a depleted node?

- When nodes deplete: The dataset at the sink is incomplete
  - May lead to wrong predictions about the monitored environment
  - The network may be temporarily out-of-operation
- Early / frequently depleted nodes increase management cost
  - Battery replacement
    - Cost manhour
    - May be difficult due to harsh environment
- Early / frequently depleted nodes is a source of irritation and frustration, for instance
  - Domestic applications
    - Battery replacement is challenging for some people (old, disabled, ..)
    - May not understand that something in the network is broken or the devastating consequences it may cause
  - Industrial application, manufacturing and smart grid
    - Processes may stop, go wrong
  - If a node depletes
    - In the middle of a military operation: loosing track of the enemy
    - WSN used in healthcare: cannot locate the person suffering from dementia
    - Environmental surveillance: cannot detect imminent land-slide
    - ..



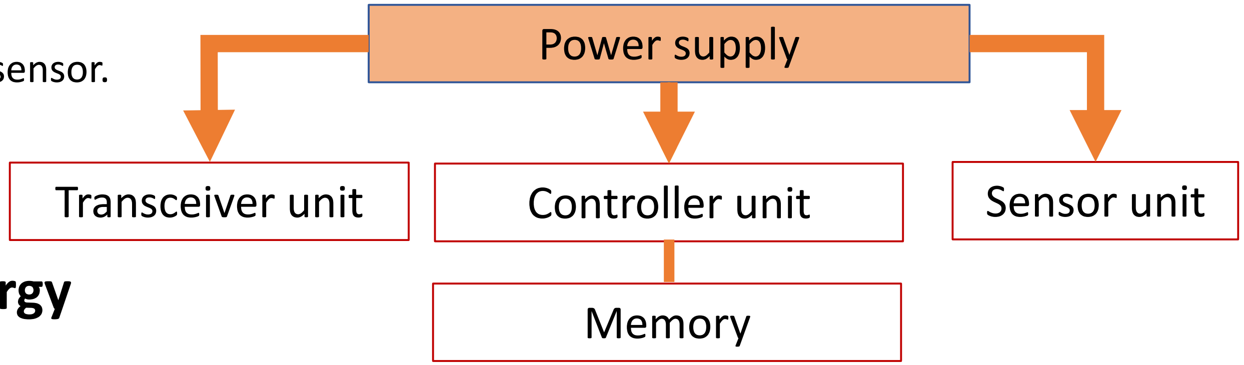
The red depleted node cannot provide any more data. Unless these yellow/ brown nodes find a new path toward the sink, their data are also lost.



Which processes in a node consume energy?

Which processes in a node consume energy?

- The power supply provides energy for the various units
  - Senor
    - In general, the communication is not affected by the sensor.
      - Sensors’ consumption is therefore not taken into account.
  - Controller and memory
  - Radio



- **Unless a node is switched off it consumes energy**
  - for sensing
  - for processing data
  - for transmitting and receiving data
  - to listen for activity..
  - ..and for sleeping

- Not unexpectedly, the least energy is consumed when the nodes are in sleep state.
- **The radio is generally the unit that consumes most energy. [1][2]**
- **The radio switches between different states: transmitting, receiving, idle and sleep**

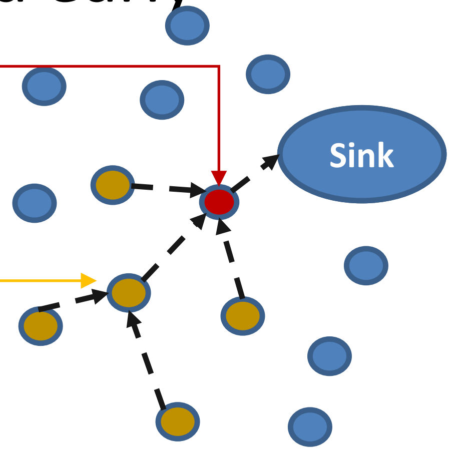
1: Đ. Banđur, B. Jakšić, M. Banđur, and S. Jović, "An analysis of energy efficiency in Wireless Sensor Networks (WSNs) applied in smart agriculture," Computers and electronics in agriculture, vol. 156, pp. 500-507, 2019.
2: 2: Nakas, C., Kandris, D., & Visvardis, G. (2020). Energy Efficient Routing in Wireless Sensor Networks: A Comprehensive Survey. *Algorithms*, *13*(3), 72.

Reduce energy in Wireless Sensor Networks

- To reduce energy consumption:
- Focus on the most energy-intensive activities
  - ➢Transmitting, receiving and listening

- Reduce the energy-consuming active periods of the nodes
  - ➢Make the nodes enter sleep state when possible

➢Balance the energy consumption in the network to avoid early depletion of key-nodes

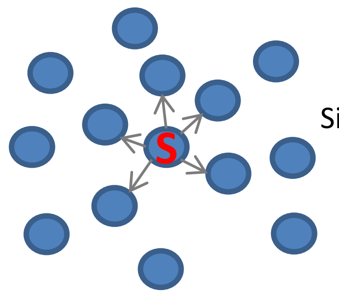


What is the probability that a network is partitioned when a node depletes?

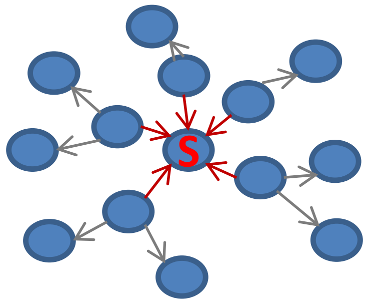
What is the probability that a depleting key-node partitions the network?

- Depends on the location of adjacent nodes
  - Are any of the adjacent nodes located such that they can assume the role of the depleted successor node?
- To assess the question, we assume a network running Routing Protocol for Low-Power and Lossy Networks (RPL) as routing protocol
  - Using hop-count as metric
- The next slide introduces RPL, thereafter the probability of network partitioning is presented

RPL routing - basics



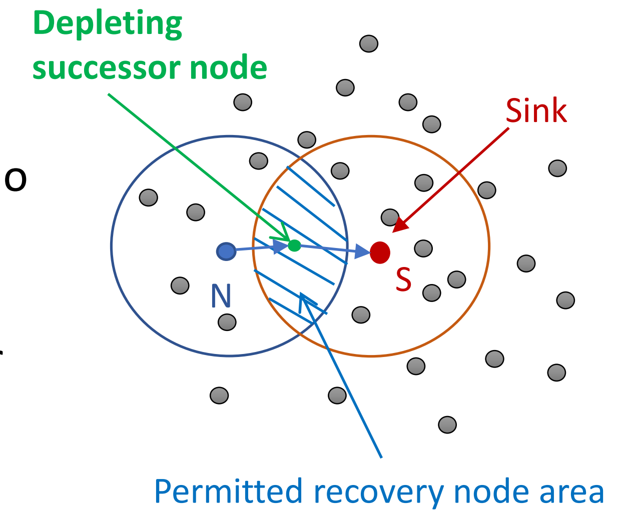
- Creates a Destination Oriented Directed Acyclic Graph(DODAG) that is directed from the nodes toward the sink.



- The DODAG is made by broadcasting Destination Information Option message (DIO)containing rank and Sequence Number information.
  - The Rank defines the nodes' level in the routing graph
    - , i.e., hop-count distance to the sink
  - DIO spreads like a wave from the sink toward the leaf nodes creating the DODAG.
  - A packet from a one-hop node are sent directly to the sink
  - A packet from a two-hop node must be forwarded by a one-hop node to reach the sink, and so forth.

RPL – node disconnected from sink?

- Node N (the blue node) is disconnected if there is no new successor node inside the blue shaded area when the green current successor depletes.
- Note: Node N has a recovery node if there is two or more nodes inside the blue shaded area.



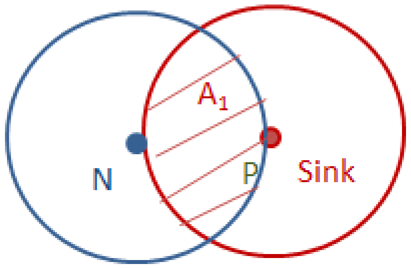
Extreme points for simulation and calculations

- **We want to find the probability that a node is not disconnected when successor node depletes**
  - Are there any nodes left in area A when the successor depletes?

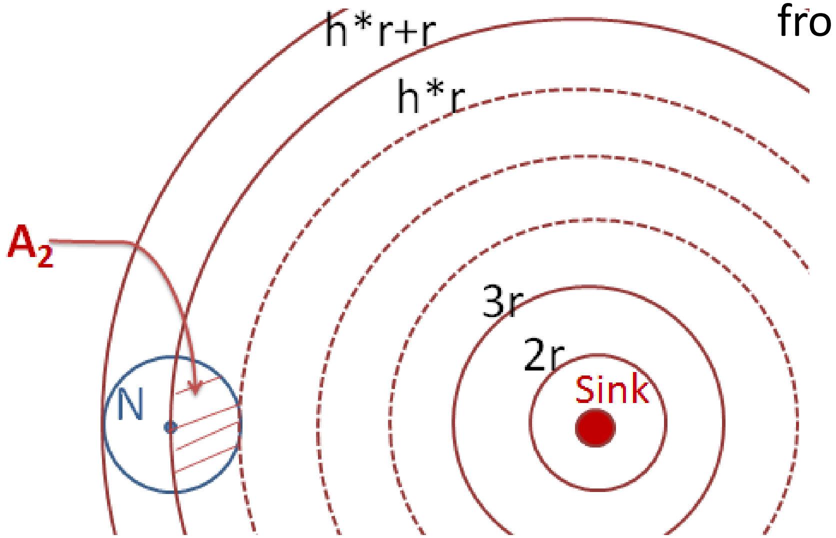
- Two extreme node-N locations define the borderline-cases for the probability:

- 1) Node N is a two hop node

- 2) Node N is next to a leaf node



r: the transmission range of the nodes
h: the number of hop from the sink

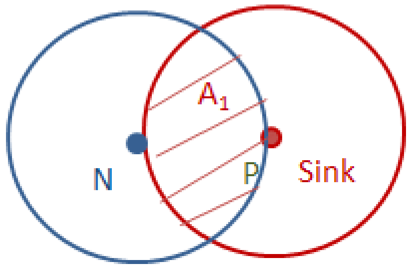


Analytical calculations

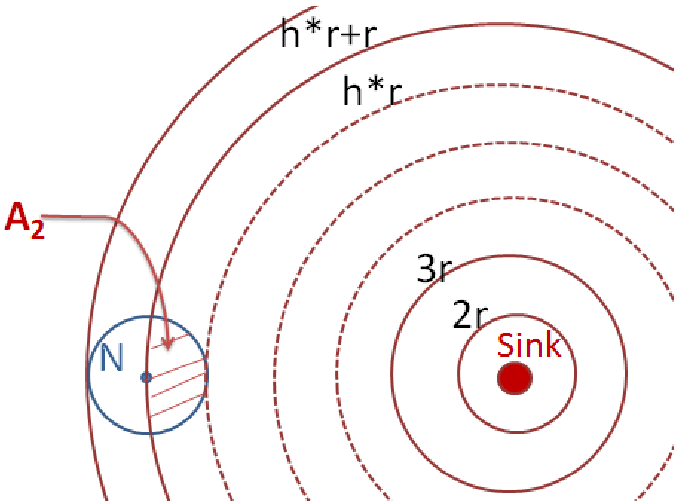
- The probability for a recovery node in A:

$$p(\boldsymbol{more}\ than\ one\ \ in\ A|\ at\ least\ one\ in\ A) =$$

$$\frac{P(2\ \ or\ more\ nodes\ in\ area\ A)}{P(more\ than\ 0\ nodes\ in\ area\ A)} =$$



$$1 - \frac{\lambda A(x)}{e^{\lambda A(x)} - 1} \qquad (1)$$



- To find the expected value of the probability that there exist a recovery node in area A, we need **the probability density function for the location of node N**

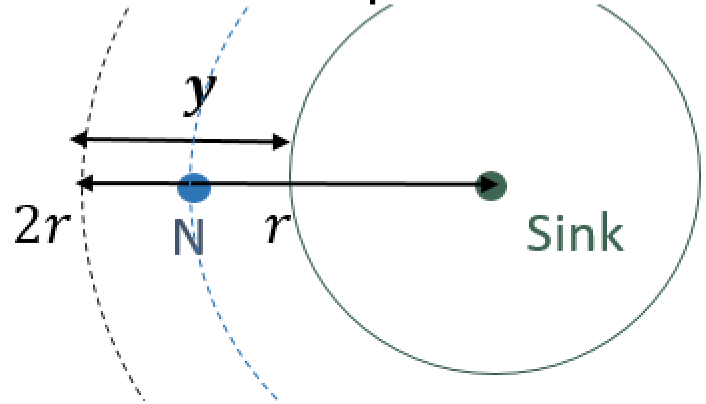
Probability density function

- The cumulative distribution function, F(y)
- Probability density function, *f(y)*

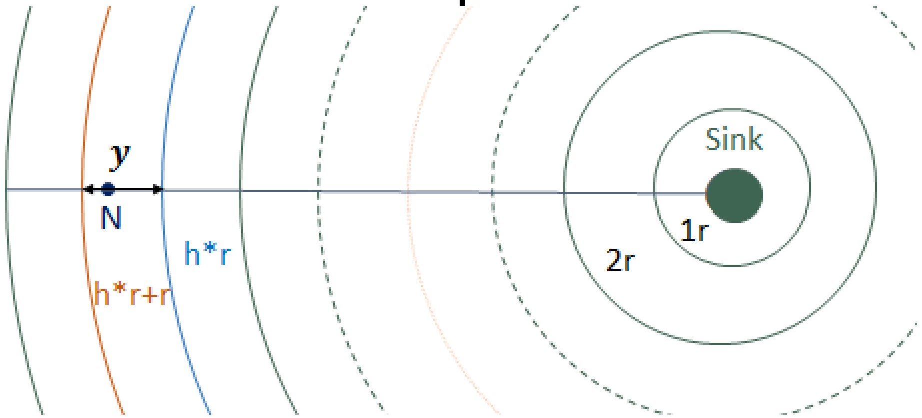
- Extreme point 1
  - $F(\mathrm{y}) = \frac{\pi(y)^2 - \pi(r)^2}{\pi(2r)^2 - \pi(r)^2} = \frac{y^2 - \mathrm{r}^2}{3\mathrm{r}^2}$
  - $f(y) = \frac{2y}{3\mathrm{r}^2}$

