2016

Greening and Optimizing Energy Consumption of Sensor Nodes in the Internet of Things through Energy Harvesting: Challenges and Approaches

David Airehrour
Auckland University of Technology, dairehrour@aut.ac.nz

Jairo Gutiérrez
Auckland University of Technology, jairo.gutierrez@aut.ac.nz

Sayan Kumar Ray
Manukau Institute of Technology, sayan.ray@manukau.ac.nz

Follow this and additional works at: http://aisel.aisnet.org/confirm2016

35. Greening and Optimizing Energy Consumption of Sensor Nodes in the Internet of Things through Energy Harvesting: Challenges and Approaches

David Airehrour
Auckland University of Technology
dairehrour@aut.ac.nz

Jairo Gutiérrez
Auckland University of Technology
jairo.gutierrez@aut.ac.nz

Sayan Kumar Ray
Manukau Institute of Technology
sayan.ray@manukau.ac.nz

Abstract

This paper presents a survey of current energy efficient technologies that could drive the IoT revolution while examining critical areas for energy improvements in IoT sensor nodes. The paper reviews improvements in emerging energy techniques which promise to revolutionize the IoT landscape. Moreover, the current work also studies the sources of energy consumption by the IoT sensor nodes in a network and the metrics adopted by various researchers in optimizing the energy consumption of these nodes. Increasingly, researchers are exploring better ways of sourcing sufficient energy along with optimizing the energy consumption of IoT sensor nodes and making these energy sources green. Energy harvesting is the basis of this new energy source. The harvested energy could serve both as the principal and alternative energy source of power and thus increase the energy constancy of the IoT systems by providing a green, sufficient and optimal power source among IoT devices.

Communication of IoT nodes in a heterogeneous IoT network consumes a lot of energy and the energy level in the nodes depletes with time. There is the need to optimize the energy consumption of such nodes and the current study discusses this as well.

Keywords

IoT, RFID, WSN, M2M, H2M, energy harvesting, sensor nodes, network lifetime.

1. Introduction

The Internet of Things (IoT) refers to an interconnection of uniquely addressable individual objects from our everyday life (e.g., vehicles, electronic devices, health devices, household utensils, roadways etc.), which when connected through the internet, can sense each other, through the use of sensors, and exchange real-time information about their states via distributed sensor networks. It's a vision of a future computing environment where ubiquitous sensing applications in diverse areas will benefit our daily lives. Future IoT communication systems are expected to support different forms of communication, including Human-to-Machine (H2M) and Machine-to-Machine (M2M) communications, and will include diversified assorted

1

communication technologies, such as Near Field Communications (NFC), Wireless Sensor Networks (WSNs), and Radio Frequency Identification (RFID), to name a few. WSN and IoT will play an important role in the evolution of the future Internet architecture that will be flexible enough to efficiently accommodate future changes to key internet issues, like, security, mobility, performance and reliability (Vermesan & Friess, 2014). IoT devices and applications could be effectively used to provide the sensorial capabilities required by multiple futuristic applications, including, smart transport, smart cities, smart buildings, smart rural areas, smart energy grids and health (Vermesan & Friess, 2014). For successful global deployment of commercial IoT networks, efficient integration between WSN and IoT nodes is critical. An important aspect in this context that calls for in-depth research is how the consumption of energy can be addressed.

A WSN consists of multiple interconnected and organized sensor nodes (up to several thousand even) that can process data and communicate with each other (I. F. Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Al-Karaki & Kamal, 2004). Research in WSNs have gained a lot of global attention and has prompted the vast development and implementation of sensors across diversified devices making them smart enough to communicate (Misra, Misra, & Woungang, 2009). However, sensor nodes are subject to constraints related to severe energy consumption of the batteries, which is a significant issue for network self-sufficiency. Thus, reducing the battery energy consumption is a paramount requirement for extending the lifetime of sensor nodes in IoT.

As sensor nodes are the essential building components of IoT devices, an insight into where energy is dissipated in an IoT node is critical towards achieving an optimal battery life (Ammer & Rabaey, 2006; Mao, Chengfa, Guihai, & Jie, 2005; Park & KumarKasera, 2005). The following are few of the several metrics adopted by researchers in determining an optimal battery life for networking nodes and these could also be applied to IoT nodes.

