AN ABSTRACT OF THE DISSERTATION OF

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Title: An Anthology of Next-Generation WSNs and Transformative IoT Use-Cases

Abstract approved: ______________________________

Huaping Liu

The Internet of Things (IoT) paradigm brought an ever-increasing dependence on low-power devices to collect sensor data and transmit that information to the cloud, placing greater demand on connectivity and lifespan. In response, rapid worldwide innovation demonstrates the trade-offs in processing, communication, and energy consumption with diverse approaches to low-power components, duty-cycle schemes, cost, and many other critical constraints for complex use-cases, such as track-and-trace (T&T). This work explores the central theme of low-power wireless sensor networks (WSNs) in the IoT and Industrial IoT (IIoT). A collection of publications evolves through the theme, from an IoT literature review to enabling densely-scalable WSNs for logistics & asset management (LAM). Next, this research enhances the WSN design by leveraging wake-up radio (WUR) and energy harvesting (EH) to achieve battery-free operation. Lastly, this work presents WSNs to improve visibility and control of airflow/microclimate management in potentially transformative IIoT use-cases, such as data centers and agriculture.

An Anthology of Next-Generation WSNs and Transformative IoT Use-Cases

by

Jennifer M. Williams

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Jennifer M. Williams, Author

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Part I

Primer for WSNs, IoT, and LAM Use-Case

Chapter 1: Introduction

This manuscript is a collection of published research in a central theme of low-power wireless sensor networks (WSNs) in the internet of things (IoT) and Industrial IoT (IIoT). Part I is a Primer for WSNs, IoT, and LAM Use-Case, followed by Part II with Special Topics in Communications & Signal Proc. Lastly, Part III contributes a Special Topic in Agriculture LAM with Final Remarks.

1.1 Summary of Contents

The herein completed works evolve through the central theme, beginning with an IoT literature review and enabling densely-scalable WSNs for logistics & asset management (LAM) in IIoT. In Part I, Chapter 1 introduces the central theme of low-power wireless sensor networks for complex, multi-scale applications. This work focuses on low data rate IEEE 802.15.4 standard 2.4GHz wireless sensor networks, presumably set-and-forget, battery-operated wireless personal area networks (WPANs) connected to an IoT gateway for edge hosting services and cloud infrastructure. Chapters 2, 3,and 4 are completed research on the trends of IoT, WSNs, and realistic scalability in IIoT. First, [1] gives background and motivation on the IoT paradigm, along with a scientometric approach to the exhaustive literature review in this growing area. Second, [2] expands on the concept of the IoT in the industrial sector by exploring densely scalable WSNs for shipping and IIoT. Further investigating on the concept of end-to-end connectivity, [3] details the WSN design and a realistic system deployment for the LAM use-case.

Part II enhances the WSN by leveraging energy harvesting (EH) and wake-up radio (WUR) to enable sustainable and/or battery-free operation of ultra-low-duty-cycle sensor nodes, especially for challenging use-cases. Chapter 5 delivers solar/photovoltaic (PV) and radio frequency (RF) EH toward battery-free tags [4]. Chapter 6 investigates adding an ultra-low-power receiver for always-on-always-sensing (AOAS) WUR, allowing the primary transceiver to remain in a low-power state until the WUR detects an upcoming message of interest [5].

This work also contributes WSNs to allow improved visibility and control of airflow management in IoT applications such as data centers (DCs) in Part II and farm-to-fork agriculture in Part III. Chapter 7 presents a novel application for these next-generation WSNs in agriculture LAM use-cases with real-world, multi-scale infrastructure challenges that exacerbate design trade-offs [6].

1.2 Synopsis

This collection focuses on design challenges and technological advancements for transformative IoT applications using resource-limited WSNs. Sensors and sensor networks can be used to detect and monitor various physical phenomena surrounding a system or system-level events, providing otherwise unavailable data for historical logging and analysis. Temperature, humidity, pressure, and other sensor types are increasingly used in technologies for industrial, consumer, scientific, medical, recreation, and more applications. With advancements in various technologies, sensing devices are offering better precision, accuracy, footprint, power consumption, system integration, connectivity, and usability. Sensing devices may be equipped with various sensors, be stand-alone or modular, passive or actively powered, wired or wireless, network connected, and may be configurable. However, connectivity and continuous radio operation consume significant power relative to when events of interest are experienced.

In response, researchers continue to improve the design of low-power WSNs by building upon fundamentals and latest reports by leading institutes and industry/professional standards organizations, such as IEEE and the IEEE 802.15.4 Standard for low-power wireless personal area networks (LP-WPAN). Worldwide research in low-power WSNs has grown tremendously with the IoT paradigm (as studied in Chapter 2), with contributions ranging from the physical (PHY) layer to the application (APP) layer of compute platforms. WSN design considerations in the context of densely-scalable deployments include (as disseminated in Chapters 3 and 4):

- **Architecture -** Low-power hardware, sensing, and communications
- **Topology and Participants -** Star, tree, mesh, etc. with servers, clients, relays, and leaf nodes
- **Operational Phases -** Provisioning, association, managed, and recovery

- **Energy Considerations and Use-Cases -** Energy consumption, power management, energy harvesting, wakeup triggers, and use-case-informed implementation

With the IoT paradigm underway and 4th Industrial Revolution ahead, sensor devices, data, communication systems, digital signal processing tools, and plug-and-play architectures are more prolific and widely available. WSNs are becoming ubiquitous in modern culture and placing more demand on real-time connectivity, pervasive sensing, seamless mobility, and perpetual device lifespan. Energy harvesting is a promising trend with potential to support battery-free WSN node operation (as modeled in Chapter 5). EH and ultra-low-power radio front-end designs can enable potentially transformative features such as WUR for RF-based duty-cycling depending on implementation (as presented in 6). As designs decrease the dependence on a battery, battery size can decrease which allows for smaller form factor, lower cost, improved tolerance of harsh environments, reduced environmental impact of more/larger dumped batteries, and many more benefits being noticed across applications.

WSNs are trending toward lightweight, low-power, and mobile making them feasible for transformative applications such as the IoT and IIoT. The visibility to sensor data (i.e. temperature, humidity, light, etc.) and remote control of sensor systems (i.e. devices, cyber-physical systems, clusters, etc.) provides new opportunities to improve quality, efficiency, safety, and other metrics of success. Examples with broader impact include LAM, DCs, and Agriculture detailed in Chapters 3, 4, 5, and 7. However, applications of WSNs such as these expose the electronics to dynamic, harsh, set-and-forget, resource-limited real-world deployments that exacerbate the dependence on power supply and connectivity.

Internet of Things: A Scientometric Review

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Chapter 2: Internet of Things: A Scientometric Review

Abstract: Internet of Things (IoT) is connecting billions of devices to the Internet. These IoT devices chain sensing, computation, and communication techniques that facilitates remote data collection and analysis. Wireless sensor networks (WSN) connect sensing devices together on a local network, thereby eliminating wires, which generate large number of samples creating a Big data challenge. This IoT paradigm has gained traction in recent years, yielding extensive research from an increasing variety of perspectives, including scientific reviews. These reviews cover surveys related to IoT vision, enabling technologies, applications, key features, co-word and cluster analysis, and future directions. Nevertheless, we lack IoT scientometrics review that uses scientific databases to perform a quantitative analysis. This paper develops a scientometric review about IoT over a data set of 19035 documents published over a period of 15 years (2002-2016) in two main scientific databases (Clarivate Web of Science and Scopus). A python script called ScientoPy was developed to perform quantitative analysis of this data set. This provides insight into research trends by investigating lead-author's country affiliation, most published authors, top research applications, communication protocols, software processing, hardware, operating systems, and trending topics. Furthermore, we evaluate the top trending IoT topics and the popular hardware and software platforms that are used to research these trends.

2.1 Introduction

Internet of Things (IoT) connects billions of devices to the Internet and has gained tremendous popularity in the past decade as a diverse and pioneering technology. In general, IoT devices combine sensing, computation, and communication techniques to deliver remote data collection and system control. Today, these "things" range from everyday consumer electronics to specialized industrial systems [3], such as fitness-tracking wristwatches [7], transport logistics [2], and smart cars [8] to manufacturing [9] and smart grids [10]. Contingent on implementation, an IoT device may be used for real-time alerts, data archiving, trend analysis, and forecasting by leveraging related technologies such as cloud services [11]. Furthermore, the technology has proven useful for small- and large-scale networks, generating a vast portfolio of enabling hardware and software at various complexities [12,13]. IoT technology has led to solutions in use-cases ranging from smart appliances, utilities, biomedical, industrial, data center management, agriculture, body area networks (BANs), surveillance, and more.

Proliferation of IoT research has contributed to increased availability, affordability, responsiveness, diversity, miniaturization, mobility, and more. Recent studies have demonstrated that IoT, cloud computing, and mobile solutions are among the top technologies that will shape our future in the next 3-5 years [11]. Not surprisingly, connectivity and intelligence are becoming a contributing factor to many designs fueling advanced development. Therefore, the number of new designs and publications categorized under IoT continues to grow exponentially.

Evolution of IoT has spearheaded many research fields such as wireless sensor networks (WSNs), Big Data, and cloud computing. Wireless Sensor Networks (WSN) comprise: sensor nodes, specialized firmware [14], relay devices, and data sinks called a gateway. In addition to facilitating data archiving and local processing, the gateway also acts as a hub that connects to the worldwide web for cloud storage and services using a WiFi or cellular network.The computational complexity of analysis and functional use of the data towards trend and forecasting has grown rapidly, such as in the data center management use-cases [15]. The radio frequency (RF) communication protocols and the interaction between these sensor entities continue to place stringent hardware requirements. Implementations using one software stack over another could achieve better range, quality-of-service (QoS), and spectral efficiency, at the expense, however, of additional processing, storage, power, and form-factor [13]. Additionally, the connectivity and archiving with WSN results in a large volume of samples that create a "big data" challenge.

While IoT is not a new paradigm, it is gaining traction in recent years around the world and yielding extensive research from diverse perspectives. As a result, IoT and similar technologies are progressively challenging topics to review. Starting in 2010, Atzori et al. made a survey about IoT enabling technologies and applications [16]. Then, in 2013, Gubbi et al. defined a cloud center vision for worldwide implementation of IoT, describing the key enabling technologies, applications domains and future directions [17].

In 2014, Borgia presented an extended review about IoT key features, driving technologies and protocols, applications, challenges, IoT initiatives, and research directions [18]. Next, in 2015, Yan et al. developed a co-word analysis, generating seven clusters that represented the intellectual structure of IoT, which were analyzed by a co-occurrence matrix [19]. The following year, in 2016, Mishra et al. composed a bibliometric study about the future vision, applications, and challenges of Internet of Things [20]. In that review, Mishra et al. identified the top contributing authors, key research topics, most influential works, and emerging research clusters, limited only to future vision and applications of IoT, from a sample of 1556 papers from the Scopus database.

As noted above, when conducting a review of IoT publications in recent years, the outcome may vary depending on methodology and time spent browsing through search results. At a minimum, only publications of reputable categories from credible databases should be considered for the review process. For example, conference papers, journal articles, proceedings papers, and reviews are widely accepted as reliable information sources in the industry and academia. Additionally, the manual labor of searching thousands of bibliographic data can be reduced by scripting to facilitate the filtering and comparison activities. This allows the reviewer additional time to investigate supplementary metrics in order to render stronger and methodological conclusions.

Therefore, this paper presents a methodology for citation analysis using search results produced by two scholarly bibliographic databases: Clarivate Web of Science (WoS) and Scopus. To facilitate a thorough review of several thousand publications related to IoT, the study presented herein utilized a novel literature review script called ScientoPy to analyze document bibliographies according to predefined metrics. This scientometrics analysis provides insight into research trends in IoT over recent years by investigating a lead author's country affiliation, most published authors, and prevalence of various research topics. Using the authors' keywords, the research topics inspected in this review include applications, communication protocols, software processing, hardware, operating systems, and trending topics.

2.2 Materials and Methods

Scientometrics is the study of measuring and analyzing scientific literature by measuring the impact of the innovation and understanding the relevance of these scientific citations to this innovation [21]. Thus, a Python script for scientometrics literature review (ScientoPy) was developed by the authors to analyze content of publications related to the Internet of Things. This ScientoPy script has the capability to:

- Read Clarivate Web of Science and Scopus databases (.CSV files).
- Filter publications by document type.
- Find and remove duplicated documents.
- Graph the history of the top topics (keywords, authors, countries).
- Graph the history of selected items inside a topic.
- Find trending topics using the top average growth rate (AGR).
- Calculate the h-index for authors and countries.

ScientoPy is a Python script that automatically generates and reports the top topics (based on authors' keywords), authors, and countries, along with related documents. This automatic data synthesis avoids potential bias as in individual studies. Nevertheless, author name analysis (such as author top list) has a risk of bias across the studies due to possible similarities in names. The writers of this review know and warn about this possibility of documents' author names similarity, which is part of the limitation of any scientometrics study; thus, in this moment not all the authors and data bases have a unique author identifier, like the ORCID, associated with all entries.

2.2.1 Data Set

This scientometrics analysis used two bibliographic databases: Clarivate Web of Science (WoS), and Scopus. For the span of 1 January 2002 to 31 December 2016, the following document types were studied:

- Conference Paper;
- Article;
- Review;

Source	Article	Conference Paper	Proceedings Paper	Review	Duplicated Removed
WoS	3112	0	8215	130	55
Scopus	5283	10,068	0	312	8030

Table 2.1: Type of documents found with the search string “Internet of Things” found in Clarivate Web

- Proceedings Paper.

The search string for this analysis was ”Internet of Thing”. This string was applied to the topic search in WoS and Scopus, which includes title, abstract, authors’ keywords, and KeyWords Plus® (for WoS). With this search criteria, the data set was extracted within a day on 6 July 2017. Table 2.1 describes the number and type of documents found in the two databases totaling 27,120 documents.

2.2.2 Pre-Processing

A pre-processing technique was applied to improve reliability and precision, as detailed in the following sub sections.

2.2.2.1 Simplify Author’s Name

In general, scientific and bibliographic databases have the following inconsistencies in authors names:

- Most journals abbreviate the author’s first name to an initial and a dot.
- Most journals use the author name’s special accents.
- WoS uses a comma between the author’s last name and first name initial, but Scopus does not.

These name-related inconsistencies mean that scientometrics scripts cannot find all of the similar author’s names. For that reason, ScientoPy script applies the following steps to simplify author’s name fields:

- Remove dots and coma from author's name.
- Remove special accents from author's name.

2.2.2.2 Remove Duplicate Samples

Of the 27,120 original samples, only 72% have an associated DOI for uniqueness. Therefore, duplicated samples were identified by identical title and authors. For duplicated samples in different databases, the WoS publication was kept and the Scopus sample was removed from the set, resulting in remaining 19,035 documents. Table 2.1 shows the number of documents by type and duplicates removed for each database.

2.2.3 Time Cited and h-Index

Scopus and WoS databases report the Times Cited Count for each document; however, 47% of the Counts for the same (duplicate) document differ between sources. In such instances, the ScientoPy script selects the highest Times Cited Count, be it from Scopus or WoS, to assign the most favorable value to each document for this metric. Therefore, the h-index for authors and countries is calculated based on these Times Cited Count for the period 2006 to 2016.

2.2.4 Document's Country

In this study, the document's country was extracted from the primary author's corresponding address. Thus, only one country was associated to each document. Furthermore, some authors use different naming to refer to the same country (such as USA and United States). For that reason, some country names were replaced based on Table 2.2.

In this data set, 95 documents were missing the author's corresponding address to extract the document's country. These samples were discarded for analyses related to country.

Original	Replacement
Republic of China	China
USA	United States
England, Scotland, and Wales	United Kingdom
U Arab Emirates	United Arab Emirates
Russia	Russian Federation
Viet Nam	Vietnam
Trinid & Tobago	Trinidad and Tobago

Table 2.2: Documents' countries names replacing table.

2.2.5 General IoT Publications Growth

The yearly growth of IoT related documents were observed as in Figure 2.1a, revealing an exponential growth in both databases (WoS and Scopus), without removing the duplicated documents. Figure 2.1b shows the similar growth after removing the duplicated documents.

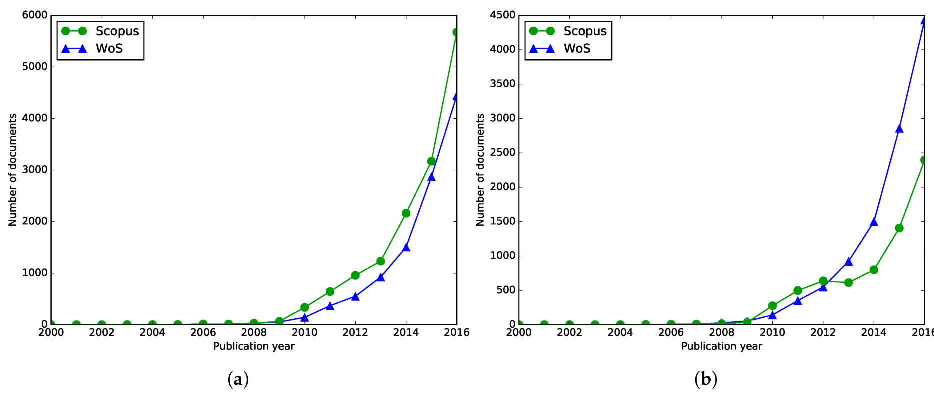


Figure 2.1: Documents per year published (WoS and Scopus) with the search string "Internet of Things" (IoT) for the period 2000 to 2016. (a) before the duplicates-removal filter; (b) after duplicates-removal filter.

The first mention of the "Internet of Things" was an article published in March 2002 reported by WoS. Published by Forbes, Schoenberger, and Upbin, this article described how the IoT could be a standardized way to help the computers understand the world [22]. In 2003, Scopus reported a paper from the Institute of Electrical and Electronics Engineers (IEEE) International Conference on Systems, Man and Cybernetic, in which

Qui and Zhang showed the design of enterprise web servers supporting instant data retrieval for a product labeled with an Radio-frequency identification (RFID) based smart tag [23]. Scopus reported a second conference paper in 2003 for the 36th Annual Hawaii International Conference on System Sciences, Traversat et al. on the stated the JXTA (abbreviation of Juxtapose) protocols as a foundation of the upcoming Web of Things [24]. In 2004, WoS and Scopus reported the same two articles: "The Internet of Things" by Gershenfeld et al. [25], and "The Supply Chain" by Luckett [26]. From 2005 to 2016, Scopus reported about 30% more publications than WoS. Nevertheless, for this research, WoS documents were given more priority over Scopus documents during the duplicates-removal process because WoS fields were more complete than Scopus, such as cited references with Digital Object Identifier (DOI) number and subject category. For this reason, Figure 2.1b shows more documents from WoS than Scopus from 2013 onwards.

2.3 Country and Author Research Analysis

In this section, analysis was focused on authors and their corresponding country. Below is a graph of the percentage of publications related to IoT each year for the seven countries with the highest occurrence in the data set. A table of the most occurring 50 countries is also provided. Another graph presents the top five authors per year, alongside tables detailing the top 20 authors and 10 most cited author documents for articles, conferences and reviews.

2.3.1 Country Analysis

A list of the countries with the most associated publications was generated. Figure 2.2 shows the top seven countries, along with the percentage of documents published per year. In 2002, one article was published on Forbes by Schoenberger; unfortunately, the database does not associate any author address for this document and the sample had to be removed from this data set according to methodology. In 2003, two conference papers were published by United States authors [23, 24]. In 2004, there was one review publication in the United States [25] and one article in the United Kingdom [26].

Germany [27] and Malaysia [28] first appear in 2005, joined by the United States

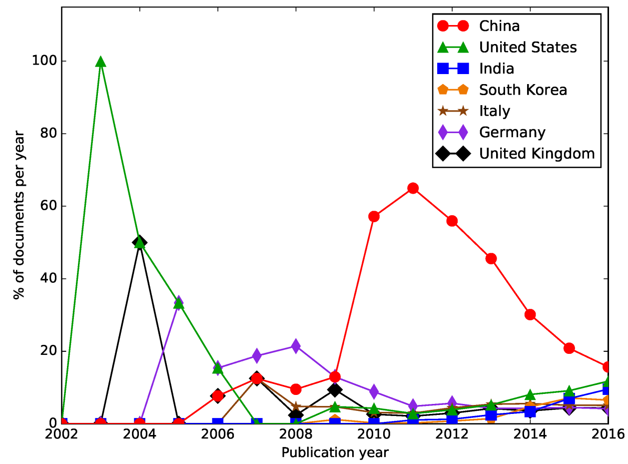


Figure 2.2: Internet of Things percentage of documents published per year by the top 7 first author's corresponding address country for the period 2002 to 2016.

[29]. These three conference papers demonstrated how the RFID can boost Internet of Things for manufacturing, packing, tracking, and automobile logistics. In 2006, the total publications grew from 3 to 12, with more countries participating, such as France [30,31], Switzerland [32, 33], and Japan [34]. From 2006 to 2009, Germany led the number of publications with 2, 3, 9, and 11, respectively. During that period, the German author Broll led the citations count with a proposed framework for integrating web services and mobile interaction with physical objects [35].