- Extreme point 2
  - $F(\mathrm{y}) = \frac{\pi\left((\mathrm{h}*\mathrm{r}) + y\right)^2 + \pi(h*r)^2}{\pi(\mathrm{h}*\mathrm{r}+\mathrm{r})^2 - \pi(\mathrm{h}*\mathrm{r})^2} = \frac{\mathrm{y}(2\mathrm{hr}+\mathrm{y})}{(1+2\mathrm{h})\mathrm{r}^2}$
  - $f(y) = \frac{2(hr+y)}{(1+2h)r^2}$

Extreme point 1



Extreme point 2

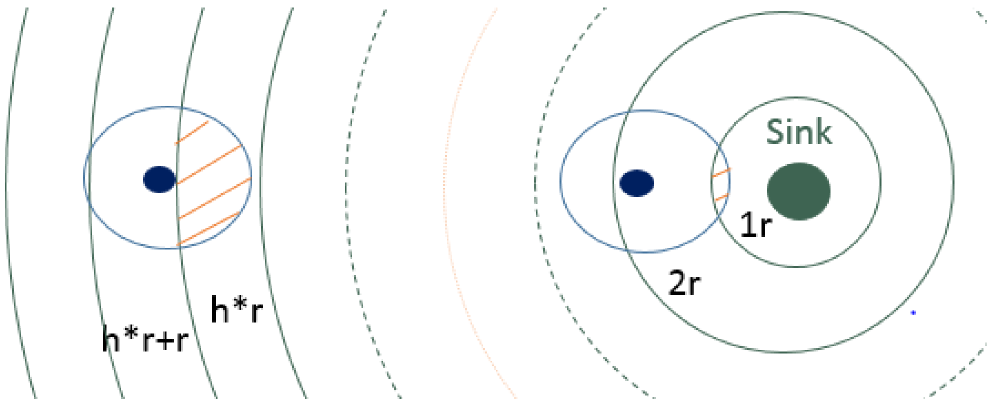


Simulations

The probability for a recovery node in A:

Java simulation performed for path breaks at:

- Extreme point 1)
- Extreme point 2)



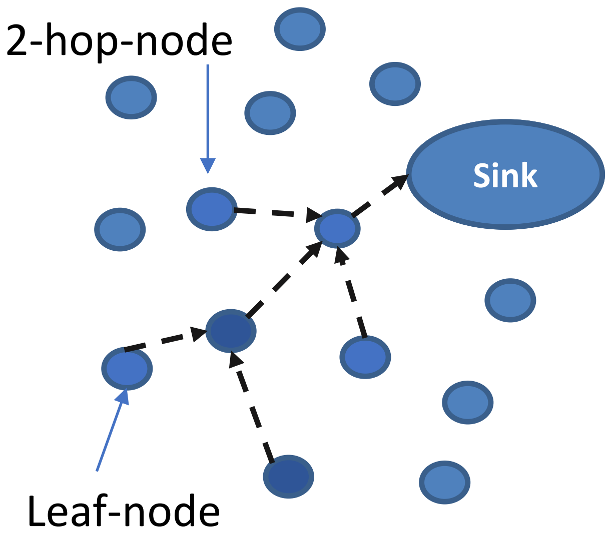
- Counted the number of nodes in the shaded area
  - $\frac{\#simulation\ with\ two\ or\ more\ nodes\ in\ the\ area}{\#\ simulations\ with\ at\ least\ one\ node\ in\ the\ area}$
  - 1000 simulation runs for each node density

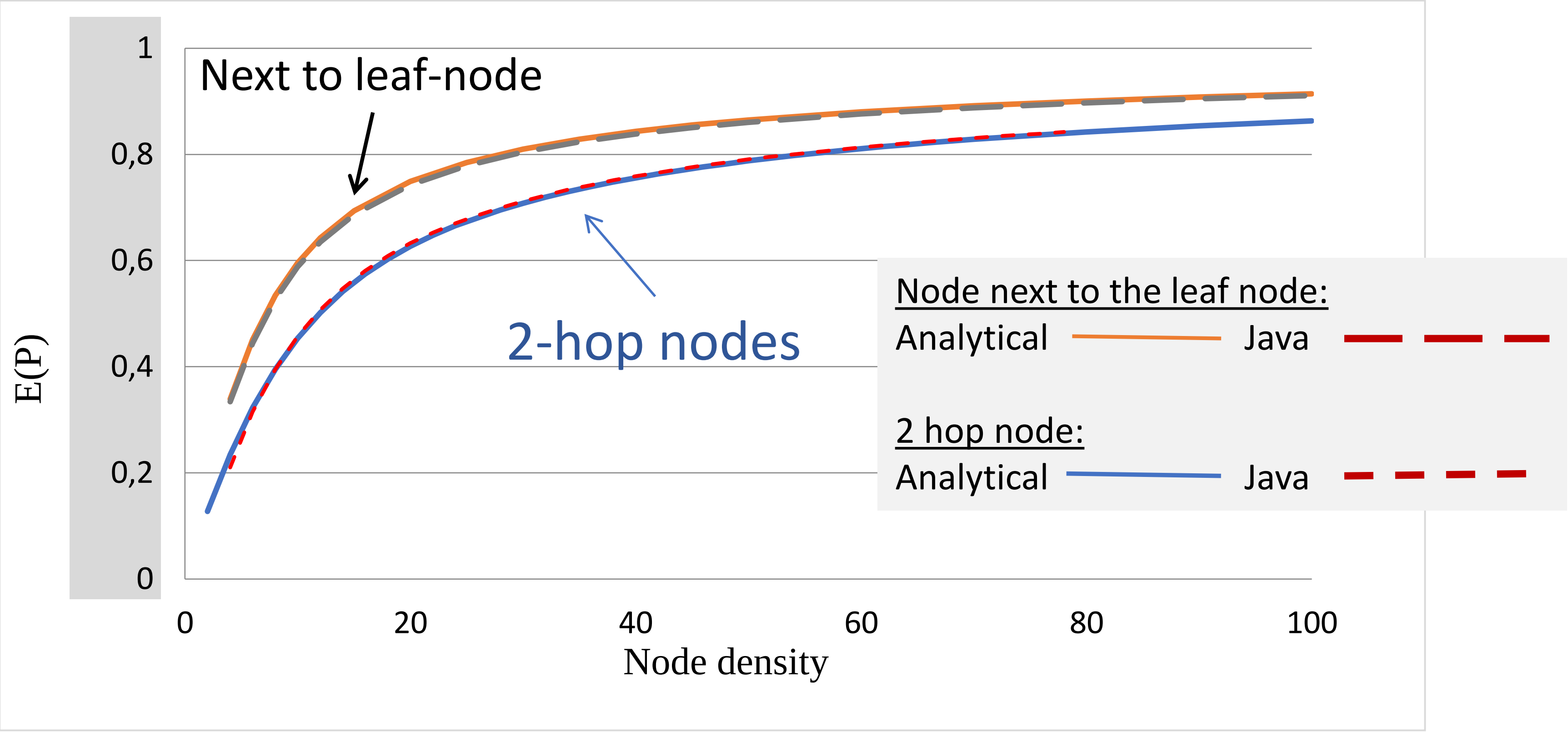
What is the probability that a depleting key-node partitions the network?

We calculated and simulated the probability of disconnection of the paths in networks running RPL (Routing Protocol for Low Power and Lossy Networks) using hop-count as metric.[1]

The graphs show the expected value of the probability that a disconnected node *are* able to find a new successor when its current successor depletes

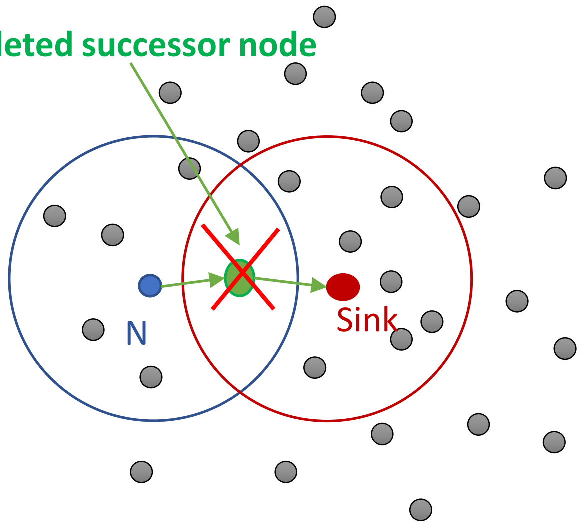
Lesson learned:
Disconnections are likely to occur !





1: Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," **An Analysis of the Need for Dedicated Recovery Methods and Their Applicability in Wireless Sensor Networks Running the Routing Protocol for Low-Power and Lossy Networks**", Proceedings of the 8th International Conference on Sensor Technologies and Applications (SENSORCOMM' 2014), pp. 121-129, 2014, ISBN: 978-1-61208-374-2

Conclusion



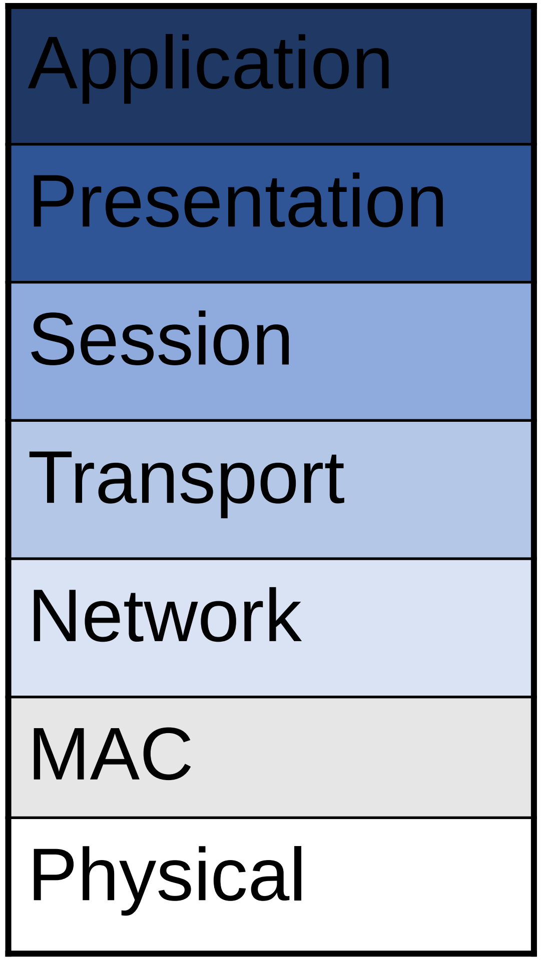
- ..what was the question? It was:
  - What is the probability that a depleting key-node partition the network?
- Calculations and simulations shows [1]
  - **When the successor depletes there is a 25% to 60% chance that the nodes gests disconnected from the sink**
    - **It is important to prevent node depletion !**
- The conclusion relates to networks running RPL with hop count as metric

1: Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," **An Analysis of the Need for Dedicated Recovery Methods and Their Applicability in Wireless Sensor Networks Running the Routing Protocol for Low-Power and Lossy Networks**", Proceedings of the 8th International Conference on Sensor Technologies and Applications (SENSORCOMM' 2014), pp. 121-129, 2014, ISBN: 978-1-61208-374-2

Energy conservation strategies at the different OSI-layers

Energy conservation strategies

- Approaches to conserve energy can be categorized based on where they belong in the Open System Interconnection model (OSI model).
  - Layers of the OSI: application, presentation, session, transmission, network, data-layer and physical
- Gathering the application, presentation, session, and transport layers into a common application layer:
  - Data compression and data aggregation
    - reduce the network traffic, thereby
    - reducing the energy consumed during transmission

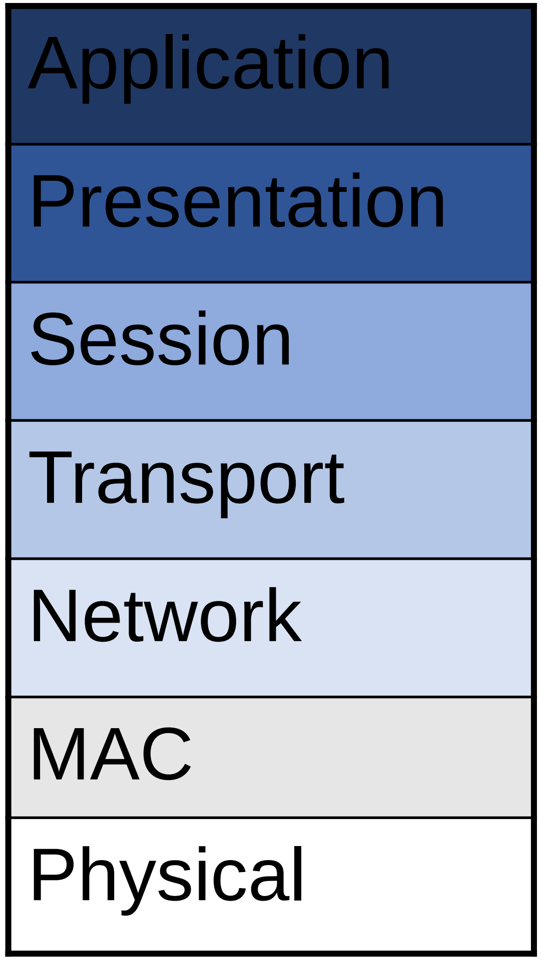


Physical layer

Energy conservation strategies

- Physical
  - Tuning data rate, carrier frequency, modulation and so on.
    - Higher order modulation can reduce the energy consumption since higher data rate reduces the transmission time.
      - However, there is a trade-off since the synchronization cost increases for high order modulation and may dominate the energy cost
    - The carrier frequency affects the energy consumption: the path loss increases with frequency.
  - Use low-power wake-up radios to monitor the communication channel and wake up the main receiver only when a wake-up signal is received.
    - Saves energy as sensor can stay in sleep state
    - However,
      - ambient noise can lead to numerous og false wake-ups of the main radio
      - may not reduce the number of overheard transmissions
      - the solution makes the nodes more complex

  - Tuning transmission range (network topology) -> next slide



Transmission range

- Adjust output power

  - Reducing output power reduces
    - the energy consumed by the power amplifier,
    - reduces the collision probability as fewer nodes are covered by the transmission, and
    - reduced the number of overhearing nodes that receive packets just to discard them.