- Network Lifetime (NLT) of a node: This is a basic metric that depends on multiple factors, among them: network architecture and protocol, network lifetime definition, network channel characteristics, data collection initiation and energy consumption model (Yunxia & Qing, 2005).

- Energy Efficiency (EE): This indicates how much energy a sensor node consumes for a specific task (Mao et al., 2005).

- Energy-Per-Useful-Bit (EPUB): This relates to a physical layer modulation that reflects the energy consumption incurred by the transmitter and receiver while amortizing the energy consumption during synchronization preamble of data bits in a packet (Ammer & Rabaey, 2006).

- End-to-End Latency: This provides an estimate of the time taken by the packets, across the network, to travel from source to destination (Alkhatib & Baicher, 2012).

- Expected Data Rate (EDR): It computes the effect of per-hop contention on multi-hop throughput (Park & KumarKasera, 2005).

In this paper we explore the various energy measurement models, modelling metrics and green energy sources for IoT sensor nodes. Recent related research efforts have focused on

performance analysis and comparisons between various low-energy routing models (Al-Karaki & Kamal, 2004) while keeping other system parameters fixed. However, determining the power consumption of an IoT node and how much of this energy is depleted during communication and processing will help in identifying potential wasteful energy consumption sources with the aim of optimizing the energy cycle of an IoT sensor device.

This paper is organized as follows: In section II, we explore the topology of a sensor node and highlight the energy consumption in each layer while emphasizing the energy consumption measurement used by various studies. Section III explores energy harvesting as an efficient technology that could be adopted in IoT. The paper in section IV gives some research directions in improving the energy consumption of IoT sensor nodes while section V examines energy metrics optimization for a greener IoT network performance. The paper concludes with a discussion about future directions in ambient technology as a much more promising area for IoT revolution and hence an area where additional research should be encouraged.

2. WSN and IoT sensor nodes

WSNs are invaluable resources for realizing the IoT vision with the sensor nodes becoming essential components in the IoT architecture. This section provides an insight into the sources of energy consumption in the sensor nodes of the IoT. The basic composition of a sensor node, depicted in Figure 1, includes a transceiver, micro-controller, power source, exterior memory and sensors which activate the actuators. A general schematic of a sensor node hardware (refer to Figure 2) shows four primary inbuilt components: sensing, processing, communication and power units (I. Akyildiz & Kasimoglu, 2004; I. F. Akyildiz et al., 2002; Al-Karaki & Kamal, 2004; Hwang-cheng, 2011). Each unit can toggle in three states; active, idle and sleep (Anastasi, Conti, Di Francesco, & Passarella, 2009) and the consumption of power in each unit depends on the state of the unit. The communication system used in transmitting information between the nodes is a fundamental functional block that is present in all wireless sensor nodes.

The design of the communication system is supported by the communication protocol stack consisting of five different layers: physical layer, data link layer, network layer, transport layer and application layer. Each layer in the communication protocol stack, shown in Figure 3, has specific metrics of its own which directly dissipates the level of energy consumption in the given layer.
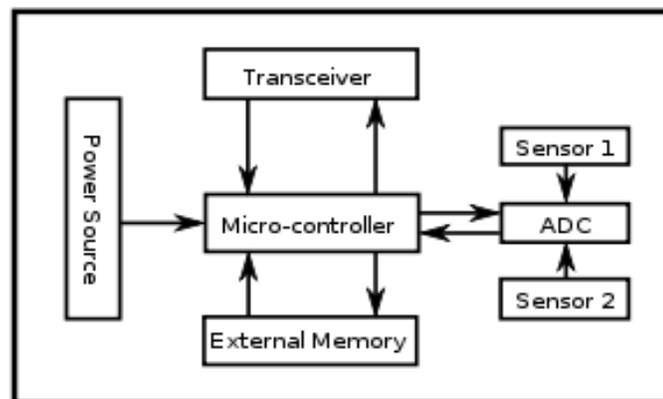

3

Figure 1: Architectural view of a sensor node (I. Akyildiz & Kasimoglu, 2004)
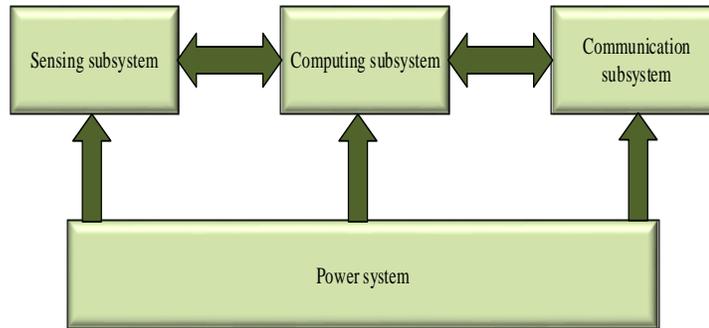