China drastically increased from 11 to 239 publications from 2009 to 2010, continuing to contribute more than half of the globally published documents between 2010 to 2013. Most of that growth resulted from China's Twelfth 5 Year Plan (2011-2015), which included the development of the Internet of Things [36]. The conference paper "IOT Gateway: Bridging Wireless Sensor Networks into Internet of Things" by Zhu was the most cited IoT paper during this period for China, as it explained how an IoT Gateway could make a bridge between wireless sensors networks and traditional communications networks to the Internet [37].

From 2014 to 2016, China maintained the highest rank, contributing 20% of the globally published documents, as well as a peak in 2016 and h-index of 47. In 2014, the United States was second to China with 187 publications and h-index of 42. India's contributions grew at a rate of 153%, 103%, 286%, and 120%, in 2013 to 2016, respectively, moving from the 8th to 3rd position in 2013 and 2016, respectively. The Indian daily "The Economic Times" forecasted the country is expected to see a rapid 31-fold growth of IoT devices to reach 1.9 billion by 2020 [38].

Expanding the results from Figure 2.2, Table 2.3 shows the top 50 countries of the primary author with the average percentage growth and the h-index of each country from the last three years (2014 to 2016). Of the top 10 countries, South Korea represents the maximum average growth with 206%, where the mobile carrier SK Telecom (Seoul, South Korea) launched the first commercial low-cost Internet of Things (IoT) network in 2016 [39]. However, this growth is not reflected yet (next year) in the available literature and thus the data set has an h-index of 16, only half of its successor in this list, Italy. In the same way, this list includes the top growing countries with low h-index but anticipated to be higher next year: Indonesia, Turkey, Russian Federation, and Pakistan.

The International Data Corporation (IDC) predicts that, by 2019, 20% of local and regional governments in Indonesia will use the Internet of Things to turn infrastructure such as roads, street lights, and traffic signals into assets instead of liabilities [40]. In addition, the Dutch IoT start-up, Xeelas (Arnhem, Netherlands), and Turkish group, Sade (Ankara, Turkey), partnered to build Turkey's largest LoRaWAN (LoRa, Long Range Wide-area network network) in Istanbul to enable business, local governments, and conservation groups to collect and analyze from connected devices [41]. In Russia, the Internet of Things market is expected to reach USD 74 Billion by 2023, where the Russian government's Internet start-up fund (FRII) has joined forces with tech giants GS Group (Saint-Petersburg, Russia) and mobile operators to launch a national Internet of Things (IoT) consortium [42]. In Pakistan, by January 2017, 17 Internet of Things start-ups were launched, on their own or incubated, at Plan9 (Lahore, Pakistan), NEST i/o (Karachi, Pakistan), and i2i (Islamabad, Pakistan) [43].

2.3.2 Author Analysis

The data set analyzed here includes 31,422 authors of the 19,035 documents related to Internet of Things. In addition, 592 of these authors have 10 or more publications in WoS or Scopus. Figure 2.3 shows the top five authors with the most published documents per year. Y. Zhang was positioned first with 130 published documents related to IoT

N.	Country	Total	Average Growth	h-Ind.
1	China	4822	16%	47
2	United States	1561	116%	42
3	India	1089	169%	15
4	South Korea	894	206%	16
5	Italy	874	61%	32
6	Germany	811	64%	24
7	United King.	711	71%	25
8	France	543	126%	21
9	Spain	463	42%	23
10	Japan	449	166%	11
11	Taiwan	438	68%	16
12	Brazil	272	90%	9
13	Finland	266	50%	20
14	Canada	259	104%	15
15	Australia	249	59%	22
16	Sweden	216	68%	17
17	Switzerland	193	31%	19
18	Portugal	191	45%	13
19	Greece	180	46%	14
20	Romania	169	72%	9
21	Belgium	164	87%	11
22	Austria	146	113%	12
23	Malaysia	137	71%	9
24	Russian Fed.	134	271%	8
25	Ireland	126	116%	9
26	Netherlands	109	122%	12
27	Singapore	109	112%	8
28	Poland	104	77%	6
29	Czech Rep.	101	153%	5
30	Turkey	92	319%	5
31	Pakistan	82	210%	7
32	Saudi Arabia	80	122%	7
33	Norway	72	119%	11
34	UAE	71	180%	6
35	South Africa	60	162%	9
36	Denmark	59	39%	11
37	Tunisia	55	163%	6
38	Serbia	53	−1%	6
39	Croatia	51	159%	6
40	Hungary	51	24%	6
41	Indonesia	51	410%	3
42	Egypt	49	159%	4
43	Morocco	47	163%	4
44	Iran	42	94%	5
45	Colombia	39	146%	3
46	Algeria	38	113%	5
47	Jordan	38	108%	5
48	New Zealand	38	86%	6
49	Mexico	36	172%	5
50	Thailand	32	107%	4

Table 2.3: Internet of Things top 50 countries of first author's corresponding address. Country number position (N.), total number of publications (Total), average percentage growth from the last 3 years (2014 to 2016), and h-index (h-ind.) from 2006 to 2016.

and RFID, security, electric vehicle, artificial immune system, smart grid, and cloud computing. In 31 documents, Y. Zhang appeared as a first author. His most cited document is the article titled "Toward Cloud-Based Vehicular Networks with Efficient Resource Management" [44] with 96 citations.

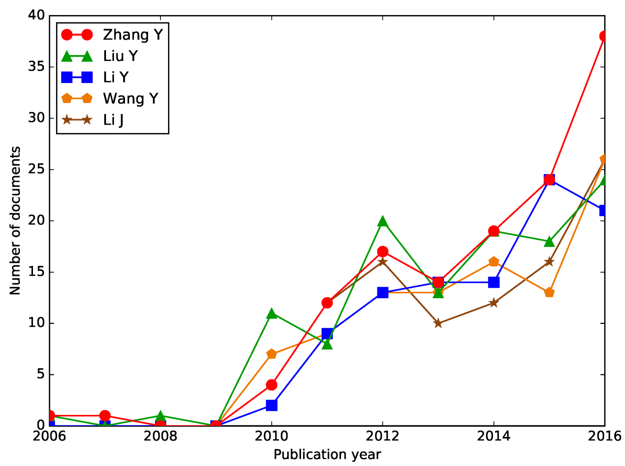


Figure 2.3: Internet of Things top 5 authors with most documents published per year, for the period 2006 to 2016.

Y. Liu is positioned second with 115 documents, of which 36 list him as the primary author. His publications are more focused on hardware such as Raspberry Pi, test bed, optical communications, ZigBee, and RFID. The article titled "IOT gateway: Bridging wireless sensor networks into Internet of Things" is his most cited document with 134 citations [37]. Y. Liu shares the authorship in four publications with the first author in this list, Y. Zhang.

Y. Li is the third in this list with 97 publications, with 37 as the primary author. His focus was on RFID, big data, and databases. "Towards a theoretical framework of strategic decision, supporting capability and information sharing under the context of Internet of Things" [45] is his most cited publication with 39 citations. With the same number of publications, 97 and 39 as the primary author, Y. Wang is next in this list. His research is related to RFID, smart gird, security, logistics, and big data. His most cited document is [46] with 16 citations. Lastly, fifth on this list is J. Li with 96 publications with 33 as the primary author. His papers related to RFID, ZigBee, and standardized breeding, with his proceedings paper in [47] being his most cited paper with 97 citations in this set.

Table 2.4 shows the top 20 authors with the most published number of documents, along with the author's h-index in IoT, most cited document, and top research topics. Nevertheless, the two-top h-index authors in this case are not in the top 20 number of documents. L.D. Xu is the author with the highest h-index of 21 and 33 publications. Similarly, L. Atzori has second place in h-index of 14 and 41 documents.

N.	Author	Total Documents	h-Index	Most Cited Document	Top Author Topics
1	Zhang, Y.	130	12	[40]	RFID, security, Electric vehicle
2	Liu, Y.	115	11	[33]	RFID, name service, ZigBee
3	Li, Y.	97	9	[41]	RFID, big data, database
4	Wang, Y.	97	5	[42]	RFID, smart grid, secirity
5	Li, J.	96	9	[43]	RFID, ZigBee, standarized breeding
6	Zhang, J.	82	6	[44]	RFID, WSN, monitoring system
7	Wang, J.	80	8	[45]	RFID, 5G, sampling
8	Zhang, L.	79	13	[46]	Cloud computing, cloud manufacturing, ZigBee
9	Wang, X.	78	6	[47]	RFID, ZigBee, service selection
10	Chen, Y.	72	8	[48]	RFID, WSN, ZigBee
11	Jara, A.J.	72	13	[49]	6LoWPAN, smart cities, big data
12	Zhang, X.	72	6	[50]	Logistics, RFID, WSN
13	Li, H.	71	7	[51]	RFID, authentication, security
14	Wang, H.	70	9	[52]	RFID, monitoring, cloud computing
15	Li, X.	67	8	[53]	RFID, recommendation, smart grid
16	Liu, J.	65	10	[54]	Cloud computing, RFID, security
17	Kim, J.	62	7	[55]	WSN, video streaming, HEVC
18	Wang, Z.	60	8	[56]	RFID, GPRS, EPC network
19	Liu, X.	59	9	[57]	Cloud computing, RFID, Landsenses ecology
20	Kim, D.	58	7	[58]	EPCIS, 6LoWPAN, security

Table 2.4: Internet of Things, top 20 authors with most publications, total number of documents, h-index, most cited document, and top related research topics for the period 2006 to 2016.

Table 2.5 shows the most cited papers for three document types (articles, conference/proceedings and reviews). Atzori et al. surveys IoT vision and enabling technologies [16]. Second in articles, Gubbi et al. describe a cloud-centered vision for the worldwide implementation of IoT [17]. Miorandi et al.'s article surveys on technologies, applications and research challenges for IoT [48]. For conferences and proceedings, Bonomi et al. describe the Fog computing characteristics and its role in IoT [49]. Tao et al. propose cloud computing, Internet of Things, virtualization, and service-oriented combination technologies with advanced manufacturing models and enterprise information technologies to generate a new manufacturing model, called cloud manufacturing (CMfg) [50]. Tan and Wang show a skeleton of the Internet of Things with an application model that can apply to automatic facilities management in the smart campus [51].

Finally, on the reviews side, Gershenfeld et al. present a review about the Internet-0 (Internet-Zero) protocol, whose approach for the reduced complexity of the IP stack extends the notion of internetworking to interdevice [25]. Meng and Ci mention that the data type and amount is growing at a high speed due to emerging services such as cloud computing, IoT, and social media. Thus, they review the concept of big data and describe a new era for data handling [52]. Lastly, Aziz et al. surveys the topology control techniques for extending the lifetime of battery to power WSNs for the Internet of Things battery-powered devices [53].

2.4 Research Topics

IoT has a broad spectrum of research fields such as applications, smart objects, communications protocols, software processing, devices hardware, and operating systems. On the data set analyzed here, most of the authors include their research topic in the document keywords. In this section, author keywords were analyzed to find the trends in the different research topics. For Scopus, the regular authors' keywords were used, and similarly for WoS. KeyWords Plus from WoS were discharged because they are index terms created automatically from significant, frequently occurring words in the titles of an article's cited references, and they are less comprehensive in representing an article's content [54]. The top 1000 keywords were extracted, manually classified in the different research field, and grouped by plural-singular similarity and/or abbreviations. For instance, the keywords WSN, wireless sensor network, and wireless sensor networks were grouped into the WSN keyword. The following subsections describe the trend of the research topics in different fields, based on the top authors' keywords publications per year. Figure 2.4 shows the general top 10 authors' keywords.

2.4.1 Applications

There are several application fields related to IoT research and development. In this section, the authors' keywords were analyzed to find the top specified applications. Figure

N.	First Author	Document Reference	Times Cited	Publication Year	Country
Articles documents					
1	Atzori L	[12]	3239	2010	Italy
2	Gubbi J	[13]	1369	2013	Australia
3	Miorandi D	[59]	721	2012	Italy
4	Kortuem G	[65]	506	2010	United Kingdom
5	Ganti RK	[66]	494	2011	United States
6	Bobadilla J	[67]	482	2013	Spain
7	Li B-H	[46]	471	2010	China
8	Perera C	[68]	454	2014	Australia
9	Zanella A	[69]	404	2014	Italy
10	Chen M	[70]	370	2014	China
Conference and proceedings documents					
1	Bonomi F	[60]	508	2012	United States
2	Tao F	[61]	228	2011	China
3	Tan L	[62]	169	2010	China
4	Spiess P	[71]	156	2009	Not specified
5	Mainetti L	[72]	142	2011	Italy
6	Zhu Q	[33]	134	2010	China
7	Dohr A	[73]	132	2010	Austria
8	Kovatsch M	[74]	112	2011	Switzerland
9	Khan R	[75]	101	2012	Italy
10	Su KH	[43]	97	2011	China
Review documents					
1	Gershenfeld N	[21]	271	2004	United States
2	Meng X	[63]	172	2013	China
3	Aziz AA	[64]	139	2013	Malaysia
4	Domingo MC	[76]	138	2012	Spain
5	Borgia E	[14]	132	2014	Italy
6	Hancke GP	[77]	101	2013	South Africa
7	Wang ZL	[78]	98	2010	United States
8	Wang SH	[79]	83	2015	United States
9	Keoh SL	[80]	69	2014	Singapore
10	Malhotra A	[81]	64	2013	United States

Table 2.5: Internet of Things top 10 documents with most citations, divided by document type, including position number (N.), first author, document reference, times cited, publication year, and first author corresponding address for the period 2002 to 2016.

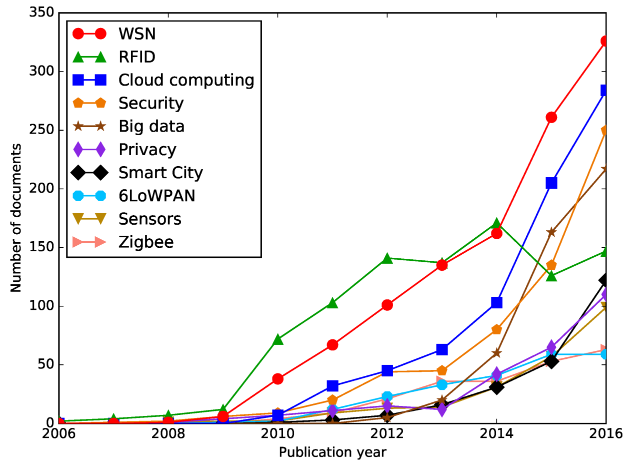
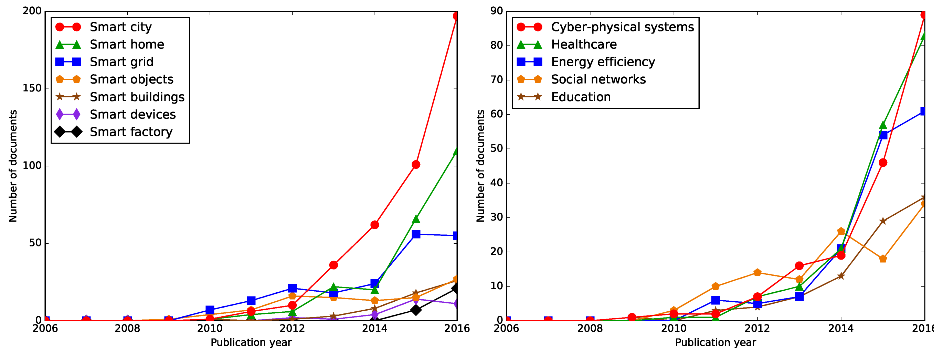


Figure 2.4: Internet of Things top authors' keywords documents published per year, excluding the keywords: Internet of Things, IoT, Internet of Things (IoT), and The Internet of Things, for the period 2006 to 2016.

2.5 shows the trend of these applications in documents per year. Furthermore, Figure 2.5a presents the applications that start with the word "smart", and Figure 2.5b those that do not.

In the data set, 1052 documents were found for applications that start with "smart". Smart city is the top one in this list, with 413 documents, and a sigmoid growth in exponential phase, 95% more publications in 2016 vs. 2015. A.J. Jara has the most number of documents in this field with 12 publications. His most cited document [55] refers to Smart and Connected Communities as a concept that is evolving from Smart cities. The leading country in this application is Italy with 50 publications, and the most important correlated topics are Big data [56–58], Cloud computing [59, 60], and Smart grid [61, 62]. Similarly, Smart home has a linear growth, with 230 documents, and 111 in the last year, with China as the leading country. The most important related topics for Smart home are security [63–65], ZigBee [66–68], and activity recognition [69–71].

In contrast, smart grid is a topic that has not demonstrated continuous growth. In 2012-2013, the documents published per year decreased from 21 to 13, and in 2015-2016 from 56 to 55. Nevertheless, an overall 194 documents were registered on this topic, with China as the leading country. The term smart grid refers to "a next generation power grid that uses two-way flows of electricity and information to create a widely distributed



(a) (b)

Figure 2.5: Internet of Things top applications based authors' keywords in documents per year, for the period 2006 to 2016. (a) applications that start with "smart" (b) applications that do not start with "smart".

automated energy delivery network" [72]. Within IoT, the research on smart grids are related to security [73–75], cloud computing [76, 77], and privacy [75, 78, 79].

According to Dumitrache, "Cyber-Physical Systems (CPS)s are physical, biological and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core" [80]. Publications of this topic related to IoT have a sigmoid growth in exponential phase, with 182 publications in 2016, noting United States as the leading country with 34 documents. The most important related topics are: Industry 4.0 [81–84], big data [85–87], and security [88–90]. Next, Healthcare and E-Health related to IoT exhibited a sigmoid growth in a transitional phase, with a total of 180 documents, and India as the leading country with 20 publications. Different IoT technologies are applied in this area such as sensors [91], RFID [92–95], 6LoWPAN [96, 97], and wearables [98, 99]. The third most growth topic was energy efficiency with 154 documents, and China and Italy as leading countries with 18 and 17 publications, respectively. Energy efficiency as an application for IoT is related in this data set with the following topics: smart buildings [100–102], energy harvesting [103–105], and RFID [106, 107]. Social networks (or Social media) is another application for IoT, with 117 documents, and Italy as the leading country with 23 publications. Among the top related topics in this field are trust management [108–110] and recommendation systems [111, 112]. Education, Learning, E-Learning, and mobile learning is the fifth top application in this list, with 93 publications and the United Kingdom as the leading country with 12 documents. The most popular related topics with education are: augmented reality [113–115], context aware [116–118], and near field radio technologies such as RFID [119–121] and Near Field Communication (NFC) [122, 123].

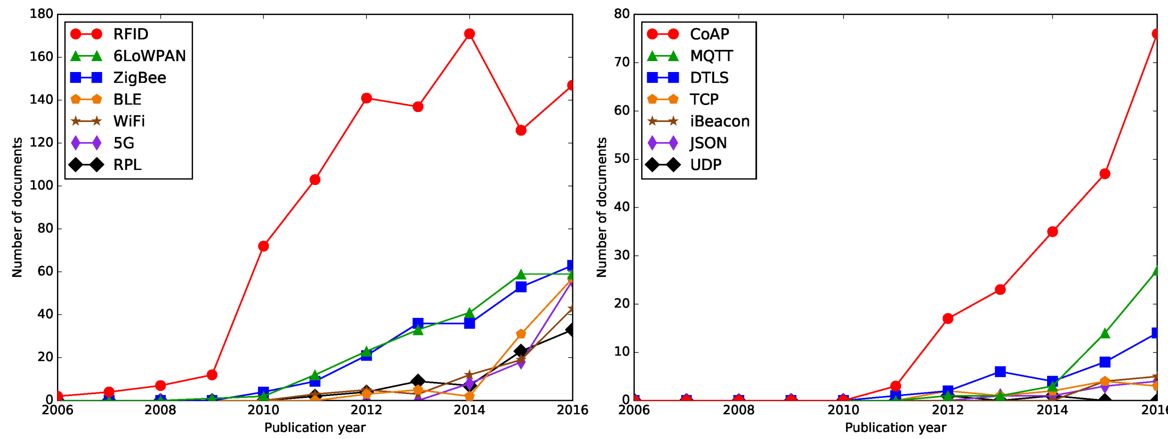
2.4.2 Communication Protocols According to Open Systems Interconnection Model (OSI Model)

Regarding telecommunications systems, the Open Systems Interconnection model (OSI model) describes the communications process in seven layers which are divided into media layers (Physical, Data, and Network) and host layers (Transport, Session, Presentation, and Application) [124]. In this review on IoT, the most used communication protocols are divided into these two layers (see Table 2.6). Figure 2.6 shows the yearly trend of the different communications protocols for media layers in Figure 2.6a and host layers in Figure 2.6a.