  - However, the number of hop between source and destination increases
    - such that more nodes use energy to forward the packet.

    - ..transmission range continues on next slide

Transmission range

- Adaptable output power
  - After selecting the successor, the nodes can tune the output power to avoid spending energy on an unnecessary long transmission range
  - For instance [1]:
    - Proactively selection of transmission power,
      - Before packets are being transmitted
    - Reactively
      - Adjust output according to feedback from network or environment
    - Cognitive protocols
      - Self-learning methods
      - Swarm intelligent, Fuzzy logic, Reinforcement learning

  - Nodes can occasionally increase output power to transmit directly to the sink to reduce the forwarding load of the one-hop nodes
    - However, the management energy-cost for adaptable approaches can be high.

[1: Chincoli M., Liotta A. (2018) Transmission Power Control in WSNs: From Deterministic to Cognitive Methods. In: Gravina R., Palau C., Manso M., Liotta A., Fortino G. (eds) Integration, Interconnection, and Interoperability of IoT Systems. Internet of Things (Technology, Communications and Computing). Springer, Cham. https://doi.org/10.1007/978-3-319-61300-0_3]

MAC layer
Various approaches

The focus in this presentation is MAC, Network layer and transmission range

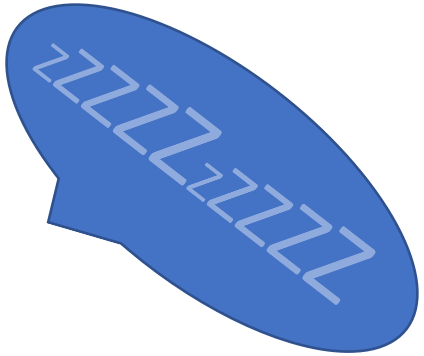
- MAC
  - The MAC protocol determines how long a node persist in the various radio states.
    - Remember, the radio is generally the main energy consumer
  - Thus, the MAC protocols have been the subject of substantial research related to energy efficiency.

MAC layer

- MAC
  - The focus is mainly on reducing idle listening, collisions, overhearing and overhead due to control-packets
  - Collisions: waste energy and requires retransmissions.
  - Overhearing: wastes energy, received packets are discarded.
  - Management/ control: Transmitting and receiving control packets consume energy.
  - Idle state: consumption is often in the same order of magnitude as for the receiving state

MAC layer

- Reduce the duty cycle (the active/ sleep – fraction)
  - Important and efficient approach to reduce energy, since,
  - the energy consumed while in sleep state is substantially lower than the energy consumed in any other state.



- Different approaches to manage the duty cycle
  - Asynchronous sleep/active schedule among the nodes
  - Synchronous sleep/ active schedule among the nodes
  - Time Division Multiple Access where the sleep/ active schedule is synchronized.
    - In addition, the transmission is scheduled to prevent collision

MAC layer

- Asynchronous sleep/ active schedule
  - Nodes set their own individual duty cycle.

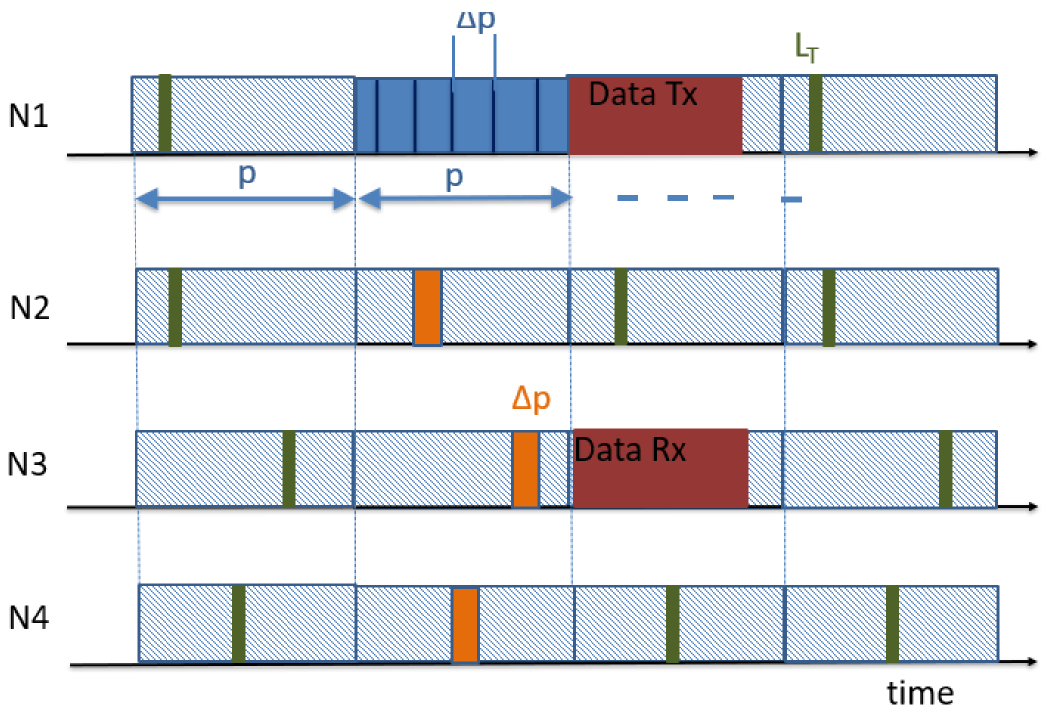
  - The basic, frequently cited approach suggested is Low Power Listening (LPL) (or B-MAC) [1][2]:
    - The nodes periodically wake up to listen for activity
    - If activity is detected, the node stays awake for the time required to receive the transmitted packet.
    - Nodes that have data to transmit start by transmitting a preamble, the length of which matches the longest known sleep interval among its neighbors.
    - Thus, the energy expenditure for transmission is high due to the extra preamble sent.
    - The periodic energy consumed for receiving is small as nodes only wake up for a very short time to check for activity.
    - But, nodes consume energy for listening through the rest of the preamble when activity is detected.
      - Method to reduce the consumption, see next slide..

1 : J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems*, 2004, pp. 95-107: ACM.

2: T. AlSkaif, B. Bellalta, M. G. Zapata, and J. M. B. Ordinas, "Energy efficiency of MAC protocols in low data rate wireless multimedia sensor networks: A comparative study," Ad Hoc Networks, vol. 56, pp. 141-157, 2017.

MAC layer

- LPL with divided-preamble [1]:
- The preamble divided into small fractions containing the receiver's address and the start-time for the data-packet transmission.
  - To reduce the energy consumed by the receiving nodes
  - A set of consecutive preamble-fractions, Δp, constitute the complete preamble, p, sent to signal data transmission.
- The figure illustrate the approach
  - The red squares represent a data packet that is transmitted from node N1, and received by node N3.
  - The green squares, L_T, illustrate the nodes' periodic listening for activity.
  - The orange squares illustrate that nodes receive and read a preamble-fraction.



1: A. Bachir, D. Barthel, M. Heusse, and A. Duda, "Micro-frame preamble mac for multihop wireless sensor networks," in *Communications, 2006. ICC'06. IEEE International Conference on*, 2006, vol. 7, pp. 3365-3370: IEEE.

MAC layer

- In X-MAC [1][2], time delay is introduced between short preamble packets.
- The preamble packets contain the identity of the receiver node.
- The intended receiver uses the time delay to interrupt the preamble transmission
  - Receiving the ACK, the sender immediately stops sending the preamble and start sending the data packet.
- In addition, the receivers’ duty cycle is dynamically adjusted according to traffic load.
- This algorithm addresses the overhearing problem, reduces transmission energy consumption and reduces the per-hop latency.
- However, the energy consumption is increased compared to divided-preamble LPL during periods of no activity;
  - this is due to the gap between the short preamble packets, which makes the nodes stay awake for a longer period than is otherwise needed in order to check the channel for activity.

1: M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks," in *Proceedings of the 4th international conference on Embedded networked sensor systems*, 2006, pp. 307-320: ACM.
2: A. Kumar, M. Zhao, K. Wong, Y. L. Guan and P. H. J. Chong, "A Comprehensive Study of IoT and WSN MAC Protocols: Research Issues, Challenges and Opportunities," in IEEE Access, vol. 6, pp. 76228-76262, 2018, doi: 10.1109/ACCESS.2018.2883391.

MAC layer

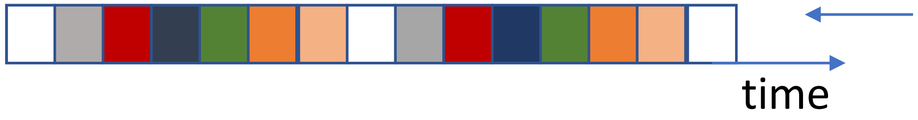
- Synchronous approach
  - Synchronize the active/ sleep - schedule among the nodes.
    - All nodes sleep during the same interval
  - Reduces the energy that is otherwise used to listen when all other nodes are sleeping.

  - The basic, frequently cited approach is Sensor-MAC (S-MAC) [1][2]
    - Synchronizes the schedule for sleep and activity among neighboring nodes.
    - During startup, a node enter the active state and listens for synchronization information from neighbors.
    - If no information is received after listening for a fixed time duration the node sets its own schedule .
    - The nodes periodically generate SYNC packets containing their schedule information
      - Neighboring nodes contend to broadcast their packets.
      - Allows the neighboring nodes to adapt to the schedule of the sender.
      - Neighboring nodes that adapt to the same schedule form a virtual cluster.
      - Nodes lying on the border between two clusters with different schedules (border nodes) must adapt to both schedules to avoid network partitioning.
      - Thus, nodes are free to talk to each other although they belong to different clusters with different sleep/ active schedules.
        - The clusters are therefore called virtual clusters.
      - All nodes periodically listen for a whole synchronization period to detect whether they are border nodes.

  - The price payed is the energy consumed to manage the synchronization.
    - Nodes must occasionally remain awake during a whole period to check whether there exit other neighboring nodes that follows other wakeup intervals
    - A challenge to make the whole network follow the same schedule

1: W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *Networking, IEEE/ACM Transactions on,* vol. 12, no. 3, pp. 493-506, 2004.
2: Y. Wei, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, 2002, vol. 3, pp. 1567-1576 vol.3.

MAC layer



Each sender-receiver pair have their own timeslot, i.e., their own color

- Time Division Multiple Acc (TDMA) [1][2]
  - TDMA protocols share the medium by dividing the communication into consecutive timeslot
  - Each sender-receiver pair communicates in their own predetermined timeslot, which is repeated periodically
  - Clustering can be used to distribute TDMA management in WSN. A cluster head is selected in each cluster, and nodes can only talk to members of their own cluster.
  - Low-Energy Adaptive Clustering Hierarchy (LEACH) is a frequently cited Cluster protocol in which the clusterhead maintains the TDMA schedule in its cluster.
  - Wireless-HART relies on a fixed length TDMA scheme where nodes may enter sleep state during all other slots than their own [3].
  - 802.15.4 can optionally run with an operation similar to TDMA when in beacon enabled mode

  - TDMA has a great advantage in that it creates a collision free medium.
  - However, TDMA needs tight clock synchronization to make sure that the time slots of nodes do not overlap.
    - This may require frequent message exchange.
  - Thus, it is energy consuming to maintain firm synchronization and to manage the slot activity.

1: Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: a survey," *Communications Magazine, IEEE,* vol. 44, no. 4, pp. 115-121, 2006.

2: C. S. R. M. B. S. Manoy, "Ad Hoc Wireless Networks Architectures and Protocols," ed: Prentice Hall, 2004, p. 857

3: Rault, T., Bouabdallah, A., & Challal, Y. (2014). Energy efficiency in wireless sensor networks: A top-down survey. *Computer Networks*, *67*, 104-122.

4: *Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE Std 802.15.4™-2011, 2011.

Mac layer

- Recommended reading if you want to learn more about MAC layer approaches to reduce energy consumption: [1][2][3]

1: A. Kumar, M. Zhao, K. Wong, Y. L. Guan and P. H. J. Chong, "A Comprehensive Study of IoT and WSN MAC Protocols: Research Issues, Challenges and Opportunities," in IEEE Access, vol. 6, pp. 76228-76262, 2018, doi: 10.1109/ACCESS.2018.2883391.

2: T. AlSkaif, B. Bellalta, M. G. Zapata, and J. M. B. Ordinas, "Energy efficiency of MAC protocols in low data rate wireless multimedia sensor networks: A comparative study," Ad Hoc Networks, vol. 56, pp. 141-157, 2017.

3: V. L. Quintero, C. Estevez, M. E. Orchard, and A. Pérez, "Improvements of energy-efficient techniques in WSNs: a MAC-protocol approach," IEEE Communications Surveys & Tutorials, vol. 21, no. 2, pp. 1188-1208, 2018.

Investigate impact of sleep state

What is the impact of switching nodes to sleep state?