Figure 2: Architecture of wireless sensing node (I. Akyildiz & Kasimoglu, 2004)
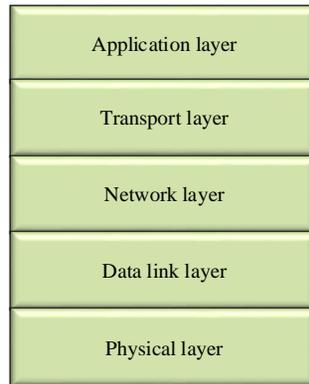

Figure 3: Topological architecture the communication protocol stack of asensor node

Figure 4 depicts the energy consumption metric in a wireless sensor node. A description of the functions of each layer and their sources of power consumption are provided below (I. F. Akyildiz et al., 2002; Al-Karaki & Kamal, 2004; Alkhatib & Baicher, 2012).

i. Physical layer (PHY): This layer concentrates on the reliability of the transmission of bits between the sensor nodes via point-to-point wireless links. Coding, modulation, and power control are the key tasks performed at this layer. The major sources of energy dissipation in the PHY are in the hardware of the sensor nodes (processor, sensor sensing, transceiver and the power unit), or linked to the wireless channel error, modulation schemes (such as QPSK) and physical layer overhead.

ii. Medium Access Control/Data link layer (MAC): The MAC layer controls the efficient sharing of the channel spectrum by diverse users. Allocation of the spectrum is usually carried out using either deterministic or random access approaches. The major sources of

energy consumption in MAC layer include, MAC protocol overhead, overhearing of data frames and collision of frames and the type of schedule-based or contention-based MAC protocol in use.
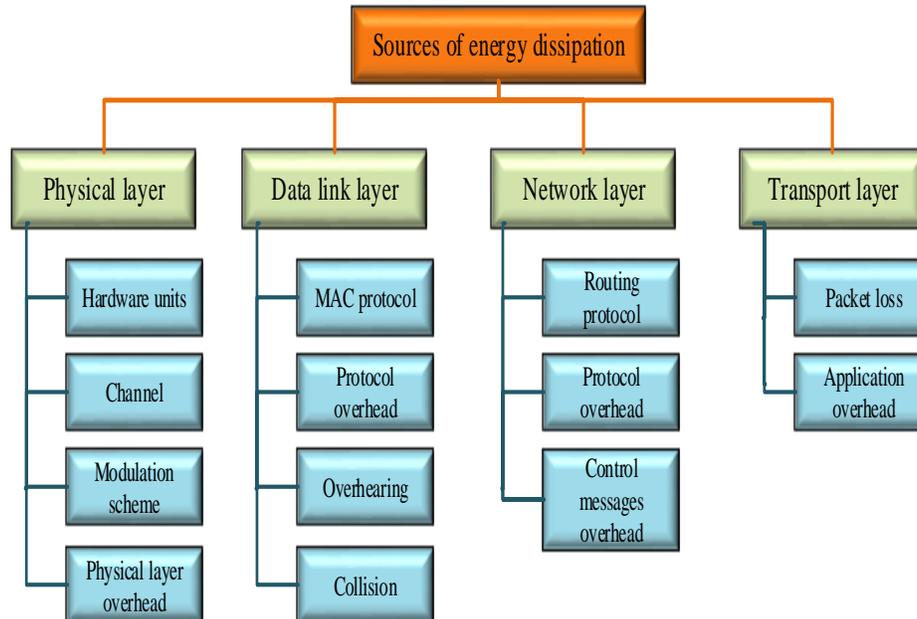

Figure 4: Energy consumption metric in a typical wireless sensor node

iii. Network layer: This layer guarantees the mechanism for transferring data sequences from source to destination. In this layer, network routing and dynamic resource allocation are carried out. The sources of energy consumption in this layer are widely influenced by the type of routing protocol and the overheads that some of these protocols have or procure during routing operations.

iv. Transport layer: This layer is tasked with providing connection-oriented data stream, end-to-end error recovery and flow control. Although, packet delivery in the transport layer is mostly guaranteed, sometimes the occurrence of packet losses between the source and the destination leads to increased energy dissipation.

v. Application layer: This layer, respectively, creates and processes data to be sent and received over the network. The representation of data in readable format is the main function of the application layer (source coding). Energy dissipation in this layer is dependent on the type of application in use.