	Layer	IoT Communication Protocols
Host layers	7. Application 6. Presentation 5. Session	CoAP, MQTT, JSON, iBeacon
	4. Transport	TCP, UDP, DTLS
Media layers	3. Network	IPv6, 6LowPAN, ZigBee, BLE, RPL
	2. Data link 1. Physical	RFID, 802.15.4, WiFi, BLE, 5G

Table 2.6: Internet of Things Open Systems Interconnection model (OSI model) communication protocols.
Abbreviations definition: Constrained Application Protocol (CoAP), Message Queue Telemetry Transport (MQTT), JavaScript Object Notation (JSON), Transmission Control Protocol (TCP), User Datagram Protocol (UDP), Datagram Transport Layer Security (DTLS), Internet Protocol version 6 (IPv6), IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN), Bluetooth Low Energy (BLE), Routing Protocol for Low power and Lossy Networks (RPL), Radio-frequency identification (RFID).

RFID is the top used author's keyword in the analyzed data set and the most used media layer communication protocol in the authors' research. On IoT 923 publications



(a) (b)

Figure 2.6: Internet of Things media and host layers communication protocols based on authors' keywords in documents per year, for the 2006 to 2016 period. (a) media layers' communications protocols; (b) host layers' communication protocols.

are related to RFID, where security authentication [125–127], wireless sensors networks [128, 129], privacy [130, 131], and electronic product code (ECP) [132, 133] were major applications. Next, 6LoWPAN appears in 230 publications, with documents related to upper layer protocols such as Constrained Application Protocol (CoAP) [134, 135], Routing Protocol for Low power and Lossy Networks (RPL) [136, 137], and operating systems like Contiki [138, 139], and Android [140, 141]. With similar growth, ZigBee follows with 222 documents, and research integrates this protocol with solutions such as RFID [142–144], or applications like smart home [67,145,146], and health care [147–149].

Bluetooth Low Energy (BLE) has experienced a rapid growth in the last three years, near 100% from 2015 to 2016. A total of 98 documents on IoT are related to BLE, with one of the most cited articles by Gomez et al. at 176 citations. In this article, the authors describe the main features and potential applications for BLE technology [150]. This data set shows BLE related applications such as home automation [151–153] and indoor location [154–156] and health care [157–159]. WiFi is the other network protocol used for IoT research, with a total of 85 publications, and applications related to: home automation [160, 161], indoor localization [162]. Nevertheless, with this wireless technology, some authors have focused on how the 2.4 GHz spectrum could be efficiently used with other IoT network protocols [163–169]. Similarly, 5th generation mobile networks (5G) appear in IoT with 82 publications, much more than 4G and LTE, with 54 documents both combined. The most cited paper is a suvery on 5G architecture and emerging technologies written by Gupta et al. [170] with 109 citations. Network Function Visualization (NFV) and Software Defined Networking (SDN) [171–173] were the top related technologies, which offer different architectural options to address IoT needs for 5G. Finally, RPL is discussed as an IPv6 Routing Protocol for Low-Power and Lossy Networks as a mechanism for multipoint-to-point and point-to-multipoint traffic for these kinds of networks [174]. This protocol has 78 documents with publications related to the Contiki OS and its simulator tool Cooja for WSN [175, 176], and mesh networks [177–179].

At the host layer, communication protocols publications are led by the Constrained Application Protocol (CoAP), which is a specialized web transfer protocol for use with constrained nodes and constrained networks [180]. A total of 201 publications were found in this area, with some of these publications related to: 6LoWPAN [135, 137, 181], and Datagram Transport Layer Security (DTLS) [182, 183]. Second, the Message Queue Telemetry Transport (MQTT) shows up with 46 documents. This is a lightweight, and open client-server publish/subscribe messaging transport protocol [184]. Next, Datagram Transport Layer Security (DTLS) protocol follows this list with 35 publications. This DTLS provides communications privacy for datagram protocols based on the stream-oriented Transport Layer Security (TLS) [185]. This protocol helps to enhance the security of others' higher layers protocols like CoAP [186, 187]. Finally, iBeacon is the fifth on this list with nine documents. This is a protocol designed by Apple (Cupertino, CA, United States) to describe its own implementation of BLE Beacon, which emits a signal that can be detected by any BLE enabled device within a close range [188]. Most of the applications for this protocol include indoor localization [189, 190].

2.4.3 Software Processing Techniques

The proliferation of IoT has significantly increased the data collection and the strain it places on faster data analytics. Several software processing techniques have been researched, developed, and published. In these published documents, the various software processing techniques used were specified in the authors' keywords. Figure 2.7 shows the top authors' keywords for these processing techniques. Machine learning is the most popular research technique for data processing with 100 publications. This technique is used for data prediction [191, 192], activity recognition [193, 194], and data classification [195, 196]. Next, data mining appears with 89 documents, with distributed data mining [197], and applications such as event detection [198, 199] as sub-techniques.

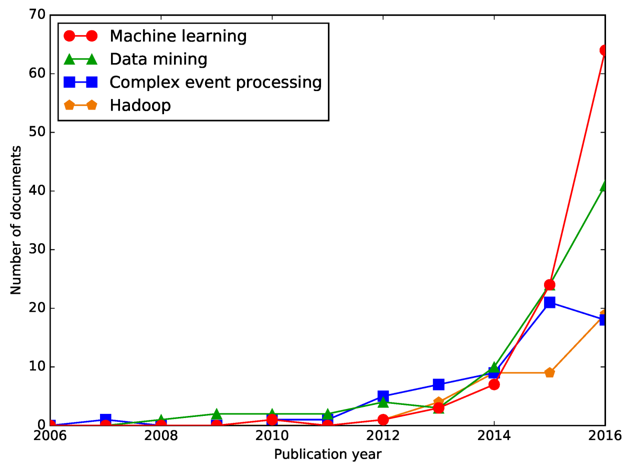


Figure 2.7: Internet of Things software processing techniques based on authors' keywords in documents per year, for the period 2006 to 2016.

Complex event processing is a method of tracking and analyzing streams of data surrounding events or anomalies and basing a conclusion from them [200]. It was found that 63 documents are related to this processing technique with applications such as supply chain [201–203] and health care [204, 205]. Apache Hadoop (or Hadoop) is a software framework used for distributed storage and big data processing using the MapReduce programming model [206], appearing with 42 documents and applications including smart cities [207–209], and Social Internet of Things [210].

2.4.4 Device Operating Systems (OS) and Hardware

The data set analyzed here shows that the investigations used different IoT devices (end devices and gateway devices), operating systems (OS), and hardware. Figure 2.8 shows the top authors' keywords per year for the most employed OS and hardware. Android is the most used OS for researchers, with 87 documents. This OS is used for

IoT gateways [211–214] or end sensing devices [215–217]. Contiki is a lightweight OS for memory constrained systems (like microcontroller-based systems) designed for low-power wireless devices [218]. A total of 56 publications were found related to this OS, where the author uses capabilities like embedded protocols: 6LoWPAN [138, 219], CoAP [220], and RPL [221]. In addition, some publications use the Contiki network simulator Cooja to simulate routing protocols [222] and performance evaluation [223].

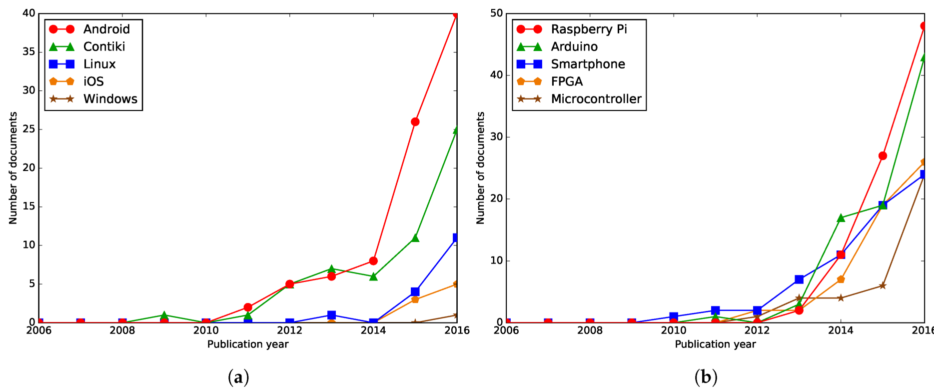


Figure 2.8: Internet of Things devices operating systems (OS) and hardware based on authors' keywords, for the period 2006 to 2016. (a) most used operating systems in authors' keywords per year; (b) most used hardware in authors' keywords per year.

Other operating systems, such as Linux, are used in IoT for image processing [224] and gateway services [225]. The iPhone Operating System (iOS) is used as user interface for presentation, configuration, and remote controlling for IoT environments [226]. Finally, last year, Culic et al. demonstrated the potential of Windows 10 IoT Core (Redmond, WA, United States), a light-weight version of Windows 10, as an IoT operating system optimized to run on small devices that have no display [227].

On the hardware side, some authors' keywords detail the hardware devices employed (see Figure 2.8b). Raspberry Pi is a small single board computer (SBC) capable of supporting operating systems like Linux Ubuntu, Windows, or Android. The Raspberry Pi is the most popular platform employed for IoT, with 88 publications, as a versatile platform for a gateway [228–230] or monitoring system [231, 232]. Arduino boards are single-board microcontroller kits, in which the developer connects sensors, actuators, or RF communication interface easily using shield boards. For this specific IoT publications data set, 83 documents refer to Arduino hardware. These boards are widely used for IoT learning [226, 233, 234] and monitoring devices [235–237].

Presently, smartphones are highly capable embedded systems that run full OS, with integrated sensors. Sixty-six documents were found related to smartphones in IoT, be they used as sensors [238, 239], gateway [240–242], or user interface [243, 244]. The Field-Programmable Gate Array (FPGA) is a hardware reconfigurable component that contains an array of computational (logic) elements, with a functionality specified by a hardware description language [245]. These FPGAs are used in IoT investigations for data encryption [246–248], routing algorithms [249], and parallel simulation [250]. A microcontroller (MCU) is a small computer on a single integrated circuit, which includes a processor core, RAM/ROM memory, peripherals, and, in some cases, RF transceivers. For IoT, the MCU plays a fundamental role in sensing end devices [228, 251, 252] and actuators [253].

2.4.5 Top Trending Topics

For this analysis, the top trending topics are the authors' keywords, which have higher average growth rate (AGR) over the others. These topics represent concepts that have a large impact on IoT research. To find these trending topics, two-year AGR time periods (2011-2012, 2013-2014, and 2015-2016) were found using the following Equation 2.1:

$$AGR = \frac{\sum_{i=Y_s}^{Y_e} P_i - P_{i-1}}{(Y_e - Y_s) + 1}, \tag{2.1}$$

where:
AGR = Average growth rate;
Y_s = Start year;
Y_e = End year;
P_i = Number of publications on year i.

Figure 2.9 shows the top eight trending topics with the AGR time periods. Cloud computing leads, with an AGR of 90 publications/year for 2015-2016, 284 documents on 2016, and a constant growth in all time periods. In 2013, Gubbi et al. mentioned that the integration of IoT with Cloud computing applications can enable the creation of smart environments such as Smart Cities and others [17]. The growth of publications about IoT related to Cloud computing shows that the mentioned integration is currently happening. The second trending topic on this list is security. This topic has a moderate growth in 2011-2012 and 2013-2014 periods (about 18 publications/years), but, in 2015-2016, its growth soared to 83 publications/year. Security backs the industry's concerns about the user privacy and confidentiality [254, 255]. The same way that the communications protocols were analyzed in this paper by layers, Jing et al. divided the IoT into three layers (perception, transportation, and application layers) to analyze features and security issues of each [256].

IoT is one of many applications of Big Data because the rapid growth of IoT devices further propels the sharp growth of data to be processed and analyzed [257]. Wireless sensors networks (WSN), such as RFID, is one of the most important technologies enabling the IoT [258]. Likewise, security/privacy is a trending topic and also a concern in IoT, which was well summarized in [259].

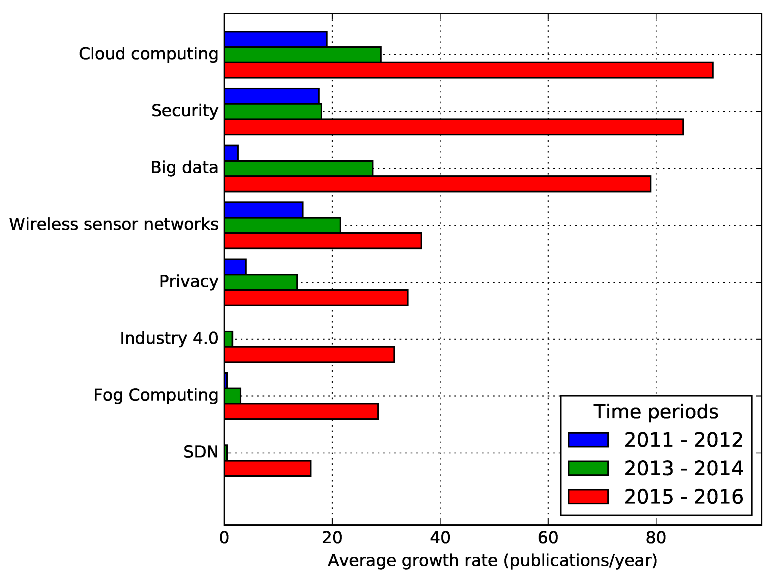


Figure 2.9: Internet of Things top trending topics based on authors' keywords, with average growth rate (AGR) for different times periods (2011-2012, 2013-2014, and 2015-2016).

Industry 4.0 is a new trending topic, without any growth in the 2011-2012 period, but with a sharp rise in publications from 3 to 66 in 2014 to 2016. Industry 4.0 includes the use of intelligent manufacturing processes, Cyber-Physical Systems (CPSs), and implementation and operation of smart factories [260]. This fourth industrial revolution aims to integrate IoT technologies such as remote control, manufacturing analytic tools and services, supply chains integration, and tracking and tracing inter- and intra-plant logistics [261]. Fog computing is also a new trending topic, with a small growth in 2011-2014 periods, but a large increase in the 2015-2016 period. Fog is a platform that provides compute, storage and networking services between end devices and cloud computing servers, most commonly, but not exclusively, located at the edge of network [49]. For IoT, this new platform is aimed to decentralize the data processing [262], decrease the latency [263], and bring more reliability for WSN [264]. Finally, Software-Defined Networking (SDN) is a novel concept for IoT, without any growth in the 2011-2012 period, but which was gaining popularity from one publication in 2013, and 2014, to 33 in 2016. SDN brings network routing intelligence via a centralized controller that connects to the network switch through the OpenFlow protocol [265], for example. This allows efficient node mobility [266], resource management [267], and improves the security of IoT networks [265, 268, 269].

2.5 Conclusions

A scientometrics review about Internet of Things was performed over a data set of 19,035 documents published during a period of 15 years (2002-2016) from two databases (Clarivate Web of Science and Scopus). A Python script called ScientoPy was developed to make a quantitative analysis of this data set, providing insight into research trends by investigating primary author's country affiliation, most published authors, and prevalence of various research topics. Using authors' keywords, the top research topics for IoT were found, including applications, communication protocols, software processing, hardware, and operating systems.

Analysis by country affiliation of the primary author shows a major increase in the number of publications for IoT in countries where the government has possibly implemented polices that improve the development of IoT. Similarly, this increase has shown in countries where private initiatives could have launched commercial low cost IoT networks (such as LoRa, Sigfox, etc.). In addition, prototype IoT infrastructure on small test environments, such as universities, creates microcosms that foster investigations for different IoT applications.

From 2014 to 2016, there was a sharp growth of smart environments including smart city, home, grids, and other surfaces with technology incorporating Big Data and cloud computing into IoT devices. Nevertheless, security [63–65] and privacy [75, 78, 79] are major concerns for many applications such as smart home and grid. Cyber-Physical Systems is an application that, when powered by the IoT, enables the targets fixed by Industry 4.0 [83]. Trends in communications protocols have changed in the last few years. The RFID publications sigmoid growth is on a stationary phase, while other media layer protocols such as BLE, WiFi, and 5G are on sigmoid growth exponential phase. Host layer protocols show a high growth rate for CoAP and MQTT. Software data processing demonstrates that the techniques designed to work with Big Data are growing on the sigmoid exponential phase for IoT data processing environments.

For operating systems, Android has become the most used OS for scientific researchers on IoT. This OS has been used for IoT gateways [211–214] and user interface in IoT devices [243, 244]. Contiki is growing in a sigmoid exponential phase with its integrated protocol stack and WSN simulator, Cooja. Similarly, in IoT research, Raspberry Pi and Arduino are the most popular platforms for learning and development. In addition, the combination is widely used wherein Raspberry Pi is an IoT gateway [228–230] and Arduino boards serve as edge monitoring devices [235–237]. Similarly, smartphones exhibit their versatility being used as gateway [240–242], user interface [243, 244], and sensing [238, 239] IoT devices. Meanwhile, FPGAs have exhibited a sigmoid exponential phase growth in the last two years, with applications such as data encryption [246–248], routing algorithms optimization [249], and parallel networks simulation [250].

Top trending topics demonstrate that cloud integration with IoT devices is enabling the implementation of smart environments. Nevertheless, security and privacy in these environments are important growing concerns for IoT researchers and industry. WSNs are one of the most utilized technologies enabling the IoT. Furthermore, Fog computing has emerged as a promising edge device to decentralize data processing, decrease latency, and bring more reliability for WSN in IoT. Likewise, research on Software Defined Networks (SDN) grew rapidly during the last year, offering more efficient nodes, mobility, resources management, and improved security of IoT networks. The related trending topics offer unique opportunities for IoT innovations and start-ups in pursuit of an efficient, secure, and reliable IoT environment.

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Enabling Densely-Scalable Wireless Sensor Networks for Shipping and Industrial IoT

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19 Oct 2017

Chapter 3: Enabling Densely-Scalable Wireless Sensor Networks for Shipping and Industrial IoT

Low-power technologies and communication protocols have enabled pervasive monitoring and the Internet of Things (IoT) for diverse applications. Yet, many wide-reaching use-cases such as shipping and industrial IoT (IIoT) demand next-generation energy-efficiency for wireless sensor networks (WSNs). The enormous growth requirements in this and related fields are not easily met by current state-of-the-art prototypes and comparisons are nontrivial among dozens of differentiating characteristics and impact factors. This work ideates a lightweight densely-scalable network of sensor nodes that must survive on a coin-cell battery for 15 days minimum, sending minute-to-minute alerts for remote analytics and control. This end-to-end solution enables status tracking throughout the shipping lifecycle with a quick-deploy WSN to detect damage/theft in near-real-time. This work contributes a scalable WSN (1) communication protocol, (2) software development kit, and (3) reference hardware. This full-stack system offers a self-configuring, customizable WSN for low-duty-cycle pervasive monitoring in a small, low-cost form-factor.

3.1 Introduction

As low-power wireless sensing gains popularity, a wide range of technologies have become available to satisfy diverse applications, yet designs still face challenges by many real-world deployment scenarios. Wirelessly connected, uniquely-addressable, autonomous devices are fundamental to the rising concept of the internet of things (IoT). IoT connects billions of devices to the internet for visibility and control, offering unforeseen solutions and challenges as the type and distribution of devices become more opportune and complex. Extensive research worldwide has led to continued standardization efforts to support the recent paradigm of low-power wide-area networks (LP-WAN) that are critically challenged by tradeoffs in connectivity, intelligence, and lifespan as networks grow larger and more distributed. In sensing and low-data-rate use-cases with more stringent design constraints, other paradigms are emerging such as low-rate wireless personal area networks (LR-WPAN) and software defined wireless networks (SDWNs) [13, 270].

Underlying each solution is a wireless sensor networks (WSNs) leveraging low-power hardware, energy-efficient software and protocols, and power management techniques [15, 271, 272]. Low-power computational hardware ranges from microprocessors, system-on-chip (SoC), microcontrollers, and others. State-of-the-art low-power communication protocols for bursty data include the Bluetooth Low-Energy (BLE) [273], ZigBee [274], and more. These distributed routing solutions aim to leverage channel hopping, reduce overhead of the IEEE 802.15.11 standard, and implement node-to-node communication for mesh and multi-hop routines [13, 273, 274].

However, existing distributed protocols can restrict scalability and demand greater radio activity than is feasible for dense low-power networks in dynamic scenarios [13, 15, 275, 276]. Further issues arise from the interdependence of software, hardware, and energy. For example, the ZigBee [274] PRO for mesh networks with a Contiki [218] operating system has a relatively large and complex software stack, demanding greater memory, processing, and energy from the hardware. Some alternatives to the popular 2.4 GHz embrace lower carrier frequencies and channel hopping for longer range, but require larger antenna and lower data rates. Research is underway to compare existing standards and SDWNs and gain insight to real-world deployments, such as those detailed in [13, 15, 270].