Energy consumption model

Energy consumption for one hop transmission:

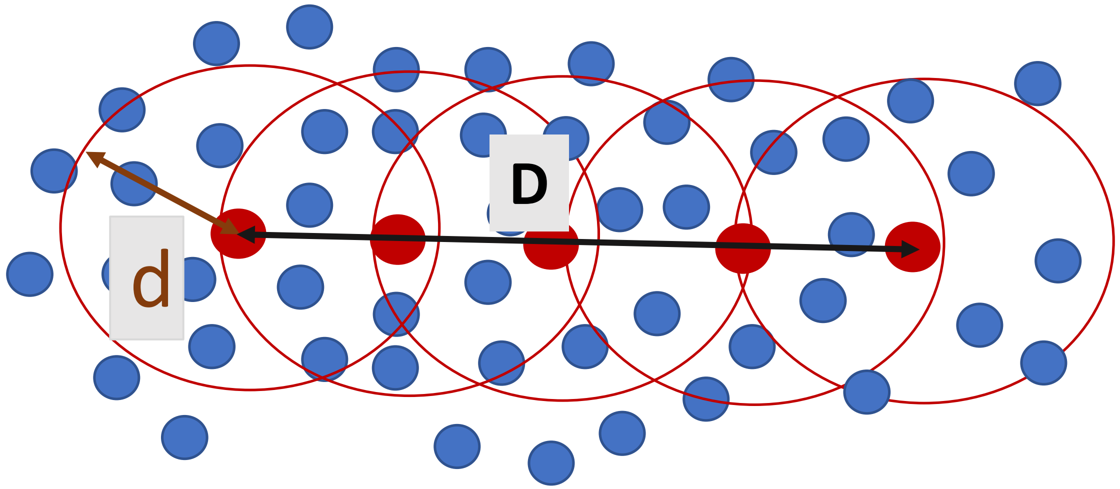
$$\mathbf{E_{TX}} = (\mathbf{k_1} + \mathbf{k_2} * \mathbf{d^2}) * \mathbf{b}$$

Receiving energy consumption:

$$\mathbf{E_{RX}} = \mathbf{k_3}(\pi \mathbf{d^2} * \lambda) * \mathbf{b}$$

Thus, total energy consumption for transmission from source to sink is:

$$E_{TOT} = b * \frac{D}{d}\left((k_1 + k_2 * d^2) + (k_3 * \pi d^2 * \lambda)\right)$$



- k_1 : represent the constant level of energy that is consumed when transmitting a bit.
- k_2 : represent the energy that is proportional to the radiated power when a bit is transmitted.
- k_3 :energy consumed per received bit.
- d: transmission range of the nodes.
- D: distance between the source and the sink.
- D/d: the minimum number of times the packet has to be relayed to reach the sink.
- b: number of data bits
- λ: Node density

Energy optimal transmission range when overhearing nodes are *not* switched to sleep mode

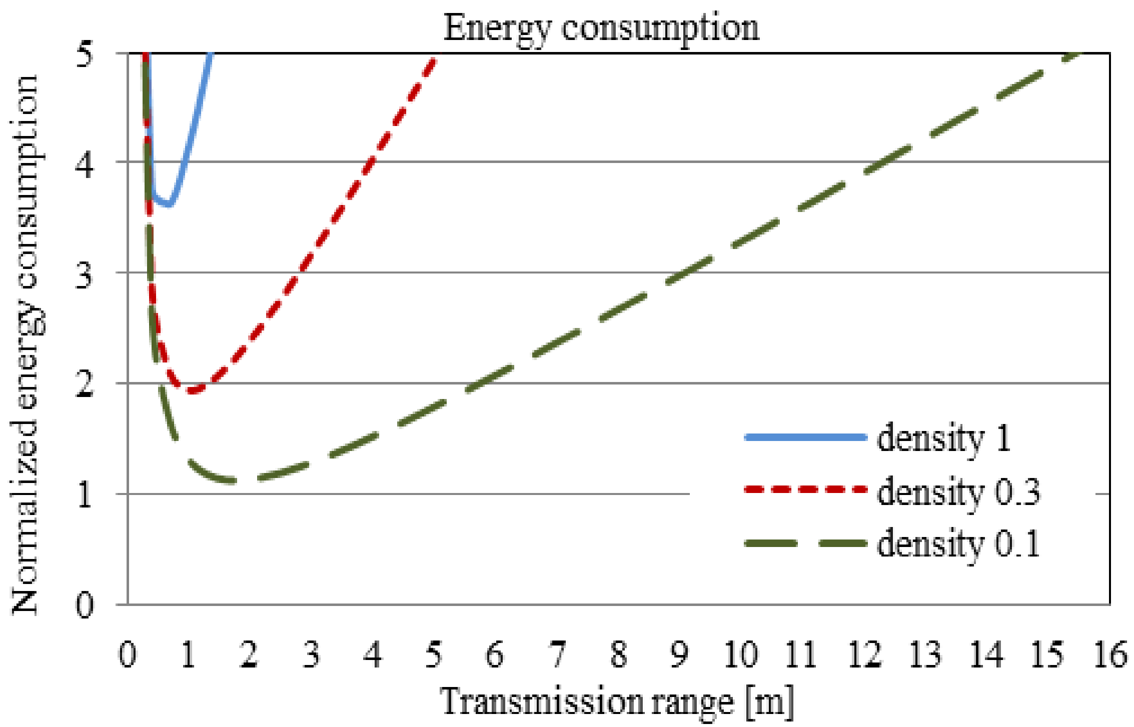
By differentiating $\boldsymbol{E_{TOT}}$, the energy optimum transmission range is:

$$\mathbf{d_{opt}} = \sqrt{\frac{\mathbf{1}}{\frac{\mathbf{k_2}}{\mathbf{k_1}} + \frac{\mathbf{k_3}}{\mathbf{k_1}} * \boldsymbol{\pi} * \boldsymbol{\lambda}}}$$

$k_1=2.7*10^{-5}$
$k_2=1.7*10^{-11}$
$k_3=2.9*10^{-5}$

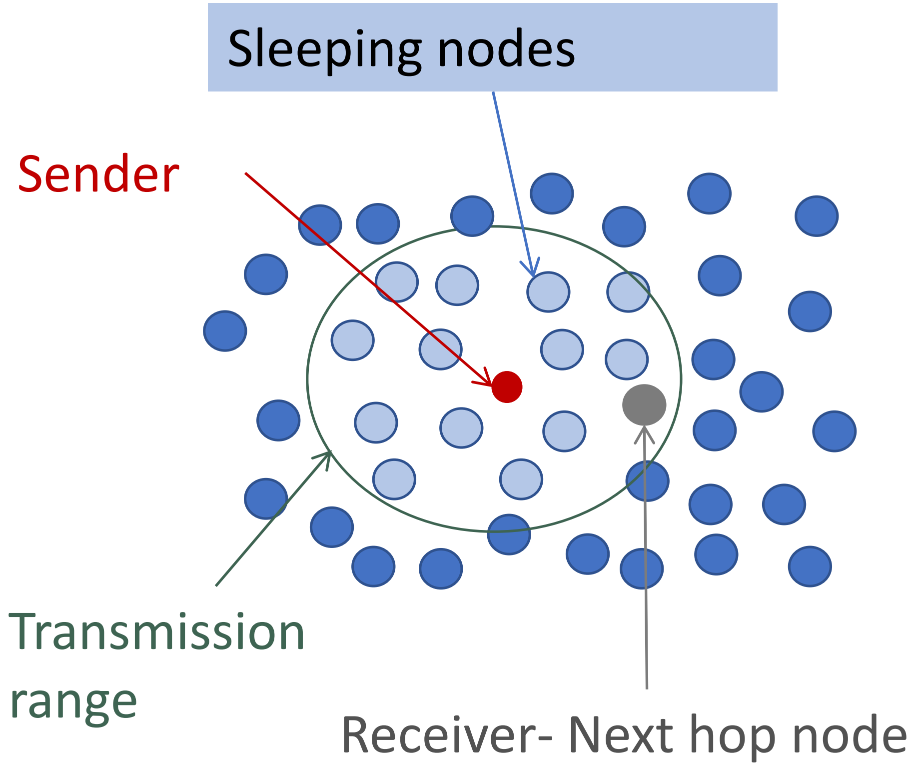
Overhearing is the main energy consumer

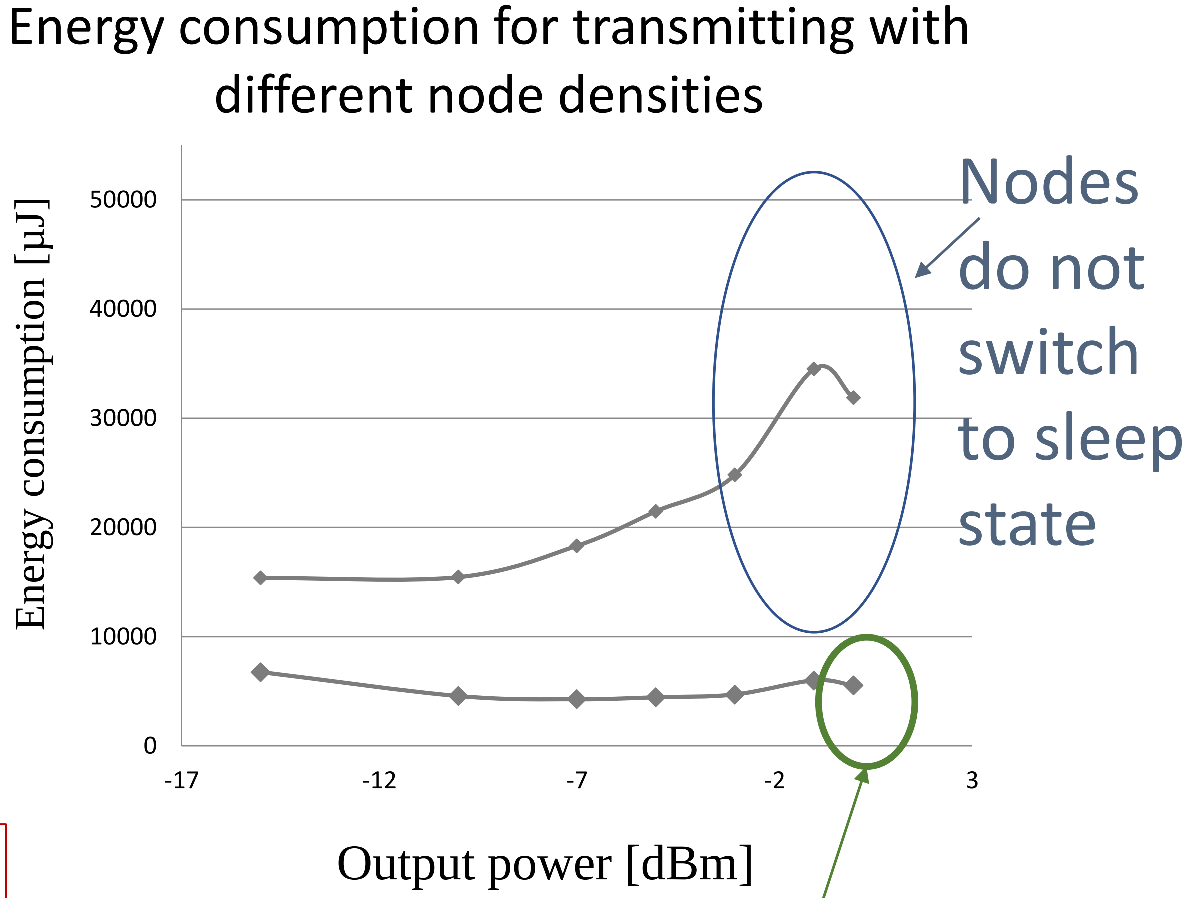
The energy optimal transmission range is the shortest range needed to keep the network connected



Number of covered nodes when using energy optimal transmission rage:
0.62: AT86RF230
0.96 : CC1000 433

What is the effect of switching overhearing nodes (the nodes that are covered by the transmission but are not the intended receivers) to sleep state during packet transmission?





Switching to sleep state substantially reduces the energy consumption in the network

Omnet++ is used for simulations

Overhearing nodes switch to sleep state before data is transmitted

Conclusion

- Calculation performed using a simple energy consumption model, using parameters estimated based on datasheet values [1]:

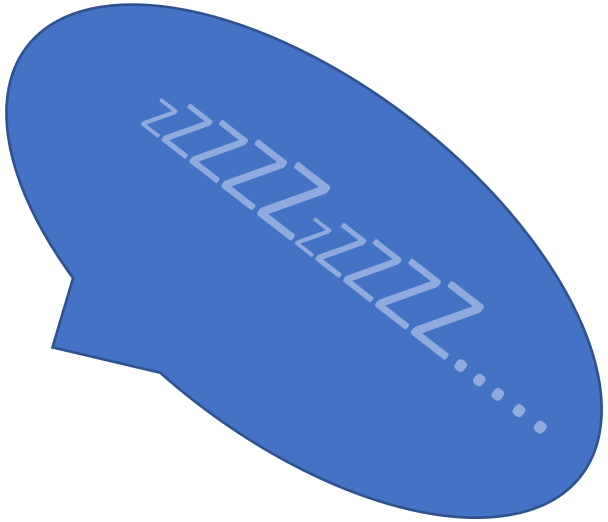
  - The energy-optimal transmission range is shorter than the range deeded to avoid network partitioning, *unless* overhearing nodes are switched to sleep state during transmission

  ➢ **Switch nodes to sleep state to avoid overhearing !**
    - Substantially reduces the energy consumed when packet are forwarded from source to destination

1: Anne-Lena Kampen, Knut Øvsthus and Øivind Kure,” **Energy Reduction in Wireless Sensor Networks by Switching Nodes** to Sleep During Packet Forwarding”, Proceedings of the 6th International Conference on Sensor Technologies and Applications (SENSORCOMM’ 2012), pp. 189-195, 2012, ISBN: 978-1-61208-207-3

Investigate the energy optimal distance between nodes using sleep protocol

Duty cycle (sleep) protocols



- It is energy efficient to switch node to sleep state

- So, the focus of the next few slides is on networks using

  using **LPL with divided-preamble**

- Why was the asynchronous LPL chosen in stead of TDMA?
  - It is energy consuming to maintain firm synchronization and to manage the slot activity.
  - Slot management and assignment are particularly challenging when the network topology changes, such as when nodes are added or removed.

- However, TDMA is a good solution for networks with strict delay requirement

Combining LPL with divided-preamble, and transmission range

- Investigate the tradeoff between the number of re-transmissions, transmission range, the number of overhearing nodes, and number of hops in WSN to discover the energy optimal distance between consecutive nodes along the routing paths [1].

- Re-transmissions decreases when the distance between sender and receiver is reduced
  - Re-transmissions are a waste of energy

- However, number of hops increases when the distance is short
  - Energy consumption for forwarding is increasing

- Number of re-transmissions needed can be reduced by increasing the transmission range (increase the output power) of the nodes
  - The distance from a sender to where the packet delivery rate start to degrade is increased

1: A Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," Reducing The Energy Consumed During Multihop Transmissions in Wireless Sensor Networks", (SENSORCOMM' 2020).