The network lifetime of an IoT node becomes a critical metric in the efficient design of its functionality and application. According to (Chang & Tassiulas, 2004; Ehsan, Hamdaoui, & Guizani, 2012) Network lifetime is regarded as the period from the start of the network operation to the time the first node is depleted of its energy in the network.

Some energy models and various optimization of network life time have been undertaken in the past such as; energy-aware MAC protocols, power aware storage, routing and data dissemination protocols, duty-cycling strategies, adaptive sensing rate, tiered system architectures, and redundant placement of nodes. Reviews of these have been discussed in (Delsing, Borg, & Johansson, 2011; Karl & Willig, 2007; Nikita, Satyajit, & Bhattacharya, 2014; Sudevalayam & Kulkarni, 2011). Table 1 provides a summary of some notable energy models and consumption parameter for sensor nodes proposed by the research fraternity.

Energy model	Transmitted power	Transmitted circuit power	Received circuit power	Processing power	Sensing power
The Energy-per-Useful-Bit Metric for Evaluating and Optimizing Sensor Network Physical Layers (Ammer & Rabaey, 2006)	✓		✓		
Optimization of Correlated Data Gathering in Wireless Sensor Networks (Shibo, Jiming, Yau, & Youxian, 2012)	✓		✓		
Maximum lifetime routing in wireless sensor networks (Chang & Tassiulas, 2004)	✓		✓		
ESWC: Efficient Scheduling for the Mobile Sink in Wireless Sensor Networks with Delay Constraint (Gu, Ji, Li, & Zhao, 2013)	✓		✓		
A Realistic Power Consumption Model for Wireless Sensor Network Devices (Qin, Hempstead, & Woodward, 2006)	✓	✓	✓		
Joint routing and link rate allocation under bandwidth and energy constraints in sensor networks (Cheng, Xuan, & Lin, 2009)	✓		✓		✓
Joint data rate and power allocation for lifetime maximization in interference limited ad hoc networks (Jantti & Seong-Lyun, 2006)	✓	✓	✓		✓
Minimum-Cost Sensor Placement for Required Lifetime in Wireless Sensor-Target Surveillance Networks (Liu, Chu, Leung, & Du, 2013)	✓	✓	✓		✓
An application-specific protocol architecture for wireless micro-sensor networks (Heinzelman, Chandrakasan, & Balakrishnan, 2002)	✓		✓	✓	✓
On the energy-efficient organization and the lifetime of multi-hop sensor networks (Jin & Papavassiliou, 2003)	✓		✓	✓	✓
A MAC protocol to reduce sensor network energy consumption using a wakeup radio (Miller & Vaidya, 2005)	✓		✓	✓	

Table 1: Energy measurement parameters in some energy models

3. Energy harvesting in IoT sensor nodes

Energy harvesting is the process of creating energy from environmental sources including: thermal energy, salinity gradients, solar power, kinetic energy and wind energy. The energy is converted and stored for use by various sensory devices such as wearable devices, WSN devices and even IoT devices. The power consumption depends on the communication protocols and the data rate used for transmission among the devices. The approximate power consumption for different protocols is as following GPRS (24kbps-1W), 3G (384kbps-2W), Wi-Fi (10Mbps-32–200mW), Bluetooth (1Mbps-2.5–100 mW), and ZigBee (250kbps-1mW) (Vermesan & Friess, 2014).

The key mechanisms of a self-sufficient wireless sensor include the energy processing, power harvesting transducer, microcontroller, sensor, and the IEEE 802.15.4 wireless radio. To successfully implement an energy harvesting system on an IoT sensor node there are three major areas that needs to be addressed during the energy processing phase: power conversion, power storage, and power management.