As evidenced by consumer electronics, industrial IoT (IIoT) has been recognized by industry leaders as a promising innovation, but the requirements for enormous growth are yet to be met. For WSNs to be successful in IIoT [270], the technology must exhibit

- minimized cost per unit
- optimized edge-node's energy consumption
- high network scalability
- wide network coverage

To be realistically adopted at large scale, the technology should also offer configurable granularity, compatibility with legacy systems and processes, and seamless handoff across the end-to-end (E2E) system. However, these dense short-range wireless systems deployed over large areas have inherent design tradeoffs that create differentiating characteristics, each effecting another, such as

- power consumption and lifespan
- density
- spectral efficiency
- delay tolerance
- coverage area
- uni-/multi-directional communication
- energy per byte
- memory footprint
- data rate
- quality-of-service (QoS)
- form factor
- cost of deployment and maintenance
- security

Existing solutions are segmented and suit small-scale consumer needs, yet exhibit costly overhead for next-generation, resource-limited, pervasive networks and densely-scalable IoT/IIoT. Complicating the decision is a culmination of demands for extremely low power, ease-of-use, compatibility, rapid-prototyping, and more. Thus, the complex use-case of shipping and IIoT guides this design for a near-real-time WSN whose nodes are

- provisioned opportunistically in a warehouse
- associated to an assigned network for transit

- observed in a managed mode during transit
- exposed to change-of-custody, theft, damage, etc.

This application-driven approach identifies a deterministic E2E solution for largely scalable, low-power WSNs. The contributions are a (1) dynamic communication protocol, (2)software development kit, and (3) reference hardware.

3.2 Design

This design yields a self-configuring, scalable, low-power WSN for 15 days minimum of pervasive sensing with a system of systems approach for integration to an end-to-end solution. The network is built on the IEEE 802.15.4 (15.4) standard for low-rate wireless communications such as IoT and sensing. Orchestrated by a coordinator node, the network in its simplest form employs a centralized star topology, in which edge nodes communicate directly to the coordinator as seen in Figure 3.1. Identifying edge and coordinator nodes in terms of a communication network, the Clients are equipped with sensors and communicate with the Server, which can then be connected to an internet-enabled gateway (GW). The star topology bootstraps development of this protocol to support tree and mesh topologies.

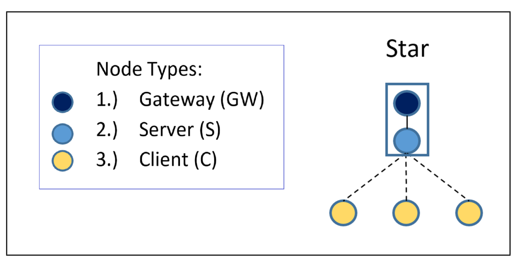


Figure 3.1: Star Topology

3.2.1 Channel

For scalability and coexistence, this design assumes Clients share a wireless channel with their Server/PAN coordinator, requiring a mechanism to minimize occupancy and interference. In smaller networks random scheduling is sufficient, however, as the number of nodes increases, traffic is prevalent and performance suffers from inevitable retransmissions [271, 275–277]. Rather here, the nodes transmit minimally at calculated, assigned time-slots using indexed time division multiplexing (TDM). TDM is deterministic, largely scalable and reduces collisions, but is challenged by synchronization [13, 275].

3.2.2 Time-Slots and Synchronization

This design assumes an n:1 Client-to-Server ratio on a TDM shared-channel, allowing n Clients to respond with alive/anomaly/data messages before the next beacon period. The time-slots are equally allocated intervals, avoiding collisions and formulating a deterministic network for scalability.

The TDM network depends on clock synchronization between nodes, which is difficult to maintain by nature. While timestamps and epoch-time are ideal, such references add complexity and cost. More simply here, each node uses timers/counters to coordinate operations.

However, typical MCUs depend on a real-time-clock (RTC) based on a crystal oscillator that inherently exhibits frequency drift over time. Furthermore, drift occurs on every node, yielding scenarios where a Client and Server may drift inversely. Thus, a guard band on radio activity forms a listening phase to mitigate offset.

3.2.3 Energy Levels

Many low-power MCUs exhibit at least three power configurations, typically ranging from high to low power consumption. The levels are employed according to operation: normal (0) with full function, suspend (1) powers down most hardware but retains data and state, and deep sleep (2) between activities to conserve battery.

3.3 Protocol

The Client and Server are roles (or node types) in the network, each operating across four states/modes: Provisioning, Association, Managed, and Recovery. Within and between each state, the node sleeps until triggered to wake by timer. These operation modes form a state machine whose transitions depend on local and network events. Executing minimal instructions quickly, and only as needed, prioritizes sleep to minimize duty cycle for longer lifespan.

3.3.1 Provisioning

In provisioning, the node is initialized with basic configurations to operate and join the network for association. At minimum, each Client needs a small unique ID, Server ID as destination, and Channel ID to which it should associate. Yet, the network is chaotic until the clocks are synchronized and nodes are assigned relative time-slots to listen/speak.

3.3.2 Association

After provisioning the Clients must associate to the Server, which rapidly broadcasts an Association Beacon with a TDM bitmapped sequence of all network Client IDs in the assigned order until all nodes respond in their slot. Figure 3.2 is a brief example with AB header and TDM bitmap that assigns Slot ID 3 for Client 0x0103 (read right-to-left) on a 3:1 network.

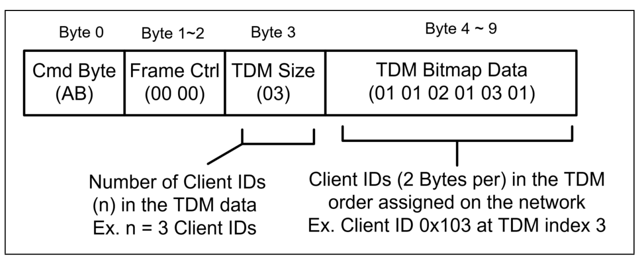


Figure 3.2: Association Beacon Example

Each node frequently wakes up to listen for the Association Beacon, upon which the Client synchronizes its timers, retrieves its Slot ID from the TDM bitmap, and responds in its slot. In this manner the chaotic network resolves into an organized TDM network. Completing this process quickly is imperative to longer battery life.

3.3.3 Managed

Managed mode uses periodic micro- and macro- frames as beacons to (1) synchronize the network and (2) exchange information, such as sensor data, configurations, or instructions. Each micro-frame (T), the Client sends a heartbeat/alive message, or anomaly data if any occurred since the last report. With similar structure, the macro-frame (kT) reports sensor anomalies and in-range samples for analytics.

In Figure 3.3, two Clients experiencing drift listen simultaneously for the beacon, and then respond in their respective time-slots.

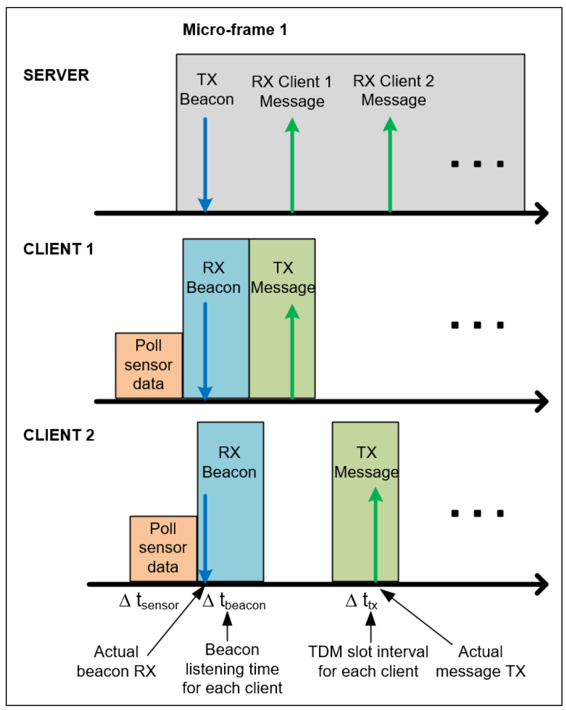


Figure 3.3: Channel Occupancy

3.3.4 Recovery (Client)

If a Client node loses synchronization or connectivity with the network, it moves to Recovery mode. Similar to Association, the Client wakes up more frequently to capture the beacon while the Server drives the network in Managed Mode.

3.3.5 Packet Structures

Packet size depends on the type of payload as indicated in the frame header. Table 3.1 shows the types of Server messages, termed beacons, and their general purpose. Depending on the type of beacon received, Clients will send one of the message types outlined in Table 3.2. Downstream and upstream messages are broadcast and unicast, respectively.

Table 3.1: Downstream Messages (Server-to-Clients)

Message Type	**Purpose**
Association Beacon	(1) Synchronize (2) Provide TDM assignments
Regular Beacon	(1) Synchronize (2) Basic maintenance
Next-is-Macro Beacon	(1) Synchronize (2) Indicate/force macro-frame next
Configuration Beacon	(1) Synchronize (2) Request Client(s) update configurations
Calibration Beacon	(1) Synchronize (2) Request Client(s) to recalibrate sensors

Table 3.2: Upstream Messages (Client-to-Server)

Message Type	**Purpose**
Micro-frame message	(1) Alive/Heartbeat (2) Report anomaly event(s)
Macro-frame message	(1) Alive/Heartbeat (2) Report anomaly event(s) (3) Report in-range/baseline samples

3.4 Software

This platform-independent WSN SDK was designed in C using an Eclipse IDE with a proprietary plug-in and driver source code BSP, provided by the manufacturer [278] for the selected TLSR8646 MCU. The BSP provides basic libraries for system boot, compiler, serial communication via I2C and SPI, and similar enabling elements of the stack. Together, the BSP and WSN SDK offer a compact full-stack solution for a low-power MCU-based sensor network with:

- Minimal transfer, access, or knowledge among modules
- Pointers rather than knowledge of contents/organization

The WSN SDK stack was divided by functional responsibility into five modules: Common, Main, Server, Client, and Sensor. The firmware and adaptation/application was approached as plug and play architecture for IoT low power devices [14]. This modular approach allowed independent development and testing prior to full integration.

Table 3.3: Software Module Descriptions

Module	**Location**	**Description**
Main	Server/ Client	Contains the main wireless network application loop; calls Server/Client module
Common	Server/ Client	Common definitions, functions, and structures shared between modules such as frame headers and buffer allocation
Server	Server	Tasks as PAN coordinator of the wireless network with Clients and wired communication toa GW, tracks status and sends alerts
Client	Client	Client tasks on the wireless network such as message transport, time synchronization, and recovery
Sensor	Server/ Client	Sensor tasks to interact with drivers to access buffers, detect anomalies, form packets, and handle events/interrupts

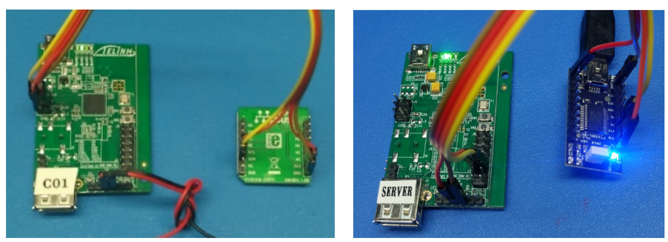
3.5 Hardware and Testbed

This implementation validates the WSN protocol in lab trials, assuming identical COTS hardware on the Client and Server nodes for practical introduction to the current assembly line. The main hardware testbed is summarized below for a n:1 Client-to-Server WSN, where each Client node used an evaluation board for a light sensor and the majority also had humidity, temperature, and pressure sensor evaluation boards. To validate synchronization and TDM channel behavior, a logic analyzer captured the wake-up signals of six Clients, Server power, and Server receive-message-flag pin.

Table 3.4: Basic Testbed Components

Component	Description
C1T80A30_V1.0 TLSR8646	MCU EVK
MIKROE-1903 OPT3001	Light sensor EVK
MKI141v2 HTS221	Humidity/temperature EVK
MET001v1 LPS22HB	Pressure sensor EVK
CR2430 3.3V Coincell batteries	Power supply
C1T53A20_V2.0 TLSR8646	MCU Programmer EVK
FT232RL-BO USB to UART	Adapter to GW simulator

Once programmed, the node is provisioned to associate with the network on power up. With minor modification, a single-sensor Client can become a multi-sensor node or Server. The Server communicates via UART with a cloud-connected GW, which can be emulated with a UART-to-USB adapter to a PC and validated with a serial monitor, 15.4 packet sniffer, and a GW simulator.



(a) Single-sensor Client (b) Server to PC (as Gateway)

Figure 3.4: Client and Server nodes using evaluation boards

3.6 Results and Discussion

The following verifies the resolution of a newly provisioned network from the chaotic state to a deterministic, synchronized behavior through Association. Figure 3.5 shows two Client nodes waking to listen, and once the beacon (top pulse) is received they know their TDM slot and respond as assigned.

In Managed mode, the network was stable and used the TDM assignments correctly, allowing the nodes to sleep for the vast majority of each frame. Each Client woke up on

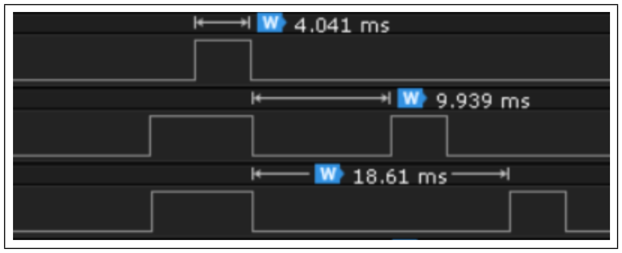


Figure 3.5: Association Beacon and alive responses in Association

(drifted) schedule to listen for the beacon, sent from the Server at the rising edge of the top row in Figure 3.6. The Clients sleep upon receiving the beacon and respond in their interval, and the data is received by the Server at the TDM intervals (second row).

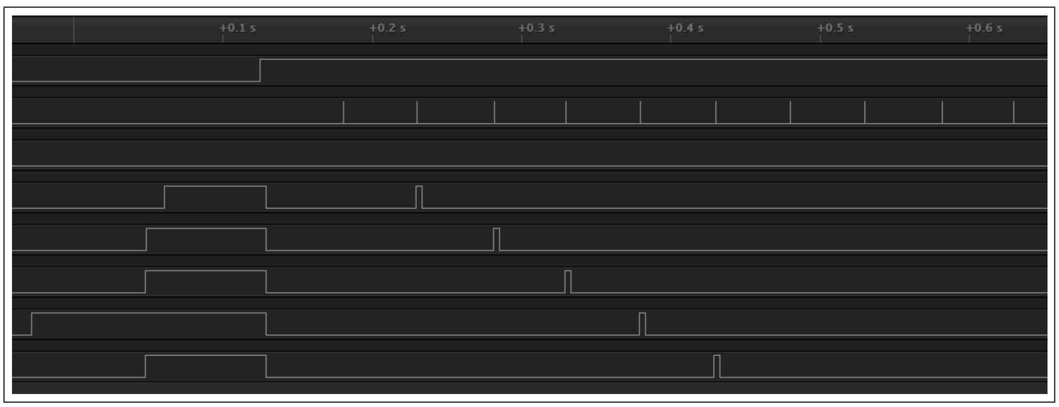


Figure 3.6: Regular Beacon from Server and Client alive/data responses

This experiment assumed synchronization every 60 sec and generous beacon listening phase of 50 ms to accommodate for possible reasonable drift experienced depending on implementation. The Client current profile for Managed mode is shown in Figure 3.7, wherein current values are relative to the maximum consumption of the Client's Managed activities, labeled A-D. The overall Client and Server activity in Managed mode is summarized in Table 3.5 emphasizing the sleep-centric protocol design.

A lifespan experiment was conducted for an n:1 network with an aggressive schedule of 2 sec and 10 sec micro- and macro-frame, respectively, shown in Figure 3.8 tracing five nodes. The curve fits a typical lithium-ion battery discharge model, and supports an estimated lifespan for a Client largely surpasses the original goal of 15 days with 60

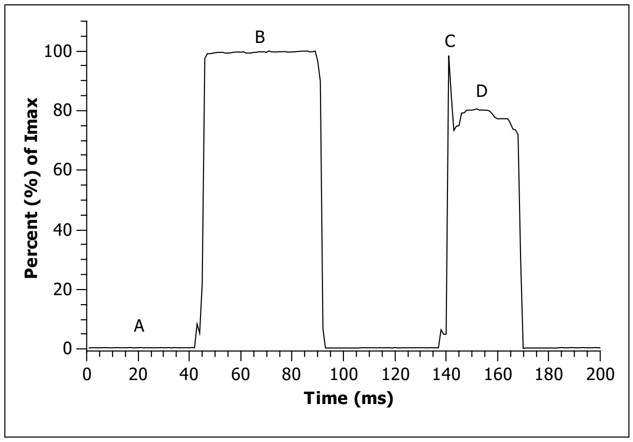


Figure 3.7: Timing and current consumption profile for a Client node in its Managed State

Table 3.5: Client and Server Activity in Managed Mode

Activity	**Time (ms)**	**Percent (%) of T = 60 sec**	**Percent (%) of Imax**
Client			
A - Deep sleep	59945	99.908	0.107
B - Listen for beacon	50	0.083	100.00
C - Send message	5	0.008	92.47
D - Collect/poll sensor data	23	0.038	76.43
Server			
Deep sleep	5700	95	0.107
Send beacon	6.4	0.011	92.47
Receive client data ($n = 50$)	2500	4.167	100.00
Admin processes	493.6	0.8227	76.43

sec anomaly reports and 15 min baseline data.

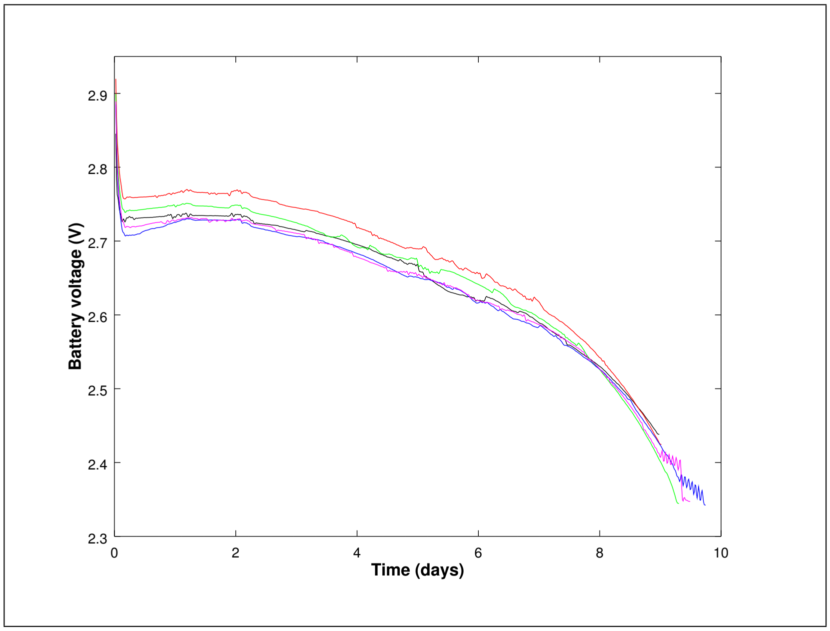


Figure 3.8: Lifespan experiment showing battery voltage for Clients on a rapid 2 sec micro- and 10 sec macro-frame schedule

The overall success of this protocol design bootstraps the development of a densely-scalable WSN with improved connectivity, performance, and extend lifespan, despite the increasingly active wireless environment. For example, this project implemented a generous beacon listening phase in the experiment, but will next explore drift mitigation and mechanisms to theoretically reduce the footprint by up to 90% with techniques such as wake-up radio (WUR) using an ultra-low-power wake-up receiver (WURx) [275].

Furthermore, relays and mesh behavior would improve connectivity in extremely challenging scenarios but at the expense of power/lifespan. Delay tolerant network (DTN) schemes are also a necessary feature, yet demands greater memory per device for roaming periods and more transmissions once in range, each of which are power-hungry operations. Compressive sensing/sampling (CS) offers great promise to such applications for reducing stored and transmitted data by exploiting redundancy, correlation, and trends of the samples.

Also notable is that the receive and transmit current consumption and timings in this experiment are dependent on hardware implementation. However, the computational activity for polling/collecting sensor data is an area of improvement to the architecture. For example, the data layer could be employed such that algorithmic computational tasks are largely offloaded to external pattern matching filters or ultra-low-power FPGA modules. Other relevant technologies engaging the broader end-to-end (E2E) architecture, such as supervisory control and data acquisition (SCADA) systems with resource- and load-balancing algorithms, could dynamically identify optimal topologies in response to trends and forecasts [15, 279].

3.7 Conclusion

This work presents an E2E solution with a novel approach to low-power, low-duty-cycle sensing nodes for applications such as shipping and the IoT. With details on design and implementation, this work identifies a (1) dynamic communication protocol, (2) software development kit, and (3) reference hardware. This design offers a rapid-deployable, self-configuring, scalable wireless sensor network for low-duty-cycle pervasive monitoring in a small, low-cost form factor. Successful validation with low-power hardware and debugging tools support these contributions.