Energy consumed for each one-hop transmission along the routing paths

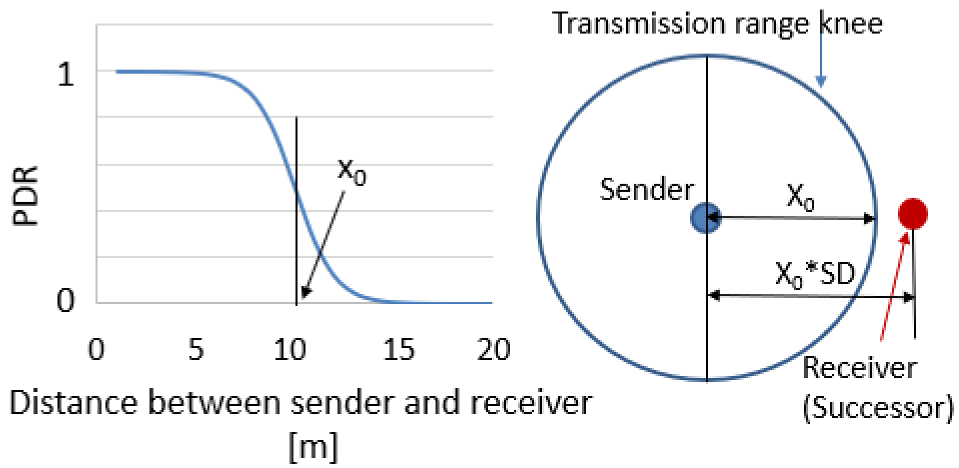
$$E = (k_1 + k_2 d^2)(b + p) + k_3 b + 1.5\Delta p(k_3 \pi \lambda d^2 - 1)$$

- Energy used by the sender to transmit data and preamble: $(k_1 + k_2 d^2)(b + p)$
- Energy used by the receiver to receive the data packet: $k_3 b$
- The number of nodes that is covered by the transmission is: $\pi \lambda d^2$
- If a node wakes up after transmission of a preamble-fraction has started, it must remain in the receiving state until it receives the subsequent complete preamble-fraction:
  - On average, receive one half preamble-fraction in addition to the complete fraction that it is able to read: $1.5\Delta p$
- The energy that the receiver and the overhearing nodes used to receive preamble: $1.5\Delta p(k_3 \pi \lambda d^2 - 1)$

Symbol	Meaning
k_1	Energy consumed to transmit, fixed part
k_2	Energy consumed to transmit, proportional to radiated power
k_3	Energy consumed to receive
λ	Node density
d	Transmission range
p	Preamble
b	Data packet
Δp	Preamble-fraction

Expected number of transmissions from source to sink

- A receiver experiences increasing re-transmissions when it is located at the border area of the sender's transmission range.
  - Because the packet delivery rate is degrading in this area
  - To account for this border effect we use the model presented in [1] to estimate the expected number of transmissions that is need to transmit a packet from a source to the sink along its routing path:
  - $ETX[N] = \frac{1-q^m-(1-q^m)^N}{q^m(1-q)}$
  - Where the packet loss rate, q is given by [*]
  - $PDR(x) = \frac{1}{1+e^{\frac{x-x_0}{x_1}}} 1$



The left-hand side of the figure shows the Packet Delivery Rate (PDR) for increasing distance between sender and receiver. Increasing the distance reduces the probability of successful delivery of packets, from PDR=1 when the distance is short to PDR=0 for long distances. The midpoint between these two extreme PDR values is marked as $\mathbf{x_0}$, and is referred to as the knee point. The small blue circle in the center of the right-hand side figure illustrates a transmitting node, and the blue outer circle is the knee-point boarder line for the transmission. That is, for receivers located well inside the blue circle it is likely that PDR=1, and for receivers located well outside it is likely that PDR=0.

Symbol	Meaning
q	Packet loss rate
x	Distance between communicating nodes
x_0	Knee value
x_1	Border area width
N	Number of nodes along a path
m	Number of transmission trials

1: K. Øvsthus, E. Nilsen, A.-L. Kampen, and Ø. Kure, "Modelling the Optimal Link Length in Wireless Sensor Networks for Two Different Media Access Protocols," 2015.

The energy consumed for transmitting a packet from source to sink

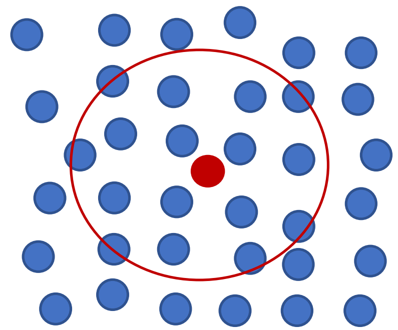
$$E = ETX[N][\,(k_1 + k_2 d^2)(b + p) + k_3 b + 1.5\Delta p(k_3 \pi \lambda d^2 - 1)]$$

- To find the total energy consumed to transmit from source to sink along the routing path:
  - Multiply the expected number of transmission with energy cost of each transmission (presented in the preceding two slides)

- Energy used by the receiver to receive the data packet: $k_3 b$

- The number of nodes that is covered by the transmission is: $\pi \lambda d^2$

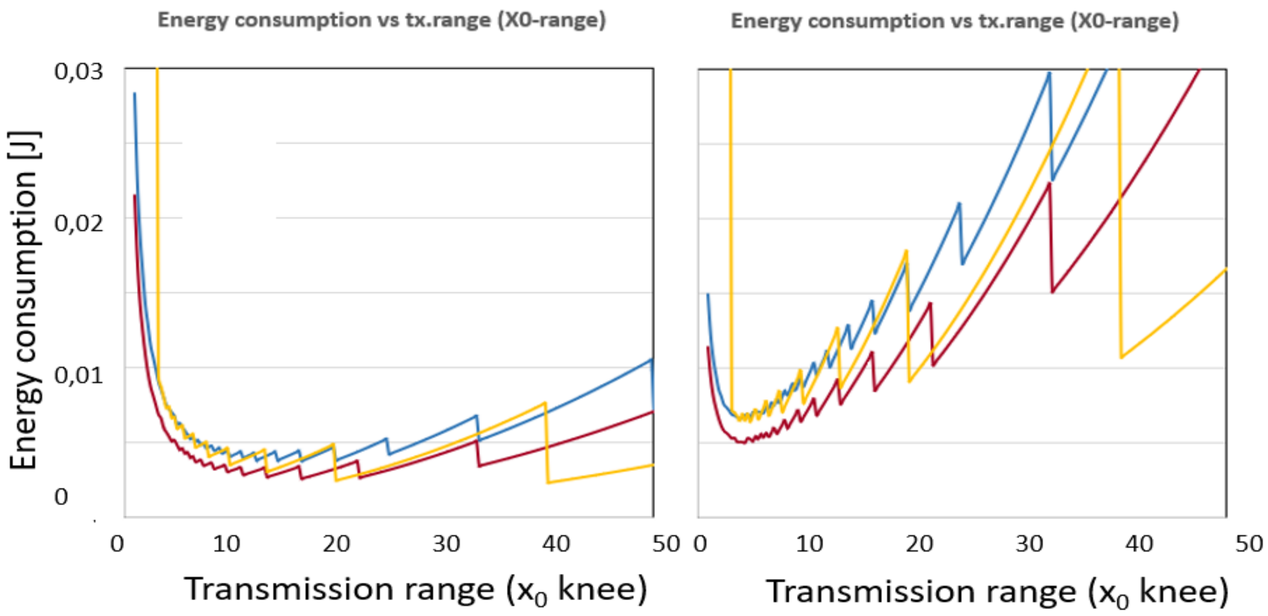
- The energy that the receiver and the overhearing nodes used to receive preamble: $1.5\Delta p(k_3 \pi \lambda d^2 - 1)$



Nodes inside the red ring is covered by the transmission form the red node.

Energy-optimal transmission

This figure shows the energy consumption related to transmission range
Analytically evaluated using the presented equations



The blue curves show the energy consumed when the distance from the sender to the receiving nodes is much shorter than the knee values (x_0) specifically $0.5 \cdot x_0$.
The distance is also shorter for the red curves ($0.75 \cdot x_0$), while the distance from the sender to the receiver for the yellow curves is longer than the knee value ($1.25x_0$).
The left-hand side of the figure shows the energy consumed when the preamble-fraction that overhearing nodes receive is 0.1 times the complete preamble.
Similarly, the figure on the right-hand side shows the results when overhearing nodes receive 0.5 times the complete preamble.

- The graphs show that energy consumption is lowest when $x_0 \cdot 0.75$ (equals ETXper-hop=1.4).

Conclusion

Investigating the tradeoff between the number of re-transmissions, transmission range, the number of overhearing nodes, and number of hops in WSN to discover the energy optimal distance between consecutive nodes along the routing paths [1].

The network uses LPL with divided-preamble

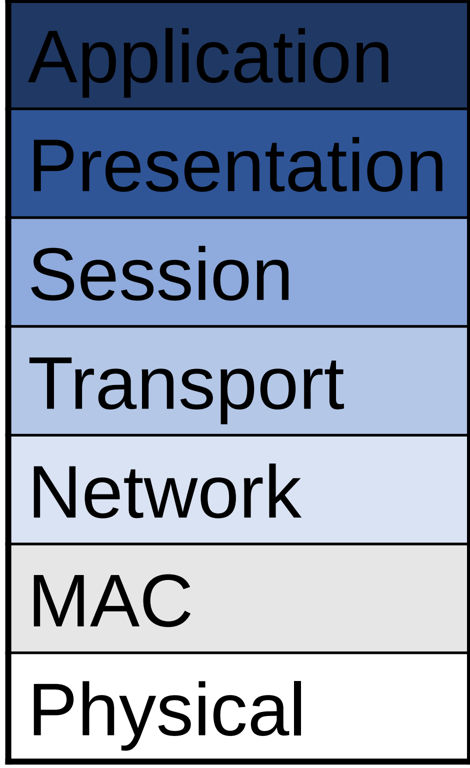
The energy-optimal solution is for the nodes to choose their successors at a distance that gives an expected number of transmissions, ETXper-hop, of approximately 1.4.

1: A Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," Reducing The Energy Consumed During Multihop Transmissions in Wireless Sensor Networks", (SENSORCOMM' 2020).

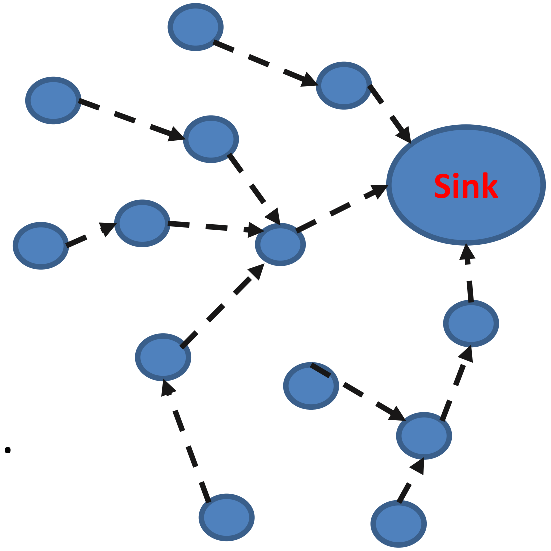
Network layer

Application
Presentation
Session
Transport
Network
MAC
Physical

Network layer



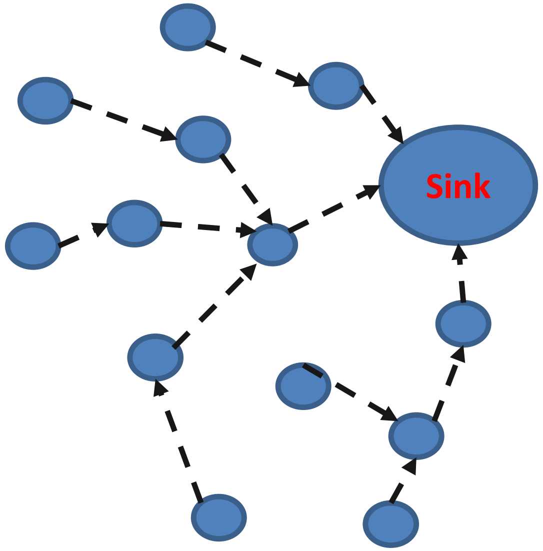
- The routing protocols generally belong to the network layer.
- The routing protocols develop the paths that are used to transmit data from source (the nodes generating the data) to sink.
- Related to energy consumption, the paths should
  - Minimize the energy consumed to transmit packet from source to sink
  - Balance the energy consumption in the network
    - Ensure that low energy nodes are avoided
    - Prevent formation of hop-spot nodes
  - Remember: The goal is to reduce node depletion and network partitioning.