The authors (Vermesan & Friess, 2014) gave an analysis of the power requirement for a node requiring 100μW energy in a 1 year as equivalent to the energy generated by 1g of lithium. The approximate energy consumption rate of a node during data communication and transfers is summarized in Table 2. They concluded that with a 100 μW harvested uninterruptedly, it is conceivable to make a complete power measurement every 1–10 seconds. They further opined that this duty cycle is sufficient for sensor node activities. While there has been substantial innovation and development in recent years in energy harvesting, energy harvesting is still considered an evolving technology requiring industry standardization and adoption.

The advancement of energy harvesting and storage systems are key to achieve the global connectivity goal associated with the IoT vision and the budding market for portable energy storage and energy harvesting systems. This could prove a great boost for the Internet of Things vision.

As it is today, the energy harvesting wireless sensor module is capable of generating and transmitting a wireless signal from a very small quantity of energy. With just 50 μWs, it could transmit 300 metres of signal in free range.

Furthermore, to enable very small IoT form factor devices a target power consumption of less than 5 milliwatt (mW) could be pursued as this will help in these IoT devices having a much longer battery life. This will further give room for various energy harvesting technologies in creating an independent RF communication system. Also, lighter IoT communication protocols for IoT devices could be developed with a perspective of reducing undue communication link to conserve power due to communication overhead on the IoT devices.

Node activity	Energy consumption (μJ)
Sending 100 bits of data consumes about	5
Measuring acceleration consumes about	50
Making a complete measurement: measure + conversion + emission consumes	250–500

Table 2: Approximate energy consumption rate of a node during communication (Vermesan & Friess, 2014)

It is expected that for the IoT vison to become effective the integration of various technologies of low power devices and the improvement of battery efficiency will create the enabling environment for the swift development and take-off of the IoT trend.

Furthermore, it is expected in the future that the vibration energy harvesters will have greater power densities (10 µW/g to 30 µW/g) while supporting a broader frequency range. Various researchers have expressed that, the goal of vibration energy harvesters is to eventually come with Plug and Play (PnP) devices which could operate in any vibrating environment.

In thermoelectric energy harvesting system, the focus is to increase the intrinsic efficiency of the thermoelectric materials so as to convert a higher portion of the existing mW of thermal energy. However, this enhancement will only be possible via the usage of micro and nanotechnologies (e.g. quantum dots or super-lattices).

Solar energy harvesting has enjoyed robust improvements over the years as photovoltaic cells which are key elements have undergone significant advancement. This technology has been deployed in many applications and has proved effective and sufficient. However, for IoT sensor nodes, it will prove useful further improving the photovoltaic cells' sizes while harvesting energy even in harsher environments.

We expect that in the near future, batteries could be recharged from radio signals while cell phones could recharge from Wi-Fi. We envisage much reduced cells (micro, pico, femto) which will result in creation of more cell sites with fewer distances between them but which will be greener and deliver savings in both power and cost while still achieving higher throughput.

4. Improving energy consumption in IoT: research directions

A fundamental challenge in IoT is how to have an efficient connectivity among IoT nodes while optimizing the limited energy of these nodes since communication among these nodes is the most energy consuming task on these IoT nodes. Many low-powered communication technologies have been developed and are considered today as enabling technologies for IoT. They can be grouped under various titles including, technologies enabling "things" acquiring contextual information, technologies enabling "things" processing contextual information, and technologies improving security and privacy. In this context, we discuss some research directions for improving the energy consumption in IoT based networks.

Earlier research on energy optimization in IoT were generally based on single-radio data transmission. However, for an extensive IoT network, futuristic IoT gateways can be enhanced with multiple heterogeneous radio interfaces enabling them to concurrently transmit data to IoT servers. For example, in the IoT development platform introduced by Open Interconnect Consortium (Open Interconnect Consortium, 2016) and AllSeen Alliance (AllSeen Alliance, 2016), gateways essentially utilize a low-power short distance radio to communicate with close IoT sensor nodes and a long distance radio to communicate with an IoT network server. Nevertheless, if these gateways are battery-powered such as the ones used in Ericsson's capillary network (Sachs et al., 2014), then further exploration is required to effectively optimize energy using such multi- radio interfaces. Also, the co-channel and neighboring channel interference issues need to be further studied to minimize their energy usage.