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Weaving the Wireless Web: Toward a Low-Power, Dense Wireless Sensor Network for the Industrial IoT

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Chapter 4: Weaving the Wireless Web

Wireless sensor networks (WSNs) combine sensing, computation, and communication for automated data collection, processing, and telemetry. WSNs use spatially distributed devices for applications in which scalable connectivity and energy efficiency are increasingly important. Thus, WSNs are a key technology for the Internet of Things (IoT), whether consumer and industrial, connecting billions of devices over the Internet for applications including health care, transportation, process analysis, and environmental assessment, to name a few. However, wireless connectivity comes at the expense of power.

Many WSN applications use small battery-operated sensors on a local network, with a gateway (GW) to provide intranet or Internet access. The frequent operation of sensors, especially radio transceivers, significantly impacts battery life. Also, resource-limited "set-and-forget" scenarios exacerbate the technical challenges for WSNs, with sensors expected to operate reliably for long periods without battery replacement. Dynamic conditions, harsh environments, and increasingly saturated wireless frequencies intensify the need to improve scalability and minimize battery usage.

4.1 WSNs, the IoT, and the IIoT

The IoT paradigm of connecting "things" to the Internet presents application possibilities in at least two major sectors: the consumer and the industrial. In both cases, the IoT combines operational and information technology to connect the edge with cloud services. On closer inspection, the Industrial IoT (IIoT) offers a multibillion-dollar opportunity for efficiency and accountability through connectivity and data analytics. Dubbed the Fourth Industrial Revolution, the IIoT offers transformative solutions but poses extreme use cases for WSNs, with heavy constraints on power, form factor, cost, and performance.

For example, logistics and asset management (LAM) demands next-generation energy efficiency from edge network hardware, software, and power control. Inexpensive sensor devices must survive on a coin-cell battery for weeks or months, while providing minute-by-minute sensor updates and alerts for remote analytics and control during transit.

Shipping in the IIoT is a complex use case, exposing electronics to both routine and unpredictable behavior (see the example in Figure 1) in a dense, wireless environment that may include thousands of sensors on dozens of pallets.

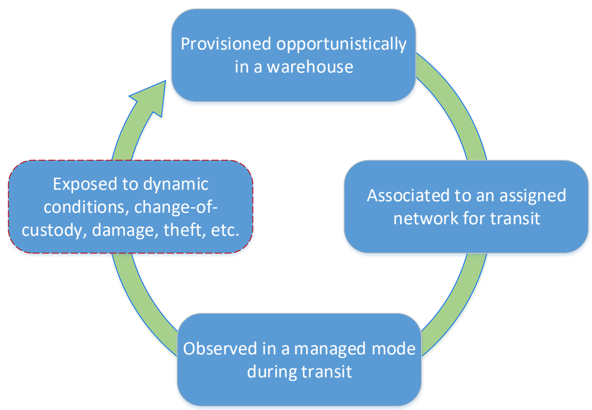


Figure 4.1: Sensing devices must endure complex life-cycle events in LAM.

Global logistics is one IIoT use case, with a US$8 trillion market in 2016 ramping up to US$10 trillion by 2020. However, billions of dollars are wasted annually due to inefficiencies in the market. Shipping is a nuisance, and the money spent here is an overhead for the shipper.

In excess of 20 billion packages were damaged, lost, or delayed in 2016. US$60 billion worth of economic value was lost due to theft, and 30% of perishables worldwide fail to reach the fork from the farm. Despite such massive pain points, which have been around for decades (and to such an extent that many have lost their lives as a result), technology has not been able to significantly impact these trends. Many market reports suggest that the IIoT is the answer.

Real-time visibility of package location and condition can significantly improve early detection and mitigate damage, theft, and spoilage. Critical asset health occurs at the package level rather than at the pallet or freight level. Existing technologies use long-range cellular radios (which are neither cost- nor size-effective) to deploy billions of packages. Some shipping technology exhibits the unique problem of “end of life,” i.e., the tracking of intended activity from source to destination only; hence, the tracking equipment must be “disposable” (i.e., refurbishable) to avoid reverse logistics and related expenses. Low-cost, low-power short-range radio is a cost-effective solution that can be deployed at the package level, but it has not yet been synthesized.

Short-range radio, by definition, is limited in range. With the help of neighboring radios, a power-efficient WSN extends this range to transmit data to a GW that, in turn, uploads the data to the cloud via a long-range radio for remote monitoring and visibility. Low-power, lowcost sensing tags attached to the packages can thus collect sensor information—such as temperature, humidity, shock, vibration, tilt, and proximity—and upload the data in packetized form to the cloud via the GW. Akin to cell towers, the GW can be a permanent installation on transport modalities and in warehouses. The tags, similar to cell phones, can leverage the network of GWs to maintain package visibility.

Furthermore, WSN techniques can extend to many other use cases in the supply chain. For example, WSNs can track the condition of wagons attached to a locomotive, thus automating inspection and reducing labor and time. The network can be used to track containers on a barge for ocean freight. Additionally, triangulation of the tags can aid in locating assets within a warehouse. For temperature-controlled goods, the tags can be used to log data and store and upload the digital history of the product. A power-efficient mesh of networked sensors at the package level will bring unprecedented improvements to visibility and efficiency in LAM. Besides LAM, some IIoT data collection schemes, such as those in manufacturing or agriculture, require covering large geographical areas. Widely distributed sensing applications, in particular, seek sustainable wireless access with optimized data flow and maximized system lifetime.

Clearly, WSNs are a popular and versatile technology for the IoT, enabling yet-to-be-discovered solutions and offering a research playground for industry and academia. Design and implementation are increasingly active areas striving for ultralow-power mobile sensing devices. In fact, cloud computing and services, mobile solutions, and the IoT are the top technologies expected to shape the near future (three to five years), as shown in Figure 2 [11].

The challenges addressed by researching WSNs in the IIoT translate to certain use cases that spur innovative solutions in existing as well as upcoming fields. Irrespective of application, evolving IoT use cases demand physically smaller operational devices with an extended life span and better connectivity, despite limited processing, storage, and battery capacity.

The energy-data tradeoff in WSN design is unavoidable. The question has shifted from “can this be done?” to “how can this be done efficiently?” and so satisfy evolving demands. Improved performance is achievable with careful hardware selection, architecture and operation, power management, and other techniques.

However, a one-size-fits-all answer likely does not exist, especially for densely packed wireless areas where most devices are within range of other transmitting devices. While many designs are available (several well accepted for small-scale deployments), they all suffer limited life span and lack customization of duty cycle and scalability. Nevertheless, demand is rapidly increasing for large-scale customizable solutions to satisfy high-volume IIoT applications, in which batteries are recharged much less frequently than in consumer use cases. IIoT use cases are driving research for densely scalable sensing and communication protocols capable of deploying at a low cost and in a small form factor.

Aside from proof-of-concept designs, industrial monitoring systems still face challenges in terms of data and power management, miniaturization, scalability, usability, standardization, survivability, and more. Each of these individual areas can involve extreme constraints. For example, survivability may impose strict design features related to power consumption and life span (or ruggedness). The devices must be able to withstand operating conditions that may be cold, hot, dirty, wet, and/or humid; along with misuse, such as drops on concrete from, e.g., forklifts, these requirements far exceed those of standard consumer electronics (CE) devices.

As a response, this article highlights existing technologies and challenges prevalent in the IIoT as related to scalability. We also introduce an application-driven approach to identify a framework for a largely scalable, low-power WSN in the context of asset tracking (Figure 3). This WSN enables an enterprise-to-enterprise (E2E) solution for packagelevel monitoring throughout the shipping life cycle, with a quick-deploy sensing system for damage/theft detection in near real time. Focusing particularly on scalability and an ultralow duty cycle, we detail a sensing and communication scheduler/protocol for low-rate wireless personal area networks (LR-WPANs) compliant with IEEE standard 802.15.4.

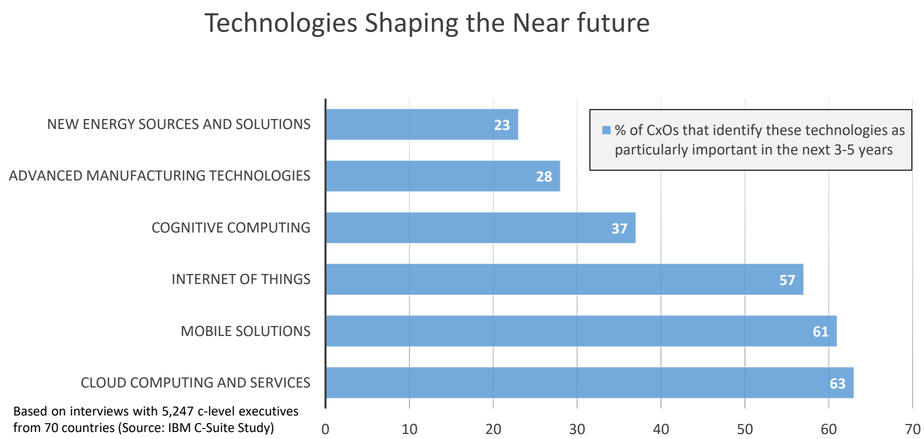


Figure 4.2: Cloud computing, mobile solutions, and the IoT are expected to shape the near future. CxOs: corporate executives at the "chief" level (C-level), e.g., chief executive officers and chief operating officers.

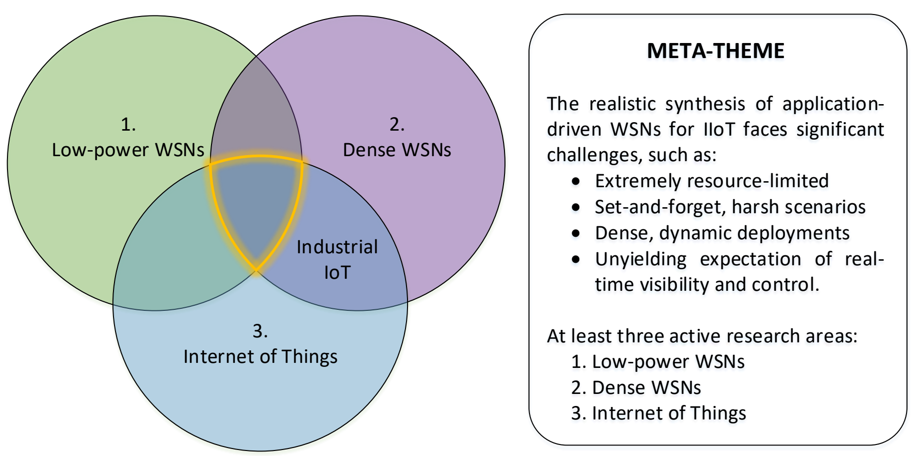


Figure 4.3: A representation of dense and low-power WSNs in the IoT as a meta theme encompassing large, evolving research areas for the IIoT.

4.2 Asset Tracking: IIoT Network Synthesis

Extensive research is underway around the world to understand and define rapidly evolving state-of-theart requirements for next-generation IoT technologies in wide-ranging applications, such as those for the IIoT. Driving this research are several recent paradigm shifts in WSN technology, most notably low-power wide-area networks (LP-WANs) and LR-WPANs, as they relate to the IoT and infrastructure. In this discussion, we focus on dense, low-power mobile WSNs for the IIoT, constrained by extremely limited resources, low data rate, and short-range wireless at 2.4 GHz for international adoption.

A thorough analysis is detailed in [270]for traditional WSN technologies, discussing how each "classic" solution fails in at least one of the following enormous growth requirements:

- minimized cost per unit
- optimized edge node energy consumption
- high network scalability
- wide network coverage.

Arguably, another requirement that should be analyzed is the seamless integration between LR-WPAN and LP-WAN technologies for end-to-end connectivity deployable in legacy industrial scenarios. In addressing these requirements, commercially available technologies exhibit differentiating characteristics, each negatively impacting another. These include

- life span
- density and scalability
- spectral efficiency
- delay between reports from edge to sink
- range
- uni-/bidirectional communication

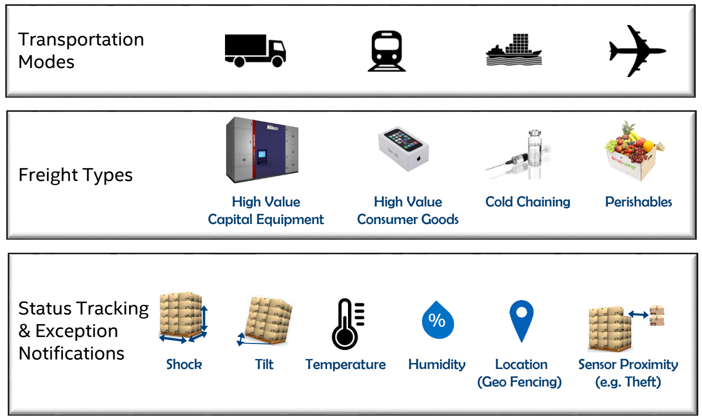


Figure 4.4: The IIoT brings tracking and alerts to LAM across diverse transportation modes and freight types.

- power consumption
- energy per byte
- memory footprint
- data rate
- quality of service
- form factor
- cost (approaching "disposable").

Significantly affecting these differentiating characteristics are several design impact factors, most recognizable at the high level of hardware, software, and power management. For example, the operating system, communication protocol, sensing algorithm, configurations, and deployment can each compromise one or many of the characteristics to improve others. Thus, the key challenges in meeting the requirements for enormous growth [270] in dense, lowpower mobile WSNs for the IIoT include

- management costs

- network organization and dimensioning
- power efficiency
- coverage area
- service reliability
- security
- deployment costs
- integration with existing infrastructure.

As of now, LAM still needs a densely deployable solution applicable across transportation modes with diverse freight types, such as those shown in Figure 4. The E2E visibility of shipments at the package level could significantly improve supply-chain operational efficiency and productivity. This is possible with the deployment of mobile sensor nodes, GWs, and dashboard/analytics support. Cloud connected GWs and their hosted sensor nodes would travel with shipments to continuously monitor environmental and location data throughout the logistics pipeline. LAM companies view this technology as a clear opportunity for a suite of services, such as

- tracking the condition of high-value, high-impact products at custom schedules
- flagging and tracking losses, errors, etc.
- redirecting inventory/shipment based on trends or optimized routes
- lessening recall (improving safety), reducing waste, etc.
- reacting quickly to market needs and changes
- improving efficiency based on increased predictability (forecasting)
- automating tasks and removing obsolete tasks (operational efficiency).

4.2.1 Network Synthesis

E2E visibility in the IIoT today is predicated on one primary tenet: alert by exception. These notifications are sent in near real time to subscribed users, and, while valuable, the process is limited to sharing the data only after they have breached a predetermined threshold. In many commodities (health care, food, and so forth), this can render the

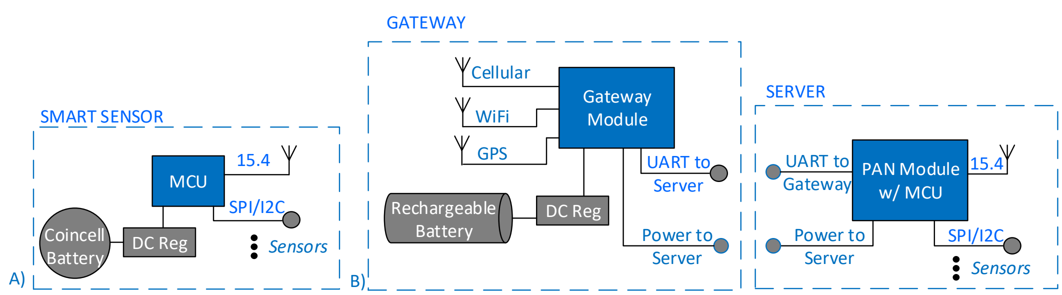


Figure 4.5: Block diagrams of (a) an SS module for a client node on the WSN and (b) a GW module and a server module for a server node or unified GW server device. Reg: regulator; SPI: serial peripheral interface; I2C: inter-integrated circuit; UART: universal asynchronous receiver/transmitter.

product unsellable. Future solutions must include opportunities to alert carriers when the system is trending toward a breach of that predetermined threshold, allowing an opportunity for meaningful intervention.

The sensing devices (termed client nodes) should have a lightweight form factor, along with so-called smart sensor (SS) tags for field use. Shown in Figure 5(a), each tag has a low-power microcontroller unit (MCU) with an embedded RF front end, an assortment of sensors, supporting circuitry, and a coin-cell battery. The SS tag design allows data to be assessed independently or coupled with another sensor metric to facilitate a specific command. For example, using the accelerometer, tilt (as its own metric) can be valuable in logistics to indicate whether a package that must stay upright has exceeded its variance. Tilt is a very common parameter for medical supplies sensitive to mixing or disruption, as well as for industrial tools that must not exceed a particular angle. If tilt is coupled with the pressure sensor, an inference can be made as to when an airplane is ascending or descending and then trigger the hardware to enter or exit airplane mode, respectively.

The central coordinating device of the WSN (termed the server node) can use the same basic components as the SS tags, with the addition of a physical wire communication with the GW device. The server is a PAN module adjacent to the GW, which can be implemented as a unified form factor for the field. The GW should contain an MCU, multiple RF modules [Wi-Fi, cellular, and near-field communication (NFC)] as a multiple-input/multiple-output (MIMO) hub,a battery, and supporting circuitry. With greater responsibility for connecting the edge to the cloud, the GW requires an MCU capable of larger processes and infrastructure than the WSN devices. Block diagrams of the server and GW are shown in Figure 5(b). Figure 6 depicts conceptual designs of the field-deployable form factor. A GW-to-cloud wireless interface completes this realization of an E2E technology solution.

Also, because this WSN has been developed with a uniquely challenging and scalable user experience (UX) in mind, it is widely applicable on even a small scale. A diverse range of usage scenarios can be accomplished with a single device type, simplifying stockkeeping-unit (i.e., SKU) management, infrastructure, and IT overhead. It can also be quickly adapted to specific UX needs on demand.

4.2.2 WSN Features and Usage

Developing a small form factor with an extensive energy budget that can withstand extreme environmental conditions and also be attached to any substrate presents industrial design challenges. Also challenging is the creation of an interface that is easily comprehended by users everywhere, no matter their language or technical proficiency. Ultimately, features must be winnowed based on these rigid requirements.

The primary interactions between users and devices occur during provisioning or shipment set up. Thus, device features must support this workflow effectively and communicate success or failure to users at each step. This workflow normally takes place in a warehouse or large industrial facility, and this constrained environment necessarily impairs cloud connectivity. The user must receive confirmation that the nodes were paired to the GW in order for journey data to be delivered to the cloud. Leveraging accepted, global CE norms for feedback and iconography reduces ambiguity and accelerates adoption. Multicolor light-emitting diodes (i.e., LEDs) can then support onscreen displays

(a) (b)

Figure 4.6: The conceptual designs for (a) field-deployable SS tags and (b) a unified GW server device. LCD: liquid crystal display.

coupled with audible feedback.

Figure 7 shows a detailed example of the workflow for a realistic distribution scenario in which shipments may experience a series of point-to-point journeys with changes of custody at each exchange. This complex life cycle requires careful design to facilitate cooperation across freight types, entities, and countries.

4.2.3 Overview of Low-Power WSNs and the IIoT

Low-power WSNs are not a new technology, having enabled pervasive and distributed sensing across applications for decades now. However, the dependency on energy and form factor limits widespread deployment of resource-limited sensor tags in dense, highly dynamic environments and scenarios. A plethora of literature is available regarding the design and implementation of WSNs encompassing a range of energy-efficient techniques from both general and applied perspectives. Advances in automated data acquisition, signal processing, and communication technologies have enabled improved performance for WSNs under a variety of constraints. The description in [280] goes further, outlining the growing importance of WSNs in the development of cyberphysical systems for applications in health-related, industrial, and environmental monitoring.

While terminology varies widely, a typical WSN in the IoT comprises sensor nodes, relay nodes, and GWs (also referred to as data sinks or base stations). This basic hierarchy is shown in Figure 8, along with trends in terms of mobility and performance at different levels.