Network layer

- A frequently used metric for energy efficient solutions is based on
  - The residual-energy of the nodes along the paths

- The nodes may inform neighbors about their rest energy by piggy-back the information in
  - ack-packet,
  - data-packets,
  - hello-packets,
  - routing-management packets or
  - sending energy-information packet, but this is probably a waste of energy

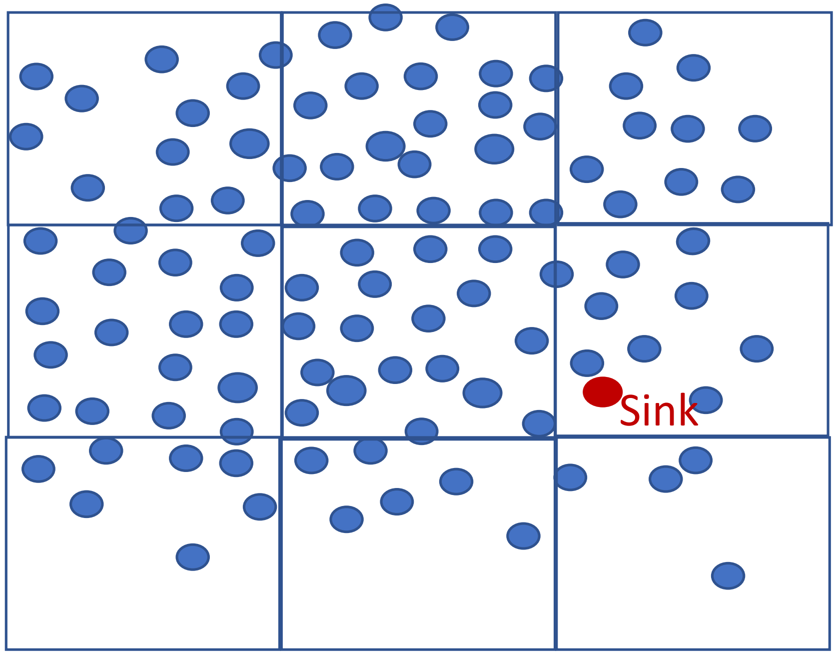


Network layer

- There broad range of energy-efficient network layer approaches are found in literature. These can be categorized in various ways, for instance

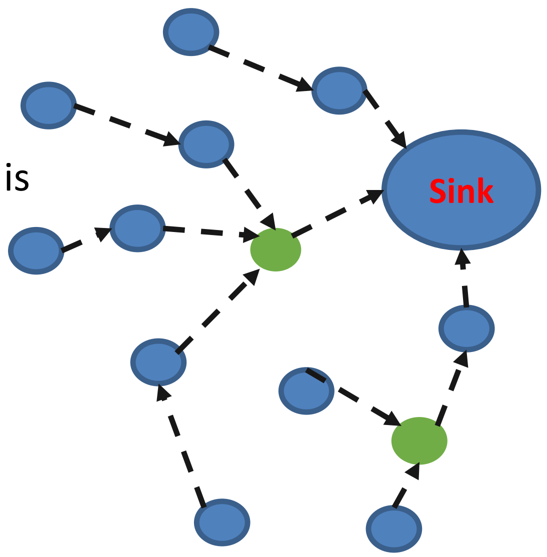
- Reactive versus proactive protocols
  - Proactive
    - Discover routing paths before data is being transmitted, maintain the paths to remain available
    - Reduces delay
    - Energy is used to maintain the paths
  - Reactive
    - Paths are discovered after an event has occurred
    - Energy consumption is reduced since path maintenance is reduced
    - Higher delay
  - Hybrid
    - Divide the network into zones and maintain proactive paths for communication within the zones.
    - However, reactive paths are used for communication outside the zones
    - Not very suitable for WSNs where all data is transmitted to sink
      - Data from remote sensors would always require proactive routing
      - Only nodes located in zones that also includes the sink will benefit from the proactive routes

Network divided into zones

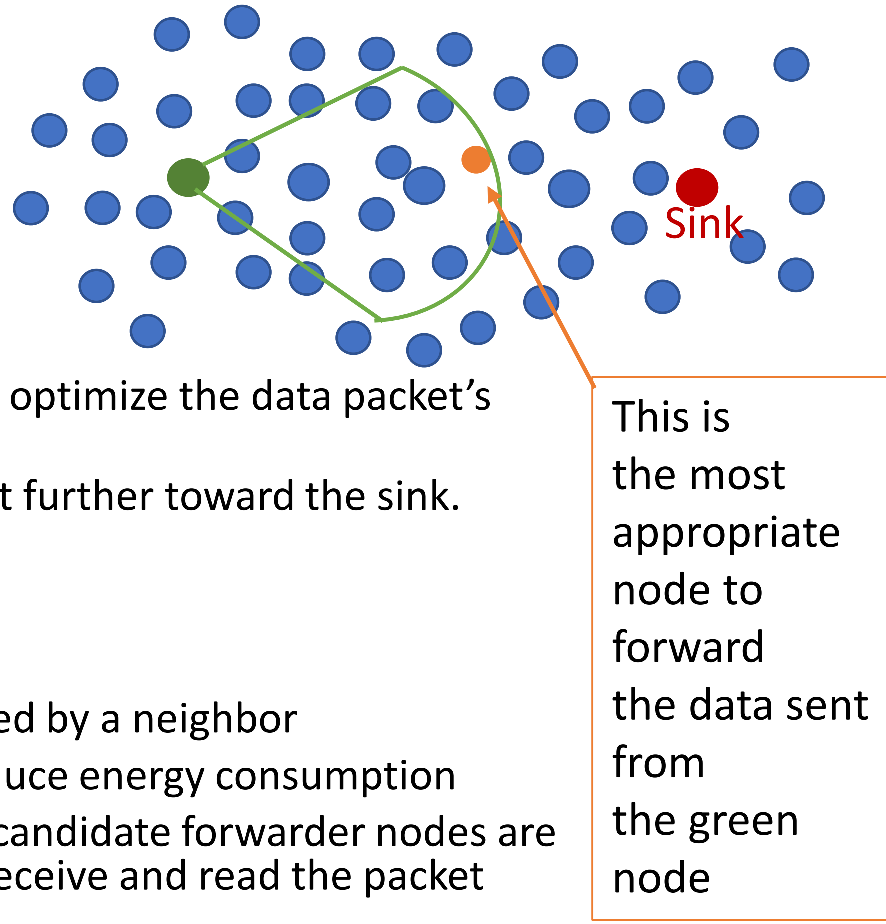


Network layer

- Negotiation based
  - The nodes advertise the data they collect using a common naming scheme. After negotiations, the node may send their data to destinations. The goal is to reduce the redundant transmission of data.
    - Not efficient unless data-packets are much larger than advertisement packets.
- Aggregation
  - Nodes processes the collected data before transmission
  - Two different approaches
    - A nodes process on its own detected data
    - Data from several nodes are collected at a common aggregator that aggregates all received data
  - This is a cross layer approach between network and application layer. The routing protocols form a hierarchical network topology with appropriate located aggregation nodes. The aggregation of the data is performed at the application layer.
  - The number and/or size of data-packet transmitted is reduced, reducing the energy consumed
  - However, the accuracy of the data collected at the sink is reduced, and the nodes must perform more complex operations



Network layer

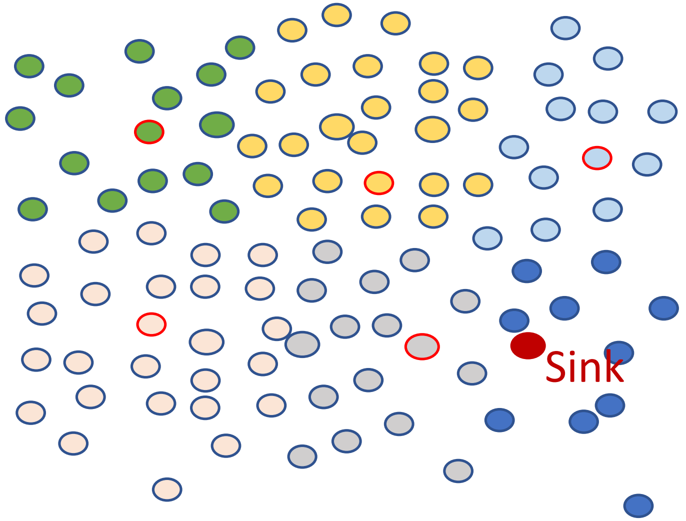


- Opportunistic routing
  - Utilized the broadcast nature of wireless media to reduce retransmissions and optimize the data packet's progress toward the sink.
  - After the packet is transmitted the most appropriate node forwards the packet further toward the sink.
  - Criteria to decide which node that is the most appropriate
    - Provides the best progress to reach the sink
    - Has energy level that is higher than the average level among the nodes
  - Other nodes refrain from forwarding when they hear the data packet forwarded by a neighbor
  - Can reduce the number of retransmissions caused by unreliable links, thus reduce energy consumption
  - However, double forwarding of a packet may occur in unreliable media and if candidate forwarder nodes are outside each other's transmission range. In addition, all nodes use energy to receive and read the packet

- Mobile sink or data-collector
  - Use a mobile sink or a collector nodes that can move without constraints among the nodes to collect their data.
  - Saves the energy sine no forwarding is needed and the transmission rage is short.
  - However, the solutions is not applicable for several types of environments

Network layer

- Hierarchical



Network divided into clusters. the nodes with red contour represent cluster head (CH)

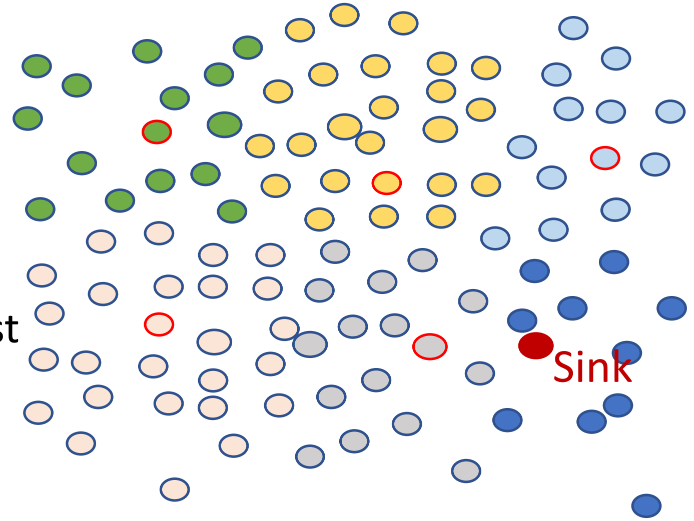
  - Cluster protocols
    - Group the sensors into several clusters
    - Select a cluster head (CH) in each cluster
    - Data from members of a cluster are sent to the CH
    - CH transmit the data to the sink
    - The nodes alternate on being a CH (to balance energy consumption between the nodes)

  - Some of the most frequent cited protocols belong herein, i.e., the LEACH protocol [1].

1: W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, ''Energyefficient communication protocol for wireless microsensor networks,'' in Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci., vol. 8. 2000, pp. 1–10.

Continues..

Network layer

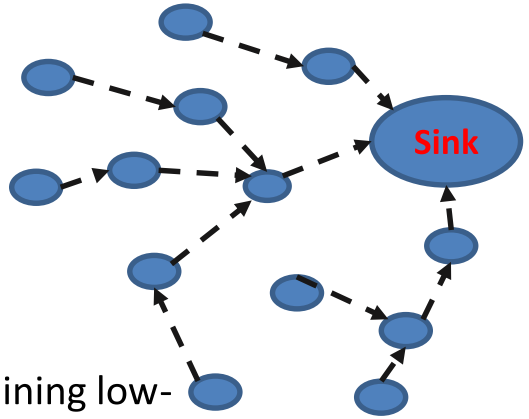


Network divided into clusters. the nodes with red contour represent cluster head (CH)

- Improvements suggested for LEACH[1]:
  - HEED [2]
    - While the CHs in LEACH transmit the data directly to the sink, HEED suggest multi-hop communication,
    - CH selection based on node residual energy and node degree.
  - Prevent low energy nodes from being elected as cluster heads[3]
    - Threshold value is based on the remaining energy of the nodes,
      - the energy required for data transmission, and
      - the probability of energy usage
  - Cluster head selection is based on [4]
    - The number of neighbors, higher number improves the probability of being selected.
    - Energy level of the nodes, higher number improves the probability of being selected.
    - Distance to the base station, nodes closer to the base station improve the probability of being selected.

1: W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, ''Energy efficient communication protocol for wireless microsensor networks,'' in Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci., vol. 8. 2000, pp. 1–10.
2: Younis, O.; Fahmy, S. HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad hoc Sensor Networks. IEEE Trans. Mob. Comput. 2004, 3, 366–379.
3: Razaque, A.; Mudigulam, S.; Gavini, K.; Amsaad, F.; Abdulgader, M.; Krishna, G.S. H-LEACH: Hybrid-Low Energy Adaptive Clustering Hierarchy for Wireless Sensor Networks. In Proceedings of the 2016 IEEE Long Island Systems, Applications and Technology Conference (LISAT), Farmingdale, NY, USA, 29 April 2016.
4: Beiranvand, Z.; Patooghy, A.; Fazeli, M. I-LEACH: An Efficient Routing Algorithm to Improve Performance & to Reduce Energy Consumption in Wireless Sensor Networks. In Proceedings of the 5th Conference on Information and Knowledge Technology, Shiraz, Iran, 28–30 May 2013.

Network layer



- Approaches to balance the energy between the routing paths includes

- Choose the successor nodes with the lowest expected number of transmissions (ETX) [1].
- Use both ETX and remaining energy to select successor node [2]
- Use residual-energy in the denominator of additive distance metric to increase the cost of paths containing low-energy nodes[3]
- Weight the forwarding load among potential successor nodes using the successor nodes' residual energy to set the weighting-factor[4]
- A hybrid multipath routing algorithm for energy-efficient and reliable data transmission is suggested in [5]. To reduce broadcast of several characteristics, they use a comprehensive metric combining node's lifetime, residual battery energy, node's idle time, node's speed, and queue length. The metric is used to assess link quality and select the best routes to the destination using link-state routing.
- The proposed protocol in [6] considers three factors to select the optimal path, i.e., lifetime, reliability, and the traffic intensity at the next-hop node. The information about the paths are updated periodically such that new optimal paths is selected to prevent depletion of current paths and balance the energy consumption in the network.