The futuristic IoT networks will be heterogeneous in nature. For them to effectively coexist, Software Defined Radio (SDR) offers a plausible approach. Aust *et al.* (Aust, Prasad, & Niemegeers, 2014) presented an IEEE 802.11ah-based Software Defined Radio (SDR) prototype to assess the efficacy of future 802.11ah WLAN protocol aiming to support an outdoor communication range of over 1 km at data rates of up to 100 Kbps. However, interference remission in base stations is critical for effective communication in IoT networks and can be achieved through the usage of cognitive radio system for IoT platforms (Lin, Wang, Wang, Shao, & Tang, 2013) showed the interference remission at a base station by means of a cognitive radio system for a wireless IoT platform. Tragos *et al.* (Tragos, Angelakis, & Papadakis, 2015) proposed an SDR framework that can address the issue of heterogeneity of IoT devices through the integration of their communication system and deploying wireless cells which can deliver access to diverse IoT devices.

Current IoT networks demand innovative means of lowering the energy consumption. The super-regenerative batteries, used in wake-up receivers, can be very energy efficient (Hyunwoo et al., 2015; Salazar, Kaiser, Cathelin, & Rabaey, 2015). They not only can remain perpetually active with a minimum amount of power, but also can trigger a signal to wake up a complete/standard receiver. However, they need to be standardized.

Furthermore, to enable very small IoT form factor devices a target power consumption of less than 5 milliwatt (mW) could be pursued as this will help in these IoT devices having a much longer battery life. This will further give room for various energy harvesting technologies in creating an independent RF communication system. Also, lighter IoT communication protocols for IoT devices could be developed with a perspective of reducing undue communication link to conserve power due to communication overhead on the IoT devices.

5. Energy optimization for a greener IoT network
Of the energy consumption sources of sensor nodes as shown in table 1, it is clear that the crucial cause of energy drains on nodes is the RF communication component. Recently, various trade-offs have been explored of communication metrics while a number of solutions have been proposed for optimization of energy consumption considering the general communication requirements and patterns specific for classes of application domains as explored in table 1.

The energy source of an IoT sensor node can be influenced by factors associated with the node's reliability and its mode of operation. Batteries are a good source of power; however, they have a specific life time cycle which places a limit in terms of time while replacement of the batteries could prove expensive for a large number of IoT sensor nodes and inconveniencing for remote locations.

Furthermore, ambient energy (energy harvested) from the physical environment could be possibly limitless, but again may prove irregular depending on the deployment scenario. Ambient energy could have the potential of impacting IoT sensor nodes and their operations

including the reliability of the IoT application although, these sources could come with specialized requirements for deployment which may cause the overall application costs to be expensive.

As a reflection on the above, battery enabled IoT sensor nodes could prove to reduce IoT application costs while arguably improving the service reliability if their energy requirement allows using a small form factor battery that could last a node's lifetime.

6. Conclusions

The Internet of Things promises to connect billions of devices globally and interoperability between devices will be vital. However, it's an uphill task to achieve this reality if these enabling IoT devices deplete their power too quickly and are not very energy efficient. It is important that these devices are able to perform more computation consuming less energy and at a lower cost This can be facilitated by not only developing and integrating different technologies (for example, technologies facilitating low power consumption, like, ambient, solar and thermoelectric) but also further enhancing the battery efficiency for low powered IoT devices.

IoT sensor nodes are able to benefit from energy harvesting technologies (e.g., vibration or electromagnetic radiation, ambient light and thermal energy) to power the nodes. The list of basic components in a sensor node includes, a sensor microcontroller, a power harvesting transducer, an energy conversion system, and the wireless radio used for communications, which implies that for such a node to make optimal use of energy harvesting there is the need to have an efficient power conversion system, an energy storage system, and a power management system. A good understanding of the sources of energy consumption in IoT nodes is the first step to reducing the energy requirements while seeking greener and improved energy sources becomes a priority.

In this paper, we have highlighted the sources of energy consumption at each layer in a wireless sensor node have discussed the various technologies that are able to support the IoT revolution. Furthermore, the study also covers existing energy metrics used by the research fraternity. Future work on this topic includes exploring how the various ambient technologies can be utilized in the Internet of Things.