The sensor node of a WSN typically contains a sensor, a digital controller, memory,

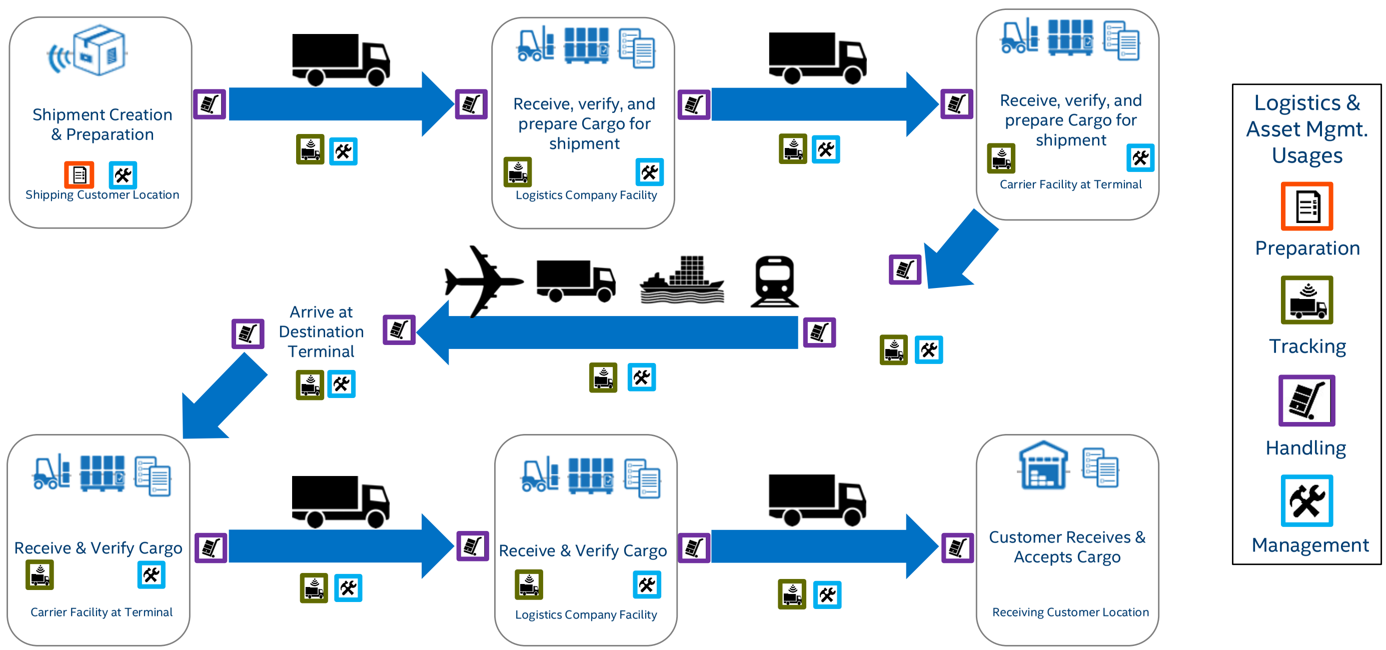


Figure 4.7: A realistic usage scenario taking the WSN through a complex life cycle.

a wireless transceiver, and a battery. Devices (or "things") collect data from one or more sensors on a defined sampling scheme, then process and store the data until a connection is made with a relay or GW. The data message is packetized, modulated, amplified, and transmitted to a relay (if used) or GW, where it may undergo further processing. As data sinks, the GWs are responsible for aggregating data received from nodes and relays, monitoring network status, and archiving data on a larger-capacity storage. For web services, WSNs benefit from satellite or cellular network connectivity, where available, at data sinks. However, power consumption remains a critical constraint

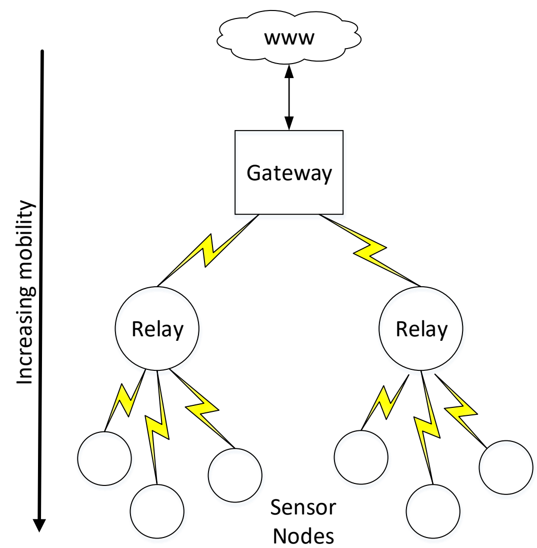


Figure 4.8: The basic WSN components showing trends regarding mobility and functionality.

across WSN application domains, driving developments in energy-efficient solutions from the device through the network levels. Power demands and constraints vary depending on the design and implementation of hardware, architecture, functionality, operation, and management. The nodes' energy consumption must be reconciled with the WSN's objectives, which can affect data volume, quality, and strength as well as the frequency of data transmitted/received.

The energy consumption of sensor nodes can be significant, depending on system state: the idle, sense, process, communication, and sleep modes of operation. The sensor node energy model presented in [280] considers the power consumption of a component/node during its active state and its sleep state, with an eye toward reducing the activity time and thereby extending the functional lifetime of nodes. Energy consumption of a node is expressed by (1), where P_{Oni} is the power consumption by the node when it is working and P_{Sleepi} when it is sleeping [280]:

$$E_u = \sum_i P_{Oni} x T_{Oni} + \sum_i P_{Sleepi} x T_{Sleepi} \tag{4.1}$$

Power consumption is much lower in sleep mode, encouraging low duty-cycle designs to save energy:

$$P_O ni \ll P_S leepi. \tag{4.2}$$

Detailed in [281] are the energy consumption and expected lifetime for a node in a disruption-tolerant system, wherein mobile nodes collect and transmit data to static nodes. These include power consumption measurements and activity durations per component, as well as delivery rates and bandwidth consumption for various routing protocols. The power-usage effectiveness (PUE) described in [15] uses real-time energy consumption measurements and performance metrics to improve efficiency in data center WSNs. The decision to collect, process, or transmit data affects the energy available for later operations. Thus, management techniques have been developed and continue to be optimized across applications.

4.3 WSNs in the IIoT

Advances in automated data collection, signal processing, and communications have propelled efficiency by providing monitoring solutions at high spatial and temporal resolutions. Many innovations in WSNs for asset tracking derive inspiration from and, in return, influence technological advances in surveillance, biomedical, and other discipline areas.

Typical IIoT sensor networks exhibit greater design constraints due to prolonged deployment in harsh or remote environments across large areas without access to grid power. Designs are further challenged in use cases involving detection or tracking of mobile sensor nodes, where the majority of sensors may be exchanging data packets within each other's communication range. Thus, many industrial applications require intelligent design of the sensor nodes and WSN from the ground up. This cohesive design process includes architectural tradeoffs in performance, cost, and energy consumption for a given life span. The constraints and challenges common to IIoT WSNs are summarized in Table 1, most notably the establishment of long-term wireless access with a densely packed network in a noisy RF environment.

An ideal IIoT WSN would collect and transmit data continuously with no loss of power, connectivity, or availability. However, dependable access to adequate power for such pervasive monitoring is not currently characteristic of asset tracking and the IIoT. Improvements in low-power components, intelligent monitoring techniques, and harvesting technologies have extended system lifetime, resulting in the development of efficient, inexpensive, and lightweight control platforms that offer adaptable power management and wireless connectivity methods.

The harsh wireless conditions associated with dense WSNs cause concern for outages, failures, and errors at the sensor node and network level. Researchers have responded with error detection and correction in WSNs. The need for real-time adaptive automated data quality control in environmental WSNs is delineated in [282], which proposes a dynamic model to detect anomalies (faulty observations) and assign values based on prediction.

4.3.1 Energy-Efficient Hardware

Low-power devices require low-power hardware and design of low-leakage architectures around the powerhungry processor or MCU. For example, consider a delaytolerant network developed for data download from a mobile device to a nearby static node. The hardware in [281] exceeds the functionality of existing solutions, reducing power consumption through the development of a custom network protocol implemented on an MSP430 low-power MCU and a TI CC2420 low-power transceiver. The TI CC2530 is a widely used system-on-chip (SoC) for low-power sensor data collection and transmission [15]. It includes a dynamic-range programmable transceiver, an industry-standard enhanced MCU, programmable flash memory, RAM, and other useful features. The SoC supports many recognized low-power communication protocols. A WSN GW implemented on a Galileo platform is detailed to demonstrate how to gather and compress data from many

TABLE 1. The constraints for an integrated system.			
Constraint Type	**Ground-Based Sensors**	**Mobile-Based Sensors**	**Satellite Remote Sensing**
Spatial	• Node observes phenomena in close proximity only • Limited distance between nodes for radio communication	• Variable distance from sensor to static WSN or availability of nearby nodes as relays	• Pixel size of data versus extent of desired data • Extent of images covering item movement
Temporal	• Energy availability and communication bandwidth	• Energy availability and communication bandwidth	• Availability of images suitable to inquiry • Acquisition frequency restricted by orbit and clouds • Timing of images • Timely data access
Logistical/ contextual	• Maintenance • Changes in sensing configuration • Other effects, i.e., shadows • Destruction • Cost versus benefit	• Battery life versus sampling frequency • Attaching sensors to items • Maintenance • Size of data sets and processing times • Destruction • Cost versus benefit	• Suitable wavelengths for observation • Seasonal calibrations • Size of data sets and processing times • Cost versus benefit

Table 4.1: The constraints for an integrated system.

subnetworks for transmission to the data sink [15].

Also, for a typical WSN node, the transceiver is the most energy-demanding component when compared to the sensors, digital controller, and memory [280, 283]. The need to simultaneously minimize the operating power demand and the energy consumed per bit is detailed in [283], preceding the presentation of an ultralow-power super-regenerative receiver.

However, there are notable data collection schemes in which the transceiver is not the most power-hungry component in the sensor node, such as cameras or gas sensors. Surveillance applications intensify power constraints with prolonged operation of such energy demanding sensing and processing components. Thus, advances in complementary–metal-oxide-semiconductor image sensor technology and microcontrollers guide the low-power design in [284] for the case of a wireless image-sensor network (WISN) in distributed outdoor deployments.

4.3.2 Energy-Efficient Architecture and Operation

A common approach to WSNs is the establishment of a tiered architecture made up of sensor nodes, relays, GWs, and data sinks. As an example, the application-driven design in [284] employs infrared image-sensor nodes scattered in an outdoor monitoring area to form a WISN. Neighboring sensor nodes may transmit images via a multihop route to a sink node, avoiding energy-consuming long-distance transmission from each sensor node. The sink node would regularly connect to the cellular network to transmit data to the base station (server) for storage and processing.

An energy-efficient approach to time-bound sensedata collection for the applied domain of data center management is presented in [15] and [279]. Improvements in performance, energy, and cost require pervasive monitoring of site-wide environmental parameters, such as temperature and humidity, that influence system performance. This WSN technique uses the measured realtime energy consumption and calculates the PUE toward automation in adaptive load-and-resource balancing. The WSN infrastructure improves data yield by employing machine-learning algorithms to optimize channel allocation and data flow. A channel-fitness function is defined to assign subnetworks, and a route-fitness function helps evaluate possible paths to deliver data from sensor to sink.

Assuming a highly dynamic environment, the design in [279] uses a genetic algorithm (GA) approach to identify subnetworks of randomly deployed sensors with the goal of establishing an optimal number of noninterfering independent subnetworks. The received signal strength index (RSSI) information is used to map the coordinates of sensor nodes via a multilateration localization scheme to determine proximity patterns among sensor nodes. This characterization of sensor nodes allows for different levels of communication hierarchy based on each node's measured ability to communicate with its neighbors. The allocation of noninterfering channels to sensor nodes and then further assignment of nonconflicting channels to each subnetwork reduces interference and the average density of the network. An intelligent data collection protocol delivers uniform data collection timings with minimum channel interference.

The power requirement for some sensors, such as those for video or gas, can equal or surpass that of the transceiver, further intensifying the power constraints to the node. Thus, [280] presents a methodology for an ultralowpower overlay for resource-intensive sensor networks, wherein power-hungry sensor nodes are tiered separately from the supplementary nodes and base station. These complementary nodes are described as sensors that typically consume considerably less power than powerhungry nodes and can facilitate power management. The overlay network can be implemented on new or existing sensor networks to minimize power consumption and maximize network lifetime

4.3.3 Power Management for WSNs

Power management at the monitoring nodes can be achieved through the use of various temporal- and event-based sampling strategies, or some combination thereof. For example, the lifetime of the battery can be extended by using timers to set the system in a lowpower standby mode when data are unlikely to occur. This approach significantly improves on the design of the energy-intensive multimedia surveillance station for agricultural monitoring in [285]. A commonly used event-triggered technique uses passive infrared sensors to indicate an event of interest, switching the main system between active and standby modes to conserve power. Improvements in motion-detection algorithms translate to fewer false triggers and appropriate energy usage.

Flexible sampling schemes have improved data collection and resource management, especially when the device is remotely programmable. A recent example is the biotelemetry sensor in [286], characterized by an adaptive sampling strategy for global-positioning system (GPS) location acquisition and General Packet Radio Service/Global Standard for Mobile communication via the cellular network. In addition, exploiting knowledge of system demand, resource availability, and event probability has proved to greatly extend lifetime and conserve storage space.

Incorporating a wake-up technique from an application-driven perspective can significantly reduce sensor system activity to lessen battery requirements [287]. Wake-up radio (WUR) is very useful in triggertype events to generate alarms upon detection of an RF beacon. The WUR and multisource energy harvesting (EH) design in [280] significantly extends the lifetime of power-hungry nodes. EH systems have been shown to enable battery-free operation for low-power sensor nodes.

Wireless information and power transfer (WIPT) techniques have also become popular for powerlimited networks, offering the potential to extend operational lifetime. Advances in WIPT are detailed and expanded upon in [288], with a focus on enhancing these methods by exploiting multi-antenna techniques. In the literature, multi-antenna–based WIPT techniques follow two transmission protocols: simultaneous WIPT and wireless powered communication (or EH communications) [288]. Scenarios for maximizing 1) information rate in traditional multi-antenna systems and 2) energy efficiency in large-scale MIMO are also presented in [288]. There is an expressed need for improving transfer efficiency and distance in these systems.

An approach to maximizing the lifetime of WSNs by optimally assigning energy supplies is presented in [289]; it involves the appropriate classification of primary nodes and secondary nodes. Primary nodes would be equipped with long-lasting or renewable energy supplies and conduct most message-delivery tasks, placing a lower communication demand on secondary nodes supported by chemical-based batteries. The optimization framework and assignment algorithm aim to maximize lifetime while reducing the average number of packet hops.

The WSN proposed in [279] uses fitness functions with machine-learning techniques in an intelligent infrastructure to unintrusively monitor the system‘s energy consumption and performance. The real-time measurements are used as input for models to forecast resource utilization and energy consumption. That approach, paired with the optimization of sensor data flow, allows automated adaptive workload balancing and efficient resource use in the dense WSN.

4.3.4 Challenges of Scalability in the IIoT

Most IIoT solutions require good data connectivity in very harsh operating environments; specifically, asset tracking applications expect rigid data reliability and network connectivity in every RF medium. Although a mesh network architecture is the obvious choice to guarantee connectivity despite a highly attenuating medium, the long battery life required for the inherent additional radio activity competes with this very objective—the energy-data tradeoff. With existing protocols such as ZigBee, IPv6 over Low-Power Wireless Personal Area Networks (6LowPAN), and others, resource-limited nodes will suffer a shorter life span on dense networks due to inevitable retransmissions using random schedulers and larger hardware to support the larger stack and routing table.

Table 2 demonstrates the diversity of a few popular technologies available in this evolving landscape: ZigBee Pro, Thread, the Internet Engineering Task Force (IETF) Routing Protocol for Low-Power and Lossy Networks (RPL), and IETF IPv6 over the Time-Slotted Channel Hopping Mode of IEEE 802.15.4e (6TISCH). Note this list is not inclusive but rather a subset of popular protocols, in no particular order, at the time of this research review.

The solution calls for a deterministic network architecture that minimizes constant network discovery and healing, thereby significantly reducing the transceiver ON time on sensor nodes. Rather, network discovery and healing are designed to be an event-driven process in this solution.

4.4 A Low-Power, Densely Scalable WSN

The IIoT pushes the limits of existing mainstream technologies for large, complex use cases, such as logistics and asset management. The WSN solution for the IIoT needs to be organized, deterministic, inexpensive, simple, and compact for scalability. Beyond this, it must be easy to use, customize, and configure for large-scale, quick-deploy use cases. The goal of the WSN is to minimize the power consumption of the sensor system while maximizing the sensing objectives (coverage and exposure).

Constructing subnetworks for the WSN involves discovery of the proximity and accessibility options between sensor nodes to the WSN's GW. While increasing the transmission power reduces the effect of noninterfering channels, this reducing the transmission power also increases the number of hops to reach the GW. If we take a closer look at the edge communication, the efficient network would be the one that connects through one or more relay hops to the sink using a cost function that optimizes the number of hops (M), communication distance between hops (D), volume of data transmitted through each hop (V), and average active period of each hop (E). If a tree topology is considered, as seen in Figure 9, the cost per byte on a dense network is most expensive at the top of the collection path, where all paths funnel to an aggregator:

$$CostFunction = F(M, D, V, E). \tag{4.3}$$

For a given collection of sensors, not all may have line of sight to other sensors or the sink. The cost function can be minimized, resulting in subtrees that expand the life of the network. The WSN terminates when at least one of its nodes stops transmitting.

4.4.1 Architecture

In this section, we discuss the WSN architecture relative to the widely used Radio Protocol 15.4. The fundamental component of the WSN is a device that acts as either a full-function device (FFD) or a reduced-function device (RFD) on the 15.4 network. An FFD acts as a PAN coordinator, while an RFD is not capable of such responsibility and is intended to conduct minimal

TABLE 2. An overview of state-of-the-art LP-WPAN mesh protocol stacks.

Stack	ZigBee PRO	Thread	IETF-RPL	IETF 6TISCH
Radio	802.15.4 (2.4 G)	802.15.4 (2.4 G)	802.15.4	802.15.4e
MAC	CSMA/CA	CSMA/CA	CSMA/CA	TSCH
Convergence	n/a	6LowPAN	6LowPAN	6LowPAN
Network/ routing	• Routers (always powered/parent) + end devices • Neighbor and routing tables • Unidirectional route discovery (broadcast) and reply (unicast) • Many-to-one routing	• Routers (always powered/parent) + sleepy end devices/ REED • Distance vector/RIP algorithm • Routers exchange MLE messages	• IPv6 addressing, routers exchange ICMPv6 control messages for a root-based graph (DODAG) • Point-to-multipoint/ point-to-point routes • Trickle algorithm adapts exchange rate of control messages	RPL-based (specific configurations for 802.15.4e TSCH MAC under development)
Low-power optimizations	Green power (GP) feature (ZigBee PRO 2012): GP device wakes up to send/ pool data to/from parent (GP sink/proxy)	Duty-cycle end devices (only wake up to send data or poll parent node)	Nodes can join as leaf nodes and implement duty cycling (implementation specific)	Scheduled transmission slots minimize power consumption, but overhead of enhanced beacons/time sync needs to be considered
Transport/app	ZigBee App Profiles (ZigBee 3.0 unified)	UDP + DTLS	Implementation dependent (UDP/ CoAP option)	Implementation dependent

MAC: medium access control; CSMA/CA: carrier-sense multiple access with collision avoidance; REED: router-elegible end device; RIP: Routing Information Protocol; MLE: mesh link establishment; UDP: User Datagram Protocol; DTLS: Datagram Transport Layer Security; DODAG: Destination-Oriented Directed Acyclic Graph; CoAP: Constrained Application Protocol; TSCH: time-slotted channel hopping.

Table 4.2: An overview of state-of-the-art WSN mesh protocol stacks.

tasks/applications. At minimum, each device must be equipped with a physical layer (PHY) containing an RF transceiver, a low-level control mechanism, and a medium-access control (MAC) sublayer to interface with the physical channel.

An adaptation layer protocol enables a configurable, scalable, deterministic WSN atop the 15.4 standard, supporting star and peer-to-peer topologies. In this discussion, we use the star network topology as a launchpad for a broader use cases and to serve as a baseline for using tree and peer-to-peer networks. Also, the nodes are identified as server and client, based on their operations (similar to FFD/RFD). The client node is a physical device/tag used for in situ data collection from environmental and device health sensors. The server (or coordinator) node can have hardware identical to that of a client but acts as the PAN coordinator and aggregator of sensor data from its client nodes. The clients are equipped with sensors and must be provisioned to associate on power-up with an assigned server, which can be connected to an Internet-enabled GW for cloud services. Each device is battery operated with limited resources, and each network of server and clients operates on a shared 15.4 wireless channel using a synchronous time-division multiplexing (TDM) schedule guided by local timers and WSN packet payloads (Figures 10 and 11).

This payload resides in server (or client) firmware, which passes the structure to the MAC layer for inclusion to the MAC payload of the 15.4 Standard PHY Convergence Procedure protocol data unit (PPDU). Then, PHY services are enabled by lower-layer firmware and RF hardware to transmit (or receive) as part of the PHY payload. The MAC payload is bundled into the PHY services data unit (PSDU) as the PHY payload in the PPDU.