1: C. Abreu, M. Ricardo and P.M.Mendes, «Energy-aware routing for biomedical wireless sensor networks,» Journal of Network and Computer Applications, p. 270–278, 2014. http://dx.doi.org/ 10.1016/j.jnca.2013.09.015

2: L. Chang, T. Lee, S. Chen and C. Liao, «Energy-Efficient Oriented Routing Algorithm in Wireless Sensor Networks,» International Conference on Systems, Man, and Cybernetics (SMC), pp. 3813 - 3818, 2013. http://dx.doi.org/ 10.1109/SMC.2013.651

3: K. S. Shivaprakasha and M. Kulkarni, «Energy Efficient Shortest Path Routing Protocol for Wireless Sensor Networks,» International Conference on Computational Intelligence and Communication Networks CICN, pp. 333 - 337, 2011. http://dx.doi.org/ 10.1109/CICN.2011.70

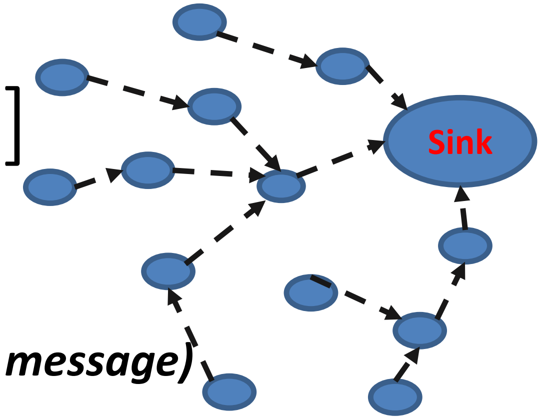
4: M. N. Moghadam, H. Taheri and M. Karrari, «Minimum cost load balanced multipath routing protocol for low power and lossy networks,» Wireless Networks,Volume 20, Issue 8, pp. 2469-2479, 2014. http://dx.doi.org/ 10.1007/s11276-014-0753-7

5: W. A. Jabbar, W. K. Saad and M. Ismail, "MEQSA-OLSRv2: A Multicriteria-Based Hybrid Multipath Protocol for Energy-Efficient and QoS-Aware Data Routing in MANET-WSN Convergence Scenarios of IoT," in *IEEE Access*, vol. 6, pp. 76546-76572, 2018, doi: 10.1109/ACCESS.2018.2882853.

6:Jaiswal, K., & Anand, V. (2019). EOMR: An energy-efficient optimal multi-path routing protocol to improve QoS in wireless sensor network for IoT applications. Wireless Personal Communications, 1-23.

Investigate various energy balancing approaches

Balancing algorithms that we have evaluated [1]



- ***Round-robin through multiple paths***
  - Transmit data packets to all member of parent list in a round-robin fashion
- ***Weighted round-robin based on energy information in DIO messages (DIO: RPL management message)***
  - The information is used to perform a weighted-fair-scheduling between the parent nodes.
  - Traffic load is shared among the nodes in the parent list according to their relative residual-energy level.

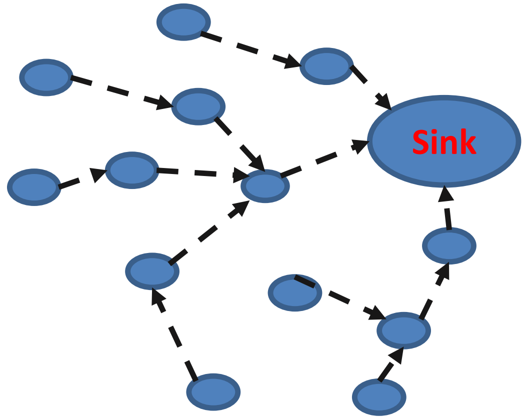
- ***Weighted round-robin based on prediction parents energy consumption***
  - Estimate the energy consumption pattern in between DIO updates
- ***Weighted round-robin while avoid lowest-energy parent***
  - The data is weighted between all parent except the lowest residual-energy parent

- ***Weighting round-robin based on energy information conveyed in ACK packets***
  - Weighting is performed based on the energy information received through ACK.
- ***Simply use the highest energy parent node***
  - Always use the highest energy parent node as the next-hop node

- Routing protocol used : RPL

1: Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," **Energy balancing algorithms in Wireless Sensor Networks**", Proceedings of the 2015 Federated Conference on Computer Science and Information Systems (FedCSIS), Volume 5 , pp. 1223-1231, 2015, Electronic ISBN: 978-8-3608-1065-1, DOI: 10.15439/2015F67

Our suggested balancing algorithms



- ***Randomize parent selection***
  - Small change in the preferred-parent selection:
  - Randomly select a preferred-parent among the nodes in the parent list
    - Instead of using a preordain selection algorithm.
  - Goal: reduce the probability of creating such hot-spot nodes
- ***Weighting round-robin based on SPOF-parent energy level***
  - SPOF node:
  - Nodes that are part of one or more parent lists containing only one item.
  - Direct traffic originating from higher rank nodes away from the SPOF nodes.
    - Nodes with a SPOF parent advertise an energy value which is the lowest of its own and its SPOF-parent's residual-energy level
  - Goal: reduce the depletion rate of the SPOF nodes
- ***Weighting round-robin based on eavesdropping***
  - Nodes read the source and destination address information in the overheard traffic.
  - The address is matched against the content in the parent list of the overhearing nodes.
  - weighted-fair-scheduling

1: Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," **Energy balancing algorithms in Wireless Sensor Networks**", Proceedings of the 2015 Federated Conference on Computer Science and Information Systems (FedCSIS), Volume 5 , pp. 1223-1231, 2015, Electronic ISBN: 978-8-3608-1065-1, DOI: 10.15439/2015F67

Simulations

- We concentrate on transmitting and receiving energy consumption.
- Applying an energy balancing algorithm will not change the average energy consumption for the nodes at the different rank
  - The total number of packet transmitted through each rank (rank = hop-count distance from the sink) is unchanged
- **We therefore considers the energy of the most depleted node at each rank**
- The energy consumption increases toward the sink as the inner nodes are obligated to relay traffic for outer nodes.
  - Presented simulations are segregated on rank.
- Simulator: OMNET++

Findings – Energy balance

Residual-energy in the nodes after each node has generated 100 data packets

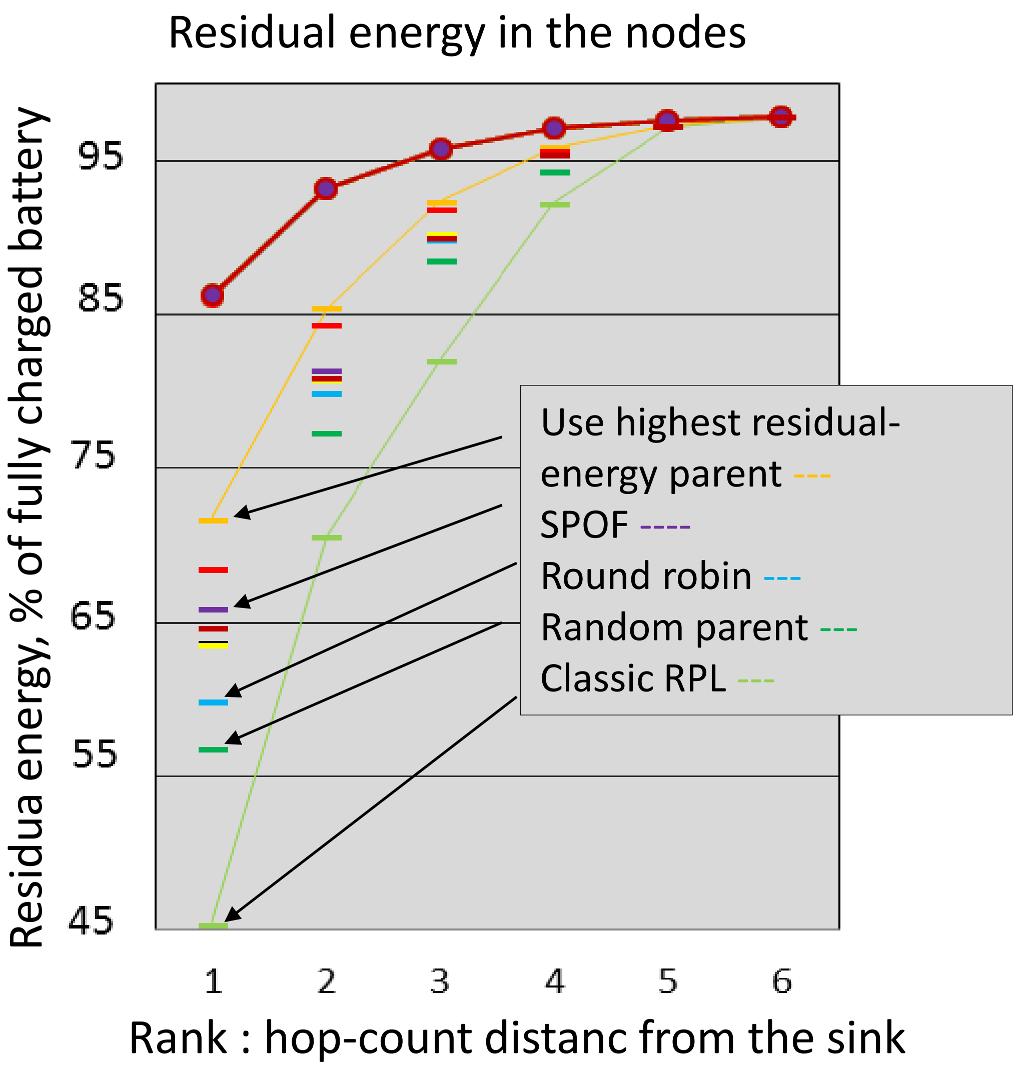
Simulations:
Routing protocol: RPL
Metric: Hop-count

The nodes are randomly distributed

Area 800m times 800m area.

Transmission range is 141m.

Node density:
20 nodes inside tx-range



Conclusion

- Energy imbalance is substantial in network running the native RPL routing protocol.

- Our suggested simple change of the parent selection algorithm gives a significant balancing effect,
  - In high density networks the residual-energy of the most depleted node is increased more than 10% compared to native RPL

- The SPOF algorithm is the best among all the weighted algorithms.
  - Increasing the residual-energy of the most depleted node with over 20% compared to native RPL.

- However: The highest balancing effect is obtained when nodes are forced to use the parent node with the current highest amount of residual-energy.
  - Increases the residual-energy of the most depleted nodes by 25% in high density networks.
  - Routing paths are continuously alternated
  - The lowest residual-energy paths are always avoided.

- Weighting the traffic between different parent nodes means that also the lowest energy nodes are used, although rarely.

1: Anne-Lena Kampen, Knut Øvsthus and Øivind Kure," **Energy balancing algorithms in Wireless Sensor Networks**", Proceedings of the 2015 Federated Conference on Computer Science and Information Systems (FedCSIS), Volume 5 , pp. 1223-1231, 2015, Electronic ISBN: 978-8-3608-1065-1, DOI: 10.15439/2015F67

Network layer

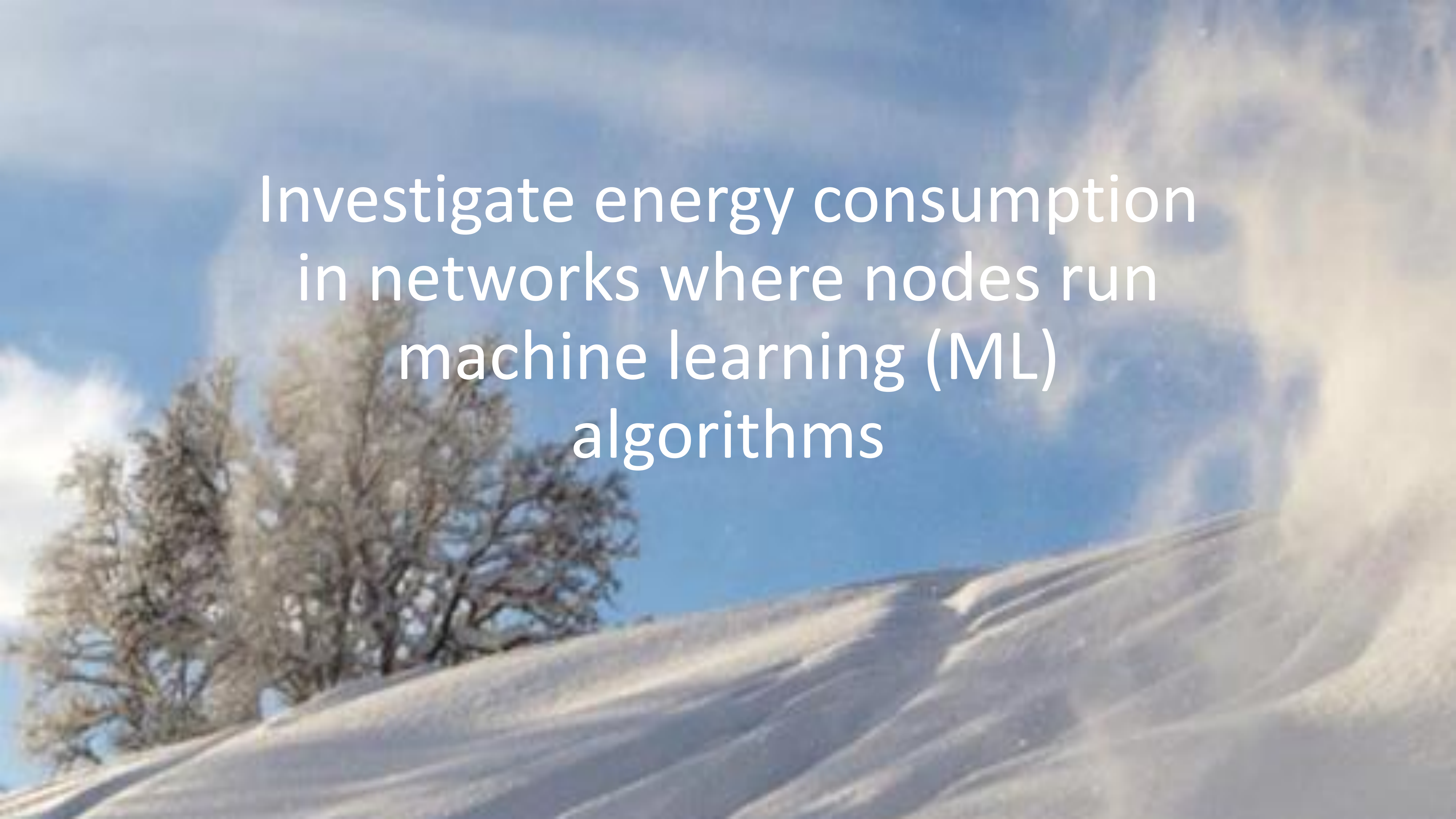
- Recommended reading if you want to learn more about network layer approaches to reduce energy consumption: [1][2][3]

1: N. A. Pantazis, S. A. Nikolidakis and D. D. Vergados, "Energy-Efficient Routing Protocols in Wireless Sensor Networks: A Survey," in *IEEE Communications Surveys & Tutorials*, vol. 15, no. 2, pp. 551-591, Second Quarter 2013, doi: 10.1109/SURV.2012.062612.00084.
2: Nakas, C., Kandris, D., & Visvardis, G. (2020). Energy Efficient Routing in Wireless Sensor Networks: A Comprehensive Survey. *Algorithms*, *13*(3), 72.
3: Yan, J., Zhou, M., & Ding, Z. (2016). Recent advances in energy-efficient routing protocols for wireless sensor networks: A review. *IEEE Access*, *4*, 5673-5686.