References

Akyildiz, I., & Kasimoglu, I. (2004). Wireless sensor and actor☆ networks: research challenges. *Ad Hoc Networks, 2*(4), 351-367. doi:10.1016/j.adhoc.2004.04.003

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: a survey. *Computer Networks, 38*(4), 393-422. doi:http://dx.doi.org/10.1016/S1389-1286(01)00302-4

Al-Karaki, J. N., & Kamal, A. E. (2004). Routing techniques in wireless sensor networks: a survey. *Wireless Communications, IEEE, 11*(6), 6-28. doi:10.1109/MWC.2004.1368893

Alkhatib, A. A. A., & Baicher, G. S. (2012). *Wireless Sensor Network Architecture.* presented at the meeting of the International Conference on Computer Networks and Communication

Systems (CNCS 2012), Retrieved from http://www.ipcsit.com/vol35/003-CNCS2012-N010.pdf

AllSeen Alliance. (2016). *https://allseenalliance.org/*. Retrieved2016, from https://allseenalliance.org/

Ammer, J., & Rabaey, J. (2006, 28-28 Sept. 2006). The Energy-per-Useful-Bit Metric for Evaluating and Optimizing Sensor Network Physical Layers Symposium conducted at the meeting of the Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on doi:10.1109/SAHCN.2006.288533

Anastasi, G., Conti, M., Di Francesco, M., & Passarella, A. (2009). Energy conservation in wireless sensor networks: A survey. *Ad Hoc Networks, 7*(3), 537-568. doi:10.1016/j.adhoc.2008.06.003

Aust, S., Prasad, R. V., & Niemegeers, I. (2014). Advances in wireless M2M and IoT: Rapid SDR-prototyping of IEEE 802.11 ah Symposium conducted at the meeting of the the Proceedings of the 39th IEEE Conference on Local Computer Networks (LCN), Demo Abstract

Chang, J.-H., & Tassiulas, L. (2004). Maximum lifetime routing in wireless sensor networks. *IEEE/ACM Transactions on Networking (TON), 12*(4), 609-619. doi:10.1109/TNET.2004.833122

Cheng, M., Xuan, G., & Lin, C. (2009). Joint routing and link rate allocation under bandwidth and energy constraints in sensor networks. *IEEE Transactions on Wireless Communications, 8*(7), 3770-3779. doi:10.1109/TWC.2009.081134

Delsing, J., Borg, J., & Johansson, J. (2011). Architecture for Extreme Low Power Sensing in Wireless Sensor Network Devices Symposium conducted at the meeting of the SENSORCOMM 2011, The Fifth International Conference on Sensor Technologies and Applications doi:citeulike-article-id:9928108

Ehsan, S., Hamdaoui, B., & Guizani, M. (2012). Radio and Medium Access Contention Aware Routing for Lifetime Maximization in Multichannel Sensor Networks. *IEEE Transactions on Wireless Communications, 11*(9), 3058-3067. doi:10.1109/TWC.2012.072512.110068

Gu, Y., Ji, Y., Li, J., & Zhao, B. (2013). ESWC: Efficient Scheduling for the Mobile Sink in Wireless Sensor Networks with Delay Constraint. *IEEE Transactions on Parallel and Distributed Systems, 24*(7), 1310-1320. doi:10.1109/TPDS.2012.210

Heinzelman, W. B., Chandrakasan, A. P., & Balakrishnan, H. (2002). An application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications, 1*(4), 660-670. doi:10.1109/TWC.2002.804190

Hwang-cheng, G. A. O. D.-y. Z. L.-j. W. (2011). Energy saving with node sleep and power control mechanisms for wireless sensor networks. *Journal of China Universities and Posts, 18*(1), 49-59. doi:10.1016/S1005-8885(10)60027-1

Hyunwoo, C., Hyunki, K., Minseo, K., Jaeeun, J., Joonsung, B., & Hoi-Jun, Y. (2015, 22-26 Feb. 2015). 21.1 A 79pJ/b 80Mb/s full-duplex transceiver and a 42.5uW 100kb/s super-regenerative transceiver for body channel communication Symposium conducted at the meeting of the Solid- State Circuits Conference - (ISSCC), 2015 IEEE International doi:10.1109/ISSCC.2015.7063085

Jantti, R., & Seong-Lyun, K. (2006). Joint data rate and power allocation for lifetime maximization in interference limited ad hoc networks. *IEEE Transactions on Wireless Communications, 5*(5), 1086-1094. doi:10.1109/TWC.2006.1633361

Jin, Z., & Papavassiliou, S. (2003). On the energy-efficient organization and the lifetime of multi-hop sensor networks. *IEEE Communications Letters, 7*(11), 537-539. doi:10.1109/LCOMM.2003.820097

Karl, H., & Willig, A. (2007). *Protocols and architectures for wireless sensor networks*: John Wiley & Sons.