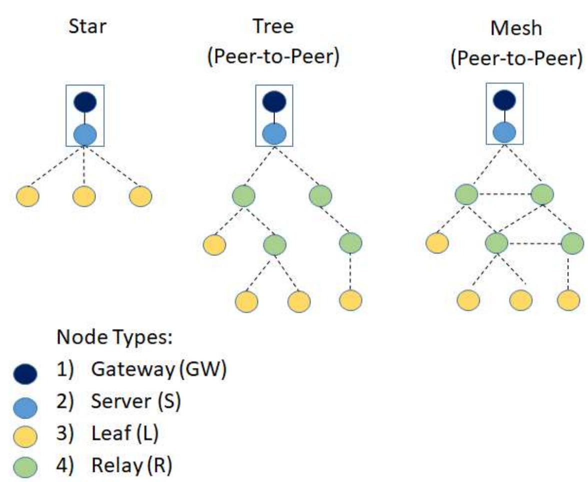


Figure 4.9: A scalable topology with relay/peer-to-peer

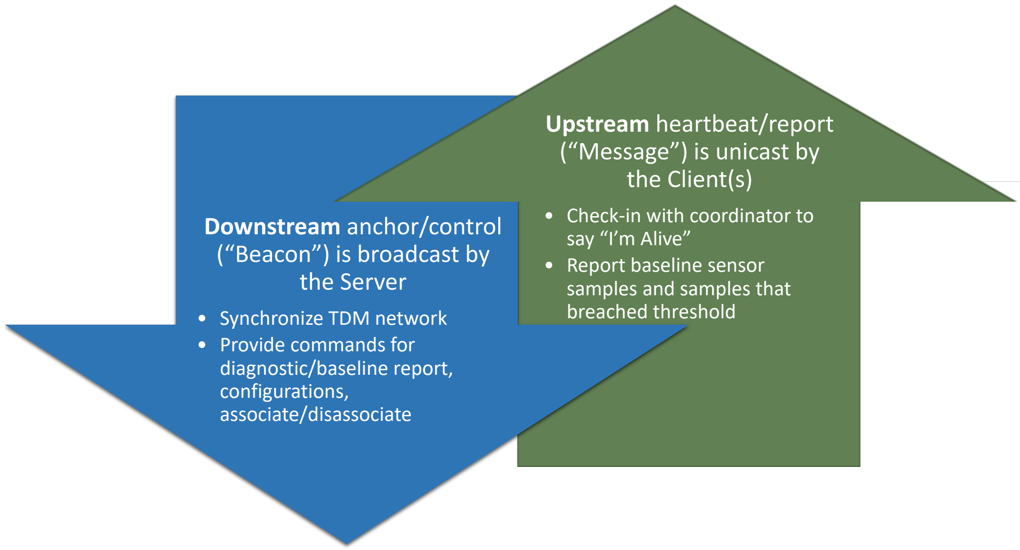


Figure 4.10: The mechanisms to maintain synchronization and provide contention and diagnostic reporting.

4.5 Operations

The placement and connected topology of a sensor network are critical to IIoT use cases. For example, when a shipment is created, a monitoring node can be placed on each shipping pallet or on an individual packet within that pallet. The server (or GW) may be placed on each shipment, where it aggregates the data from each sensor connected to multiple pallets (or packages within a pallet) that configure a shipment. Each monitoring node can act as a leaf node, relay node, or server node, depending on the optimal configuration of the routings of the nodes to the sink. The route optimizations are the result of the shipping objectives (time to ship, cold-chaining, shipping material, monitoring frequency, and so forth).

The WSN comprises N sensor nodes (clients) that connect to a sink (server). The sensor data packet that originates from each sensor traverses through M hops (relays) to reach the sink. Each subnetwork of N:1 (clients to server) operates on a wireless channel and uses weighted time-slot assignments during which the designated node is allowed to transmit to another node or set of nodes. Each client and server device uses

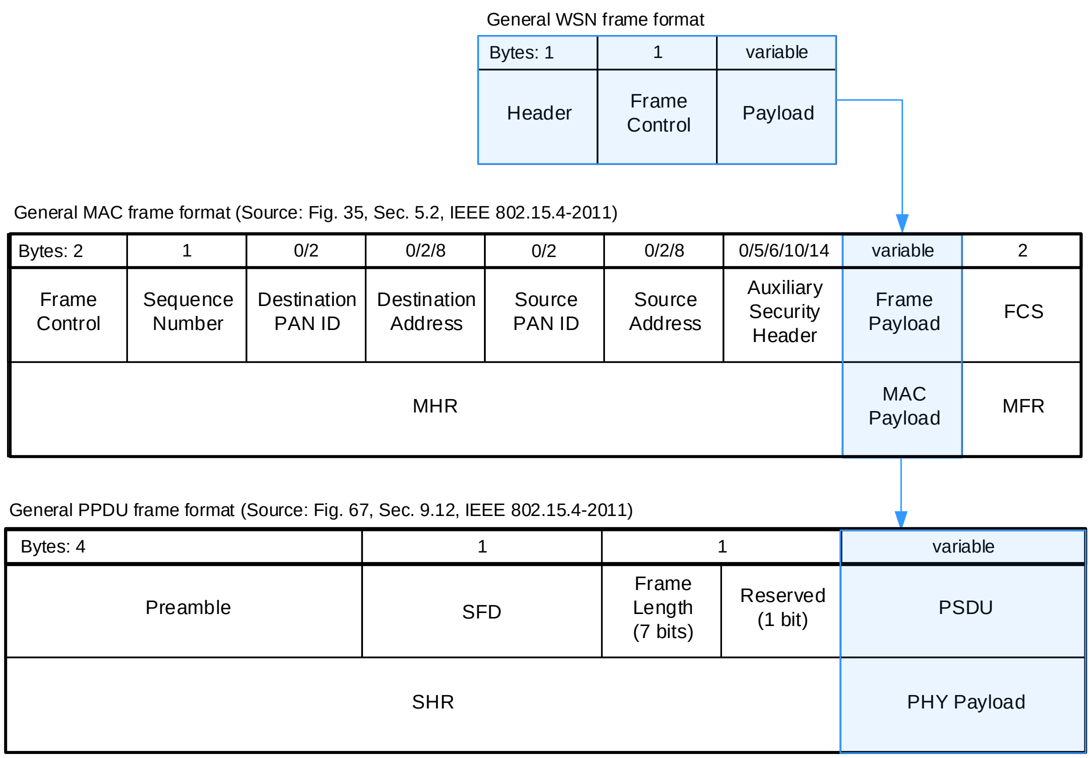


Figure 4.11: An embedded WSN frame in the 15.4 payload. MHR: MAC header; MFR: MAC footer; FCS: frame check sequence; SFD: start-of-frame delimiter; SHR: synchronization header.

local timers and counters that assist in the precise measurement of time slots and time duration, during which the sensor nodes synchronize the clock and transmit the payload. The beacon frame marks a server-initiated (or relay-initiated) “micro frame period” that allows the WSN’s member nodes to synchronize their clocks. Upon receipt of a beacon, all clients calculate their relative time slots and set up their wake-up trigger to respond with a heartbeat/report message in that time slot.

A multiple of this period is the ”macro frame period,” which differs only to signify a larger transmission scenario with all clients reporting additional information (such as long-term analysis data) in addition to breaches (”anomalies”). Once the network is provisioned, all clients (leaf nodes and relay nodes) anchor to the parent beacon for network management or data collection. Figure 12 illustrates the channel occupancy and operations for two clients on an N:1 network. Notice the drift depicted by a shifted blue receiver beacon listening window of client 2, mitigated by the beacon arrival for an accurate response time.

The typical client and server have three functional units that perform the tasks related to device management, sensor monitoring, and wireless communication:

- *Management subsystem.* This describes the state machine that assists in joining to the WSN network. This layer handles the use-case customization that reliably and securely activates the induction of a sensor node into the sensor network.

- *Communication subsystem.* This describes the state machine for data reception and transmission. This layer is responsible for clock synchronization and programming the transmission periods.

- *Sensor subsystem.* This handles the sensors’ callbacks and collects sensor data.

Although occupying the same network, the client and server nodes exhibit distinct behavior, which can each be expressed as an event-driven finite-state machine. The state machine of these functional units is customized according to the role played by the devices that form the parent–child hierarchy in a WSN, such as the following:

- *Leaf nodes.* These are the end points of the network that perform sensor data collection and transmit that data to the next hop at an allocated time slot. These nodes do not have any child nodes.

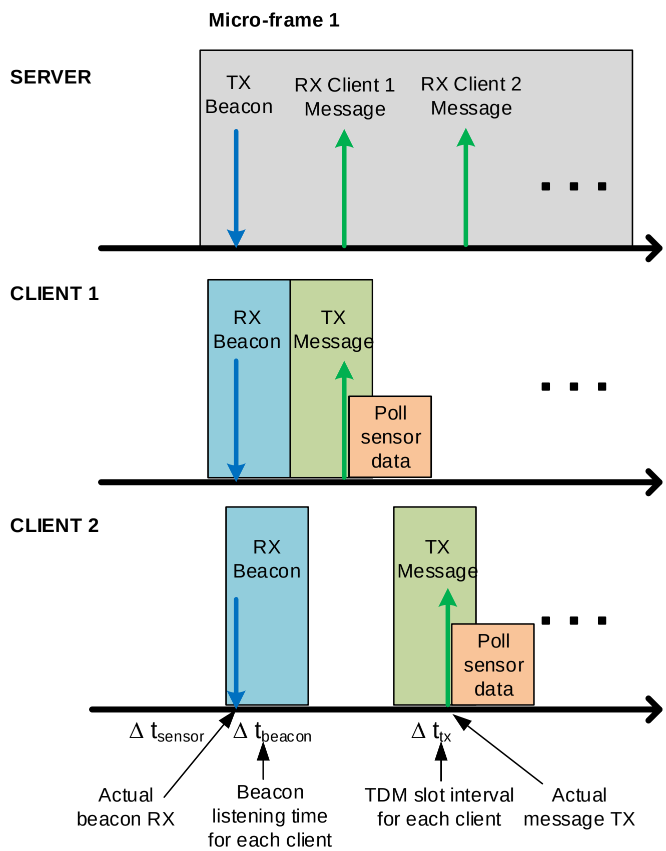


Figure 4.12: The channel occupancy and operations of an N:1 network during the managed state. Rx: receive; Tx: transmit.

- *Relay nodes.* These are intermediate nodes that perform data collection from child nodes and forward that data to the parent node. Additionally, they implement the leaf node functions.

- *Server nodes.* These act as the aggregators of the data received from the relay or leaf nodes. The data are packetized and forwarded to the cloud subsystem for further processing and analytics.

Server and relay nodes propagate as a beacon frame that acts as an anchor point to establish the sensor network, which binds the device roles with the corresponding state machines. These beacons carry information related to time slots and configuration commands destined for one or more clients downstream.

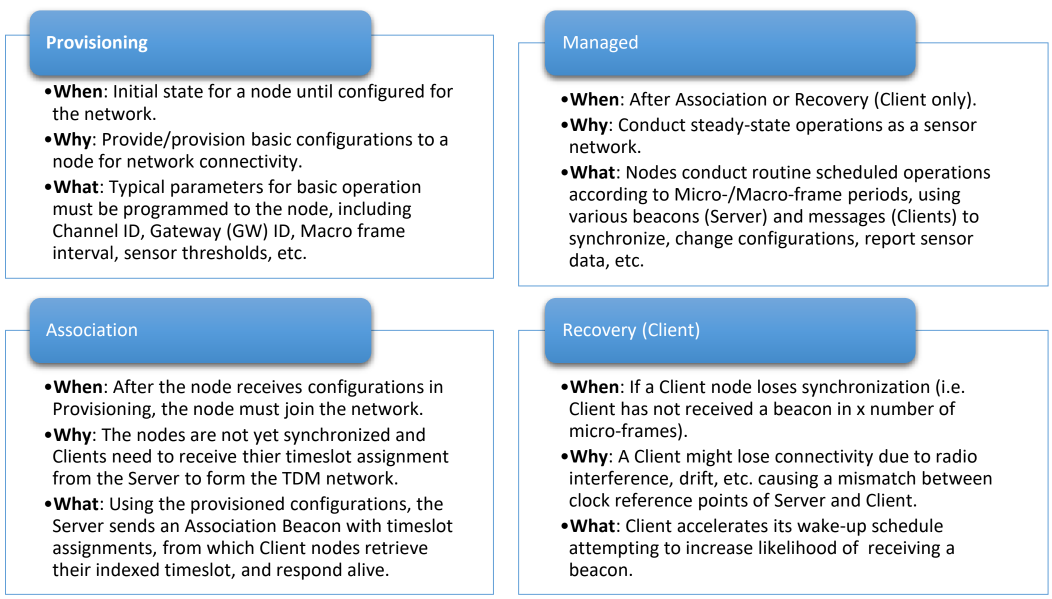


Figure 4.13: The general operation phases (or states) for WSNs.

As summarized in Figure 13, each node is responsible for managing its behavior across states: provisioning, association, managed, and recovery (client only). The client and server have different state operation and flow that are specific to their network role,

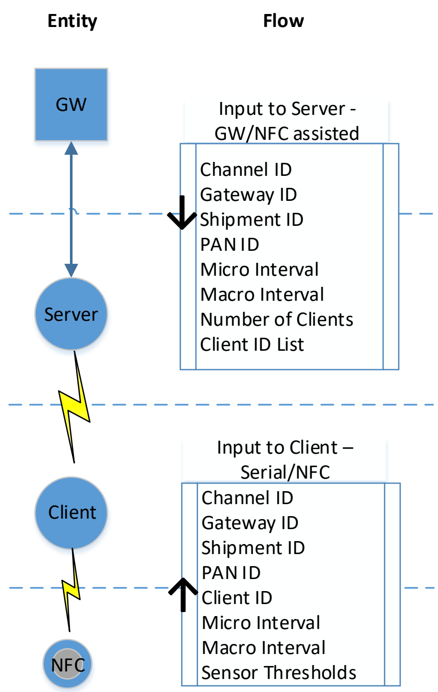


Figure 4.14: Sample provisioning of critical configurations for a node to join the network.

driven by local and network events. Within each state and between any two states, the node sleeps until triggered to wake by a timer or trigger (such as general-purpose in/out). Executing minimal instructions quickly, and only as needed, prioritizes sleep to minimize the duty cycle to allow a longer life span.

For example, prior to the initial deployment of the sensor network, each device must be programmed with the full software stack (server or client) and must also be provisioned—e.g., provided with the basic parameters to join (if client) or govern (if server) the assigned network. This requires a mechanism with which to program the network management parameter values into device memory [such as NFC electrically erasable programmable read-only memory (i.e., EEPROM)], as shown in Figure 14.

After successful provisioning, the clients frequently wake up to listen for a beacon with the GW ID to which it should associate. Once the beacon is received, the client checks in with an “alive” message and resumes steady managed behavior in sync with the server beacon. While in this state, clients report messages in their time slot, and the server sends beacons.

4.5.1 Client Architecture

The client architecture contains three main modules:

1. A management subsystem handles the main states (such as provisioning, discovery, association, managed, and recovery) corresponding to the communications subsystem.

2. The communications state machine switches distinctive communication states for leaf or relay nodes and handles the sensors subsystem callbacks

3. The sensors subsystem handles the callbacks and collects sensor data.

4.5.1.1 Management Subsystem State Machine

The client uses a state machine to assist the sensing node (relay or leaf) to join the WSN. These states can be summarized as follows (see Figure 15):

- *Provisioning state.* This is the initial state where the client reads the configuration and the radio is turned off. Upon powering up, the client device enters the provisioning state automatically. In cases where the configuration data are not present or invalid, the client enters sleep mode and wakes up when it receives configuration data. This state transitions to the discovery state once the client has a valid configuration to join the network. This state can also transition to the recovery state if a previously associated client reboots to perform any recovery.

In the LAM use case, this critical stage is where the shipping manifest, node IDs, channel ID(s), and parent address are configured to each node.

- *Discovery state.* In this state, the client routinely powers on the radio and waits for a discovery or association beacon frame containing the indexed transmission time slot (slot ID). To process the beacon in this state, the client executes the communications state machine. Upon receiving the compatible beacon frame, the client synchronizes its timers, retrieves its indexed transmission time slot (slot ID) from the TDM bit map, and responds with an ”alive” message in its time slot. This state transitions to the association state when the client receives the association beacon.

  In the LAM use case, this state allows the sensor nodes to authenticate and connect to a sink (GW) that manages the shipment (containing this asset).

- *Association state.* In this state, the client processes the association beacon containing the optimized transmission time slot (slot ID) from the server. The client retrieves its indexed time assignment (slot ID) and responds with an ”alive” message in its allocated time slot. Unless both the association beacon and slot ID (contained in this beacon frame) are received, the client will wait in the association state. The association state transitions to managed state once the regular beacon frame is received and the slot ID is retrieved.

  In the LAM use case, this state allows the sensor nodes to associate and be managed by a valid sink (GW).

- *Managed state.* In this state, the completely formed WSN is managed by cloud (through the GW). The client can send an “alive” message, sensor anomaly message, or sensor management message. This state transitions back to the provisioning state when the client receives the disassociation command from the server (end of

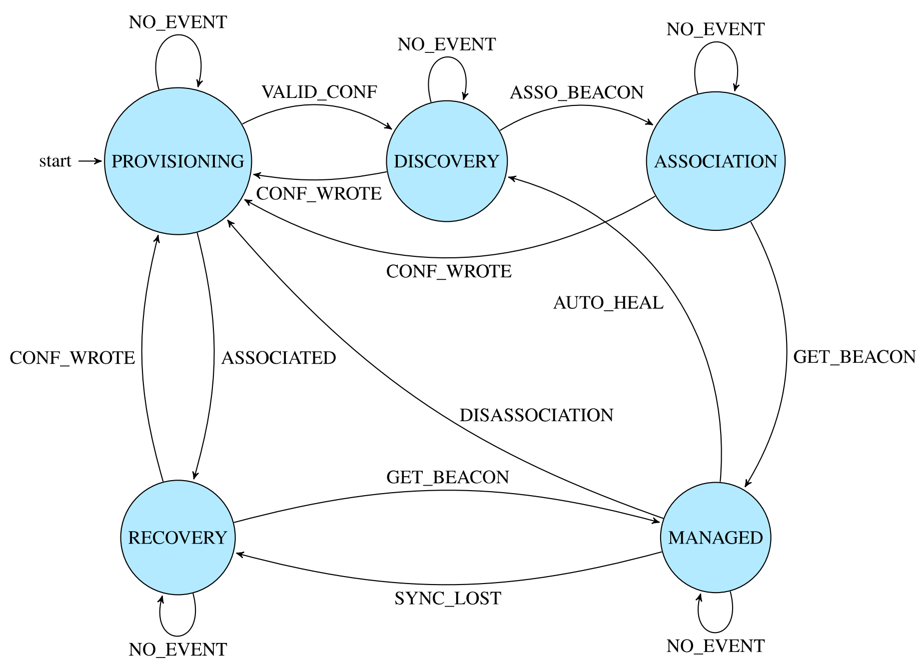


Figure 4.15: The management subsystem state machine.

journey). The managed state transitions to the recovery state if the client misses a predefined number of consecutive beacons, thereby losing synchronization with the network.

In the LAM use case, this state allows the sensor nodes to be monitored for tracking, tracing, sensor breach, theft, and locality.

- *Recovery state.* In this state, the client regains time synchronization with the server. The client wakes at an increased frequency to catch the beacon (broadcast from the server), which, upon receipt, synchronizes its timers. If no beacon is received, the client remains in the recovery state. This state transitions to the managed state when the client receives a regular beacon or an association beacon with its slot ID.

  In the LAM use case, this state allows the sensor nodes to recover synchronization due to any intermittent faults.

4.5.1.2 Communication State Machine

The communication state machine characterizes the data reception and transmission on a leaf node or relay node (see Figure 16):

- *WAIT_FOR_BEACON state.* This is the initial state wherein the client waits for and processes the beacon from a server or relay node. The client enters into the WAIT_FOR_BEACON state upon wake up and operates the radio on receive mode. It resets the MCU synchronization timer and waits for the beacon. Upon detecting the beacon frame, the beacon arrival time is stored, and the beacon information is processed. This state transitions to the SEND_DATA state or SENSOR_CALLBACK state to monitor sensor data and transmit that data to the parent node.

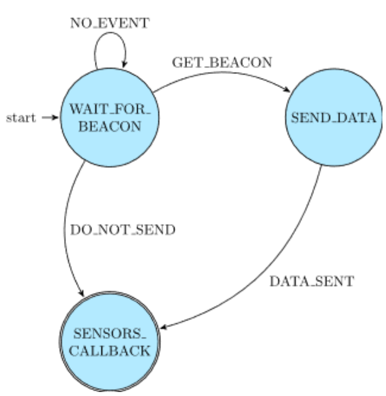
- *SEND_DATA state.* In this state, the client sleeps until its time slot to transmit the data. The client builds the transmission payload with the sensor data. It uses its transmission time slot to program the radio to transmit mode, sends the package, and waits until the transmission is completed.

- *SENSORS_CALLBACK state.* This is the state wherein the client executes the sensors' callback functions. If the client is in the managed state, it calls the sensors' callback functions to collect the sensors' data and transmit that data during the next micro frame. This is a final state, where the leaf communication state machine ends and exits.