Other energy conservation strategies

- In addition to the layered protocols, cross-layer design combines the functions and parameters of different layers in order to achieve energy optimization.
  - An example is the cross-layer optimized opportunistic routing scheme suggested in [1], where transmission power is altered to minimize delay, improving reliability and balancing the energy consumption in the network.
  - Other approaches is to prevent collision using [2]
    - different frequencies for communication between different neighboring nodes
    - directional antennas
    - ..
    - Require more management and more complex nodes

1: Xu, Xin, et al. "A cross-layer optimized opportunistic routing scheme for loss-and-delay sensitive WSNs." Sensors 18.5 (2018): 1422.
2: Rault, T., Bouabdallah, A., & Challal, Y. (2014). Energy efficiency in wireless sensor networks: A top-down survey. *Computer Networks*, *67*, 104-122.

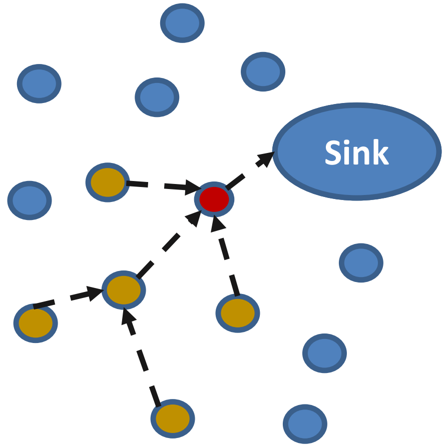

Investigate energy consumption in networks where nodes run machine learning (ML) algorithms

How do smarter nodes affect the energy consumption and energy balance?

- Smarter nodes are invented when embedding machine learning (ML) are used to enable the nodes to behave more intelligent
- The use of ML in WSN is increasing.

- Introduction of smart environments
    - Decisions moved from central location to embedded devices
    - Substantial increases the processing load in embedded devices
    - The energy consumed for processing may approach the energy consumed for sending and receiving

- How will ML affect the energy balance in the network,
- especially, how are the energy of the one-hop-nodes affected?
    - Remember, these are the most important nodes to keep the network connected !



What is the impact of embedded machine learning (ML) on the energy consumption in WSNs

- We wanted to assess to what extent embedded ML is favorable in multihop WSNs

in terms of energy consumption [1]

- Trade-off investigated:
  - Central: The energy consumed when all data are transmitted to the central for prediction
- Versus
  - Embedded: The energy consumed when the prediction is performed at the embedded device (no transmissions)

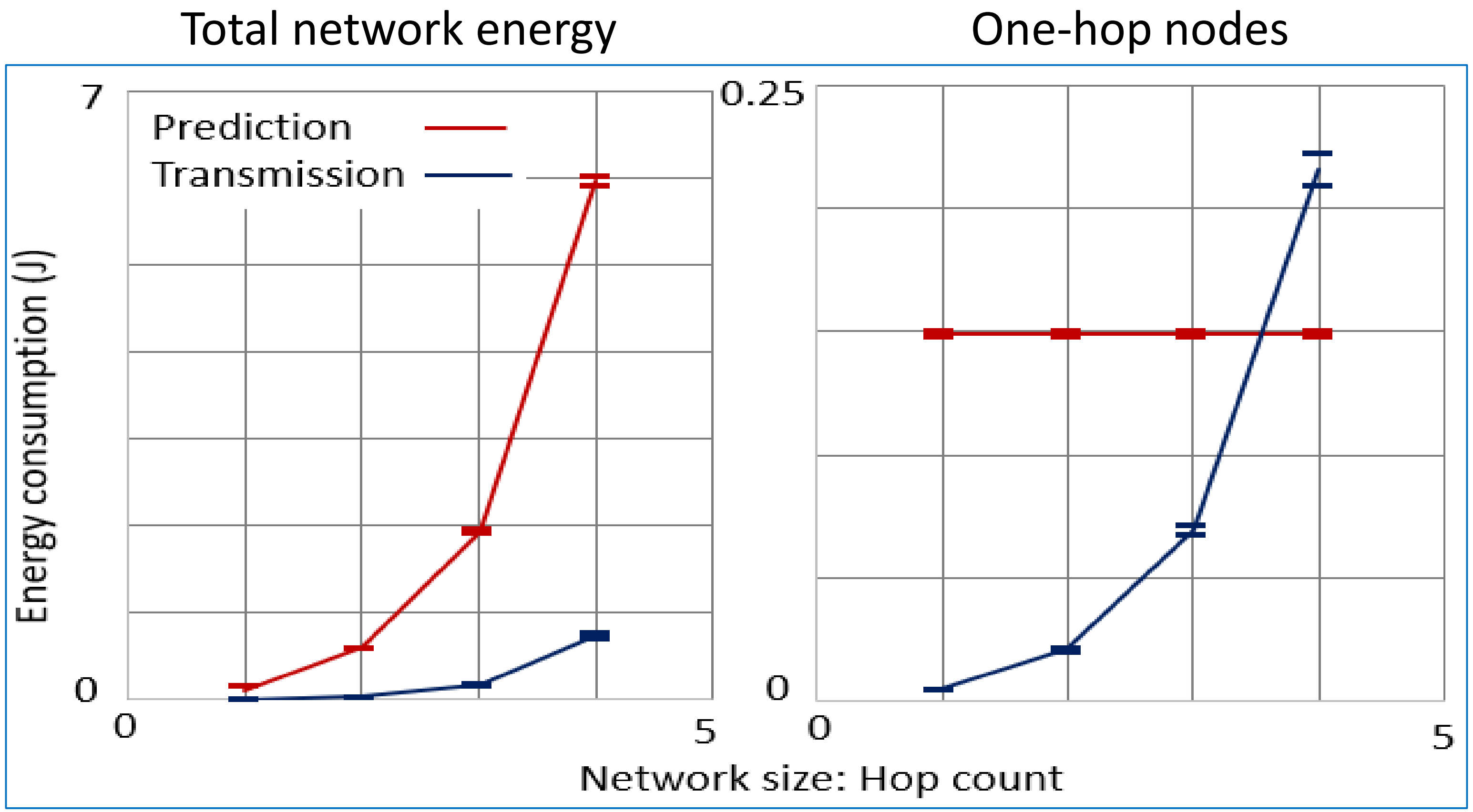
1: Kampen, A. L., & Kure, Ø. (2020). Discussing Embedded versus Central Machine Learning in Wireless Sensor Networks. *International Journal of Information and Communication Engineering*, *14*(9), 305-310.

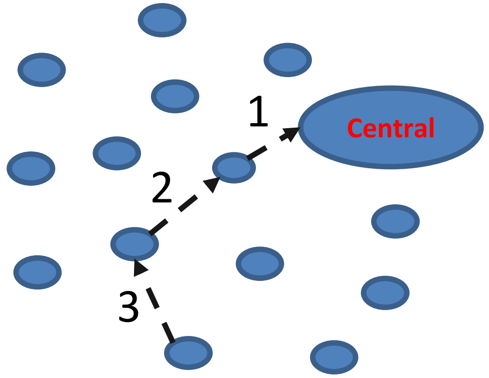
Energy usage

- Sensor nodes: Raspberry Pi
  - The nodes must have microcontroller, energy and memory that enable them to run ML algorithms
- We use the power-models presented in [1] and [2] to estimate the power consumed by the raspberry Pi
  - The CPU consumes energy for sensor data processing
  - The energy consumed for communication is focused toward the time the radio is active to transmit and receive.
- We assume a completely fair workload between the nodes

[1] F. Kaup, P. Gottschling, and D. Hausheer, "PowerPi: Measuring and modeling the power consumption of the Raspberry Pi," in 39th Annual IEEE Conference on Local Computer Networks, 2014: IEEE, pp. 236-243.
[2] F. Kaup, S. Hacker, E. Mentzendorff, C. Meurisch, and D. Hausheer, "Energy models for NFV and service provisioning on fog nodes," in NOMS 2018-2018 IEEE/IFIP Network Operations and Management Symposium, 2018: IEEE, pp. 1-7.

Comparing energy usage:
The left graph compares the total energy consumed for embedded versus central prediction. Right graph compares the energy usage for the **one-hop nodes during** embedded versus central prediction

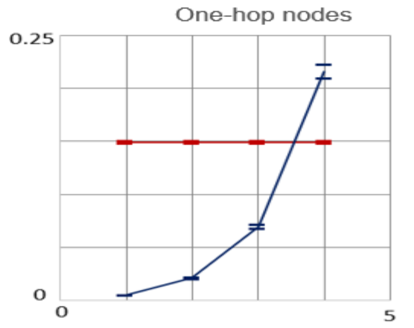




Energy consumption for prediction and training:

	Power consumption [W]	Runtime [s]	Energy consumed [J]
Prediciton	1.4893	0.1001	0.149
Tx 128 bytes	2.1939	0.0004	0.0009
Training	1.6441	208755	343209

Findings [1]



- Predictions will consume less energy as technology improves.
  - The number of computations achieved per kWh is doubled every 19 months [2].
  - Focusing on the one-hop nodes:
- In three years' time, embedded prediction would be the most energy efficient solution when the network size is larger than two hops.
  - Other radio technologies and network topologies would give other results; however, the trend is similar.
  - For further energy reduction: move prediction from general purpose CPU to specialized FPGA or chips.

1: Kampen, A. L., & Kure, Ø. (2020). Discussing Embedded versus Central Machine Learning in Wireless Sensor Networks. International Journal of Information and Communication Engineering, 14(9), 305-310.
[2] F. Kaup, S. Hacker, E. Mentzendorff, C. Meurisch, and D. Hausheer, "Energy models for NFV and service provisioning on fog nodes," in NOMS 2018-2018 IEEE/IFIP Network Operations and Management Symposium, 2018: IEEE, pp. 1-7.

Energy consumption in underwater WSNs

Underwater wireless sensor networks

- The Sustainable Development Goals were adopted by all UN Member States in 2015.
- Goal number 14 says: “Conserve and sustainably use the oceans, seas and marine resources for sustainable development. “
- As a consequence, surveillance of the underwater environment is needed. It has therefore been an rapid increased the research activity on underwater sensor networks.

- Solutions for underwater WSNs can borrow ideas from the vast amount of terrestrial WSN solutions.
- However, due to the special characteristics underwater, all solutions need adjustments

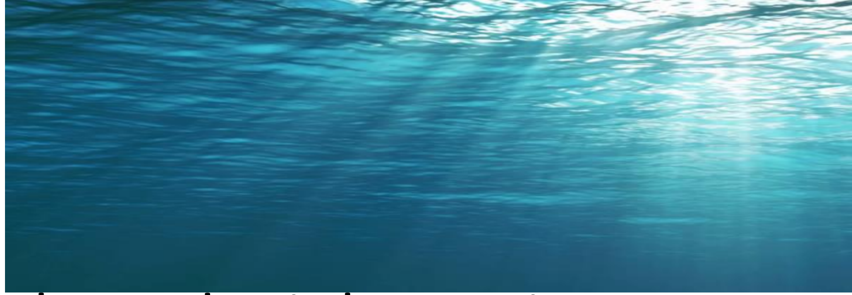
Underwater communication - Characteristics

Underwater MAC layer protocols must conform to the distinctive challenging characteristics the media, which pertain to [1]

- Low and dynamic channel capacity
  - For instance, data rate for underwater acoustic sensors can hardly exceed 100 kbps
- Substantial signal attenuation
- Time-varying multipath
- Surface scattering
- Noise
  - Man made and ambient
- Asymmetric links
- Low propagation speed
  - The signal propagation for acoustic underwater communication is five order of magnitude slower than light speed,
    - in addition, it is affected by temperature, salinity and dept.
  - The low propagation speed presents a fundamental challenge in coordinating the access to the shared communication medium.
  - Long delay means that collision-free reception is not guaranteed although the transmission from different nodes is collision-free.
  - Likewise, concurrent transmission may not lead to collision. Access-control can take advantage of the unequal delay to improve the media utilization

1: K. Chen, M. Ma, E. Cheng, F. Yuan and W. Su, "A Survey on MAC Protocols for Underwater Wireless Sensor Networks," in *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1433-1447, Third Quarter 2014, doi: 10.1109/SURV.2014.013014.0003

Underwater communication



- Similar to terrestrial networks, the energy consumption of the nodes is lowest in the sleeping state [1].
  - Thus, underwater communication protocols should switch the nodes to sleep state whenever possible
- However, the energy consumed to transmit is generally substantially higher that for receiving [1]
  - For acoustic signals, the transmission state consumes up to 100 times more than receiving [2].
- Hence, in addition to extensive use of sleep-mode, underwater protocols should focus on reducing the number of transmissions

1:A. Al Guqhaiman, O. Akanbi, A. Aljaedi and C. E. Chow, "A Survey on MAC Protocol Approaches for Underwater Wireless Sensor Networks," in IEEE Sensors Journal, doi: 10.1109/JSEN.2020.3024995.
2:S. Sendra, J. Lloret, J. M. Jimenez and L. Parra, "Underwater Acoustic Modems," IEEE Sensors Journal, vol. 16, no. 11, pp. 4063-4071, 2016.

Conclusion

- **Reducing energy consumption in WSNs is important**
  - **Maintain a complete data set in the sink**
  - **Keep the network connected**

- **Keeping the nodes in sleep state is efficient in reducing energy consumption**

- **Balancing energy consumption in the network is important in order to prevent early depletion of nodes and keep a connected network**

- **Among the broad range of energy-efficient solutions suggested in literature, there is no solution that fits all scenarios. We must wisely select the most appropriate solution for each unique scenario.**

Thank you very much for your attention !!

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