Lin, Y. H., Wang, Q., Wang, J. S., Shao, L., & Tang, J. (2013). Wireless IoT platform based on SDR technology*IEEE*. Symposium conducted at the meeting of the Green Computing and Communications (GreenCom), 2013 IEEE and Internet of Things (iThings/CPSCom), IEEE International Conference on and IEEE Cyber, Physical and Social Computing

Liu, H., Chu, X., Leung, Y.-W., & Du, R. (2013). Minimum-Cost Sensor Placement for Required Lifetime in Wireless Sensor-Target Surveillance Networks. *IEEE Transactions on Parallel and Distributed Systems, 24*(9), 1783-1796. doi:10.1109/TPDS.2012.263

Mao, Y., Chengfa, L., Guihai, C., & Jie, W. (2005, 7-9 April 2005). EECS: an energy efficient clustering scheme in wireless sensor networks Symposium conducted at the meeting of the Performance, Computing, and Communications Conference, 2005. IPCCC 2005. 24th IEEE International doi:10.1109/PCCC.2005.1460630

Miller, M. J., & Vaidya, N. H. (2005). A MAC protocol to reduce sensor network energy consumption using a wakeup radio. *IEEE Transactions on Mobile Computing, 4*(3), 228-242. doi:10.1109/TMC.2005.31

Misra, S., Misra, S. C., & Woungang, I. (2009). *Guide to wireless sensor networks*. Dordrecht: Springer. doi:10.1007/978-1-84882-218-4

Nikita, P., Satyajit, A., & Bhattacharya, P. P. (2014). Design of Low Power Wake-up Receiver for Wireless Sensor Network. *International Journal of Computer Applications, 90*(10). doi:10.5120/15757-4412

Open Interconnect Consortium. (2016). *Open Interconnect Consortium*. Retrieved2016, from http://openinterconnect.org/

Park, J. C., & KumarKasera, S. (2005). Expected Data Rate: An Accurate High-Throughput Path Metric For Multi-Hop Wireless Routing Symposium conducted at the meeting of the SECON Retrieved from http://www.cs.utah.edu/~jcpark/publications/secon_2005.pdf

Qin, W., Hempstead, M., & Woodward, Y. (2006, 28-28 Sept. 2006). A Realistic Power Consumption Model for Wireless Sensor Network Devices Symposium conducted at the meeting of the Sensor and Ad Hoc Communications and Networks, 2006. SECON '06. 2006 3rd Annual IEEE Communications Society on doi:10.1109/SAHCN.2006.288433

Sachs, J., Beijar, N., Elmdahl, P., Melen, J., Militano, F., & Salmela, P. (2014). Capillary networks – a smart way to get things connected. *Ericsson Review*.

Salazar, C., Kaiser, A., Cathelin, A., & Rabaey, J. (2015, 22-26 Feb. 2015). 13.5 A −97dBm-sensitivity interferer-resilient 2.4GHz wake-up receiver using dual-IF multi-N-Path architecture in 65nm CMOS Symposium conducted at the meeting of the Solid- State Circuits Conference - (ISSCC), 2015 IEEE International doi:10.1109/ISSCC.2015.7063016

Shibo, H., Jiming, C., Yau, D. K. Y., & Youxian, S. (2012). Cross-Layer Optimization of Correlated Data Gathering in Wireless Sensor Networks. *IEEE Transactions on Mobile Computing, 11*(11), 1678-1691. doi:10.1109/TMC.2011.210

Sudevalayam, S., & Kulkarni, P. (2011). Energy Harvesting Sensor Nodes: Survey and Implications. *IEEE Communications Surveys&Tutorials, 13*(3), 443-461. doi:10.1109/SURV.2011.060710.00094

Tragos, E., Angelakis, V., & Papadakis, S. (2015). Fighting Networking Heterogeneity in the Internet of Things. *ERCIM News, 101*, 33-34.

Vermesan, O., & Friess, P. (2014). *Internet of Things-From Research and Innovation to Market Deployment*: River Publishers.

Yunxia, C., & Qing, Z. (2005). On the lifetime of wireless sensor networks. *IEEE Communications Letters, 9*(11), 976-978. doi:10.1109/LCOMM.2005.11010