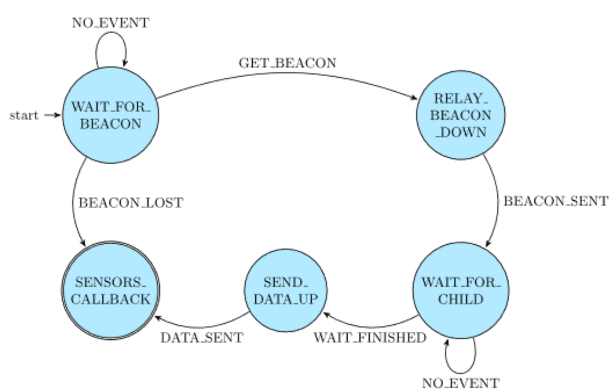
- *RELAY_BEACON_DOWN state.* In this state, the client retransmits the beacon to its children. The client modifies the beacon with its time slot ID (for beacon frame offset reference) and the tree tier. The client then transmits the beacon package during its time slot.

- *WAIT_FOR_CHILD state.* In this state, the client turns on the radio (receive mode) and waits for its children's data. These data are packaged and prepared for transmission.

- *SEND_DATA_UP state.* In this state, the client waits until its time slot to transmit its payload. The client builds the transmission payload with its own sensor data along with its children's data.



(a) the leaf node



(b) the relay node

Figure 4.16: The communication state machine for (a) the leaf node and (b) the relay node.

4.5.2 Data Transport

As introduced earlier in Figure 11, a data transport layer assists in the data exchange among the server, relay nodes, and leaf nodes. This involves multiplexing, packetizing the payload, adding source/destination address, and customizing attributes in the header of the data packet. The beacon frame (from the server or relay nodes) broadcasts downstream to clients (relay nodes and leaf nodes) and contains a beacon-type field in the header that designates the type of information in the payload. As shown in Table 3, beacon types are defined to facilitate synchronous communication between clients and server.

- *Association beacon.* This beacon type enables the association state by providing the client time-slot assignments embedded in the payload. Upon receiving this beacon, clients extract the time-slot information and set their timers to wake up during that indexed time period to respond.
- *Regular beacon.* This beacon type enables periodic synchronization to the clients, which enables them to operate conflict-free within their allocated time slot.
- *Configuration beacon.* This beacon enables the configuration command, transmitting the client-specific command by embedding its payload into this beacon frame. Upon synchronizing with this beacon, target clients extract the command payload and process the command. These commands abstract the clients' management and control operations to facilitate the journey of the monitored asset in a shipping and logistic use case.

Once the clients synchronize with one of the beacon frames (Table 3), transmitted periodically at a micro frame period, and program their time slots, they unicast one of the message types upstream to the server. As illustrated in Table 4, the header indicates the type of information embedded in the payload. For example, the macro frame notification beacon is sent by the server to inform clients that the next frame is a macro frame. This allows clients to collect and transmit extended data related to long-term analytics and management. Figure 17 illustrates the association beacon frame (transmitted by server 0 x 0201) that encapsulates the indexed time-slot information for three clients: 0 x 0101, 0 x 0102, and 0 x 0103. Each of these clients programs its transmission time slots corresponding to its index.

TABLE 3. Server beacon types.	
Association beacon	• Synchronizes clock reference • Provides TDM assignment
Regular beacon	• Synchronizes clock reference • Basic maintenance (i.e., lost node NACK, etc.)
Configuration beacon	• Synchronizes clock reference • Updates configuration parameters

Table 4.3: Server beacon types

TABLE 4. Client message types.	
Micro frame message	• Heartbeat message • Reports anomaly event(s)
Macro frame message	• Reports anomaly event(s) • Reports in-range/baseline samples

Table 4.4: Client message types

As illustrated in Figure 18, the PHY payload of the wireless network traffic can be observed using an RF packet sniffer. The WSN payload is seen in the MAC payload of this PSDU, as introduced Figure 11. In this example, server 0 x 0201 (PAN ID 0 x AABB) transmits a beacon frame that informs the clients to transmit macro responses (detailed analytics information) during the next micro frame. In the current micro frame, all three clients synchronize their clocks in response to this beacon frame and transmit ”alive” (heartbeat) messages during their respective time slots. The subsequent beacon (starting with the next micro frame) is the regular beacon followed by the client responses that contain the macro data related to the extended analytics and management information.

4.6 Topology: Scaling and Optimizing Routes

The centralized star topology delivers a baseline implementation that may be sufficient for many shipping and logistics use cases, unless they involve cold-chaining, liquids, pharmaceuticals, or organic materials. These materials can induce path attenuation that limits a communication system’s link budget. In practice, the star is suitable for basic use cases in nonchallenging wireless environments, such as line-of-sight cardboard containers in normal ambient conditions. We augment our baseline architecture to support more complex topologies that solve the problem of hidden or hard-toreach nodes.

The star topology has limited scalability and performance as the wireless environment becomes more challenging, such as in Faraday-cage, dense, or distributed scenarios. In reality, these nodes may be mobile devices in highly dynamic wireless environments. Therefore, the star can be extended to a tree by incorporating peer-to-peer communica-

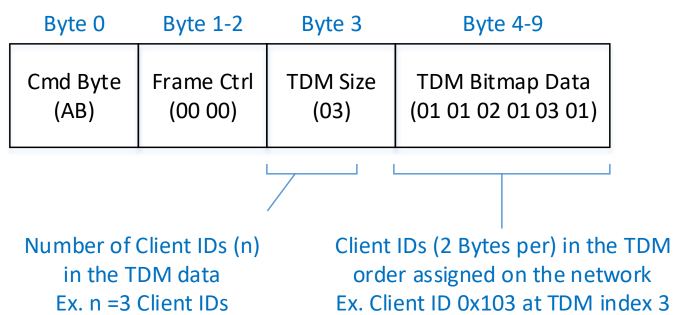


Figure 4.17: The association beacon (AB) example for a 3:1 clients-to-server network.

tion agents that relay data packets along branches of the tree. Tree networks employ a hierarchical scheme by which an arbitrary number of child nodes communicate with their parent on the network. Figure 19 illustrates a deployment scenario wherein not all nodes can reach the sink (GW) within a single hop. This can be solved by introducing a relay function that is hosted on optimally selected client nodes. The additional responsibility of the relay function can be accomplished by establishing the relay node's parent–child relationship, where child clients act as sensors from which the data payload is collected and forwarded upstream to the parent. With the introduction of relay, the connectivity problem in WSN transitions to become a process-optimization problem with the following control parameters:

- *Role selection.* Each node must be selected as a relay node or a leaf node. The optimal role selection would be the one with proportional battery capacity.

- *Parent selection.* Each relay node and leaf node is allocated a parent ID that acts

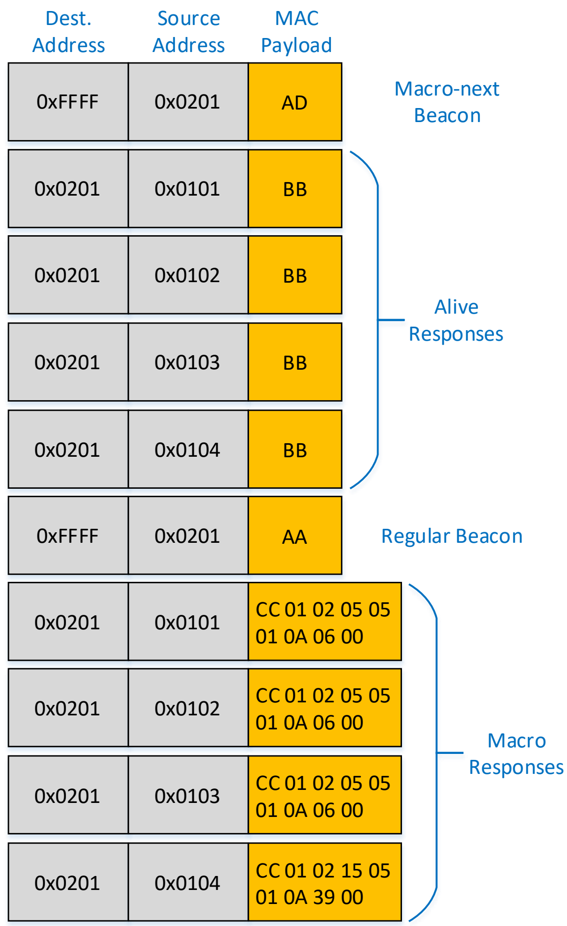


Figure 4.18: A server-client communication example.

as a waypoint for the data payload to the sink (GW). An optimal parent would be the one that has comparable load relative to other relays in the same hierarchy.

- *Children selection.* Each relay node is allocated children nodes (relay or leaf nodes) with minimal communication distance. The number of children is optimized by uniformly loading the relay nodes in the same hierarchy.

- *Network constraints.* These constraints limit the tree depth and loading of the relay nodes. They are set based on the worst-case buffer requirements and the average energy consumption of each sensor node. While a star topology may be preferred in many use cases, average transmission distance (due to path attenuation) can turn out to be a limiting factor to the life of the sensor.

As the network scales, to find the optimal solution within these control parameters (feature space), the search space for the optimal route increases dramatically. The number of routing options and the amount of traffic overhead overwhelm network bandwidth. Ideally, we would like to have efficient, self-organizing networks with low route-finding latencies (or overhead) and high probabilities of successful transmission through low-cost routes.

Large numbers of such sensors create a sensor management problem. At the network layer, the solution entails setting up an energy-efficient route that transmits the nonredundant data from the source to the sink to maximize the sensor's battery life span. This is done while adapting to dynamic connectivity resulting from the failure of some nodes and the powering up of new nodes. To rank various candidate solutions, a fitness function is needed that maps the feature space to the objective space. The objective space can be summarized as in the following.

4.6.1 Relay Loading

The relay loading (RL) objective rewards uniform loading of the relay nodes that operate at the same tier. This facilitates uniform energy consumption among relay nodes in a tree hierarchy:

$$RL = 1 - \frac{1}{D}\sum_{i=1}^{D}\left[\left(\frac{1}{N_i}\right)\sum_{j=1}^{N_i} min(1, |A_i - a_{ij}|)\right], \tag{4.4}$$

where D is the maximum depth of the network tree, N_i is the relay node count, A_i is the average number of children per relay node for the ith tier, and a_{ij} is the number for children for the jth relay for the ith tier.

4.6.2 Tree Depth

The tree depth (TD) objective rewards the tree depth if it falls below the threshold D_{th}. It counts the number of nodes to the relay nodes placed above the threshold:

$$TD = min\left(1, \frac{1}{N}\sum_{i=D_th+1}^{D}(i - D_th)\, K_i\right), \tag{4.5}$$

where N is the total number of client nodes and K_i is the total number of nodes at the ith tier.

4.6.3 Communication Distance

The communication distance (CD) objective rewards the mutual connectivity between transmitting/receiving node pairs if they can operate below power threshold levels P_{th}:

$$CD = 1 - \frac{1}{K}\sum_{i=0}^{D}\sum_{j=0}^{j=N_i}\psi_{ij}\,(P_{th}), \tag{4.6}$$

where K is the total number of clients, N_i is the client count for the ith tier, and ψ_{ij} is set (to 0) if the client j can communicate with its parent (at tier i) at a transmission power value lower than P_{th}.

4.6.4 Battery Capacity

The battery capacity (BC) objective rewards client role allocation if the battery capacity can support that role. Clients are allocated a relay or leaf node role at any position in a tree topology. Depending on the role and the number of clients dependent through that role, battery requirements may differ. This function is critical to avoid premature depletion of battery capacity resulting in the untimely termination of the tree network.

Network roles are revised frequently to avoid nonuniform load on clients:

$$\begin{aligned} B_i\left(k\right) &= f\left(i,k\right) \\ BC &= 1-\frac{1}{K}\sum_{i=0}^{D}\sum_{j=0}^{j=N_i}\theta\left(\xi_{ij}-B_i\left(m_{ij}\right)\right) \\ \theta\left(k\right) &= 1 if k\geq 0 \\ \theta\left(k\right) &= 0 if k<0, \end{aligned} \tag{4.7}$$

where $B_i(k)$ is the battery capacity target (percentage) at the ith tier with k dependent nodes (all the nodes that are connected through this branch), m_{ij} represents the total number of dependent nodes, and p_{ij} represents the actual battery capacity connected of the jth relay node at the ith tier.

The cumulative fitness can be defined by executing multi-objective optimization that results in a candidate solution for which control parameters are set in a multicriteria decision-making process, where all four objective functions must be optimized simultaneously. In many scenarios, optimal decisions may require tradeoffs between these conflicting objectives. In a simple implementation, we may use a weight vector to specify the relative importance of each objective and then combine them into a scalar cost function.

This strategy reduces the complexity of solving a multi-objective problem by converting it into a singleobjective problem. When the new solution is created, the information related to the parent of each child node is transmitted through existing paths using the configuration command embedded in the configuration beacon frame. This process repeats periodically, predicatively, or upon certain triggers (such as nonresponsive nodes) to maximize network life. The network routing is not known by the clients to keep the memory footprint small as the network grows larger.

While the server and clients are not aware of the full topology and network health, the GW has the perspective and processing capability to identify optimized routes and reconfigure the network accordingly.

4.6.5 Tree Synthesis: Machine-Learning Approach

One synthetic approach can be the use of a GA-based technique to configure the randomly deployed sensors for shipping assets into an optimal number of independent subnetworks,

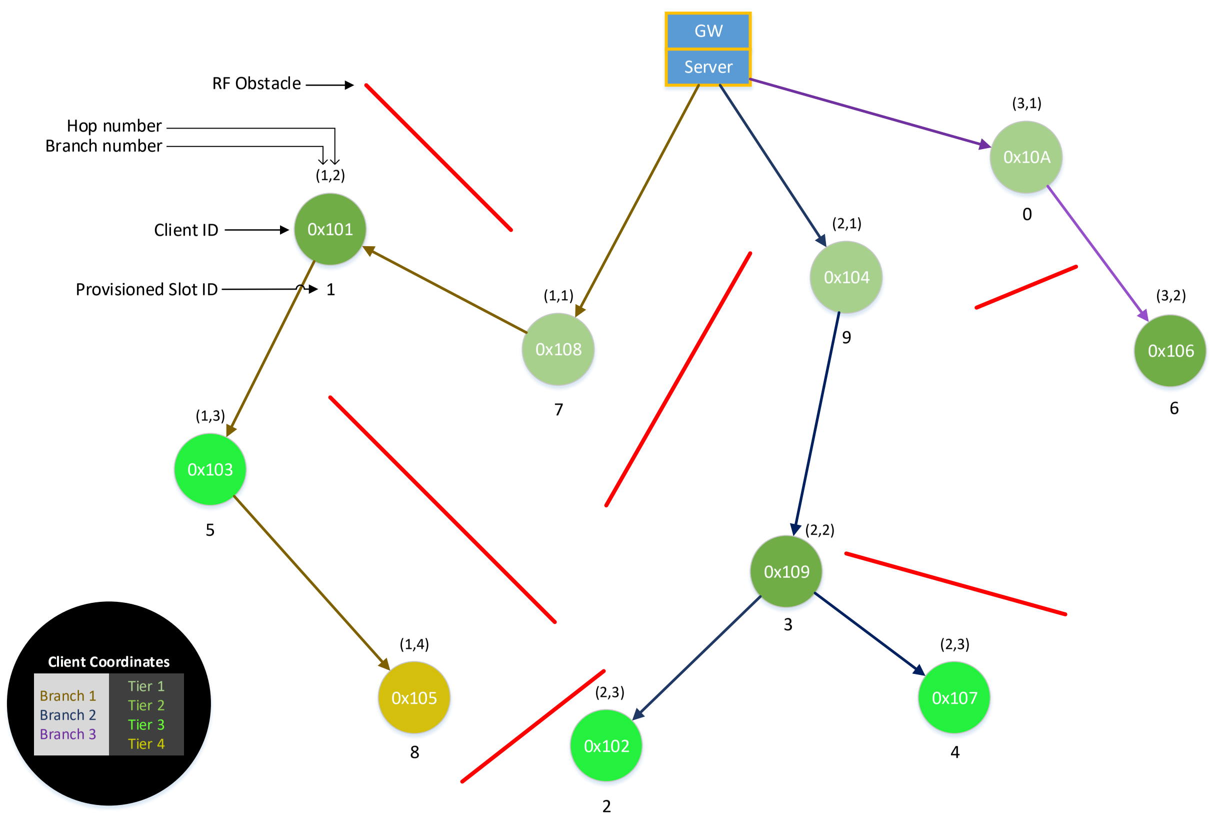


Figure 4.19: An example of a tree topology in a challenging wireless environment.

with optimal routes and sensor membership. Each subnetwork facilitates the data collection from its member sensors and sends them to the target in a compressed manner via the most cost-effective route.

As illustrated in Figure 20(c), GAs follow the principle of natural selection, in which each individual solution is represented as a binary string (chromosomes) and an associated fitness measure. Successive solutions are built as a part of the evolutionary process, where one set of selected individual solutions gives rise to another set for the next generation. Individuals with a high fitness measure are more likely to be selected into the mating pool, based on the assumption that they will produce a fitter solution in the next generation (next run).

Solutions with weaker fitness measures are naturally discarded. We use roulette-wheel selection to simulate natural selection, in which the elimination of solutions with a higher functional fitness is, although possible, less likely. There also exists a small likelihood that a weaker solution may survive the selection process, as it may include some component (genes) that may prove useful following the crossover process. Mathematically, the likelihood of selecting a potential solution is given by

$$P_i = \frac{F_i}{\sum\limits_{j=0}^{n} F_j} \tag{4.8}$$

where P_i represents the likelihood of a solution to be selected for the mating pool, F_i represents the operating fitness of an individual solution, and N is the total number of solution elements in a population. This GA has proved useful in solving complex problems with a large search space that are less well understood with little domain knowledge.

WSNs may use a coding scheme in which each individual client node's parent code is represented by an N-bit binary number called a gene [Figure 20(b)]. These genes constitute the subnetwork to which each node belongs (called the allele). The chromosome of the GA represents the building blocks (allele) to a solution of the problem that is suitable for the genetic operators (crossover and mutation) and the fitness function. As illustrated in Figure 20, two candidate solutions undergo a modification using a crossover function and yield a new candidate solution that undergoes evaluation for candidacy in a new mating pool.

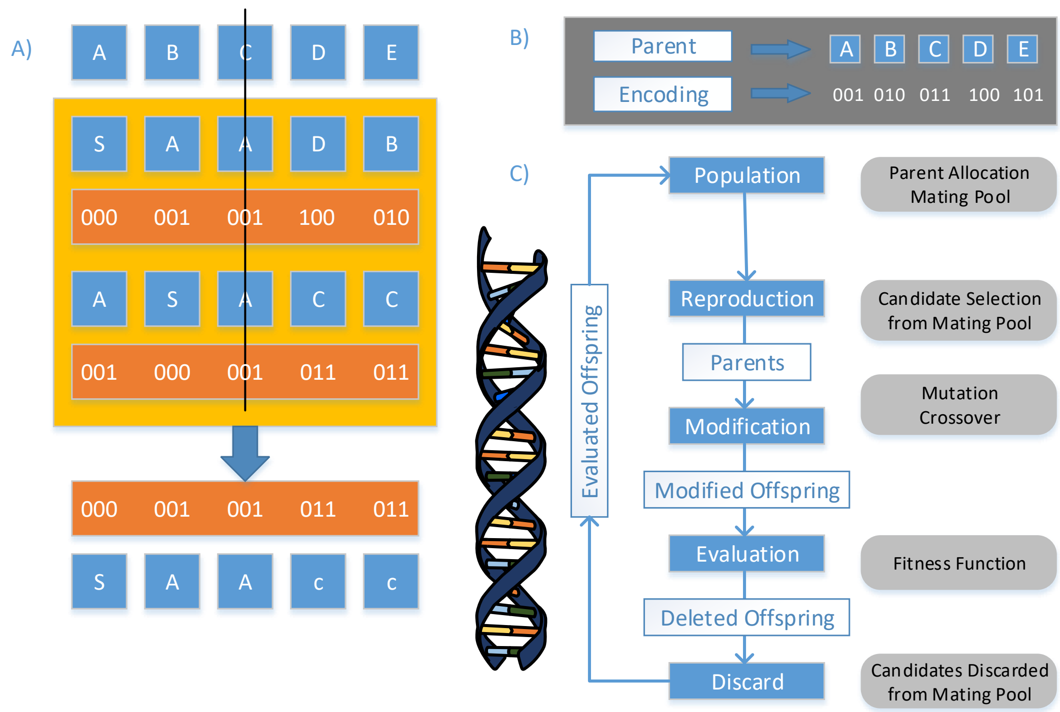


Figure 4.20: (a) The crossover process of N-parent allocation candidates producing an offspring candidate for new parent allocation. (b) The parent allocation N-bit coding scheme. (c) A GA for producing parent allocation candidates.

This solution will result in a graphical representation, as illustrated by Figure 20(a). The evaluation process of the candidate solution uses the weighted sum of the individual objectives, as defined in the ”Topology: Scaling and Optimizing Routes” section, to calculate the quality of overall fitness (also called cumulative fitness). Each individual objective function measures the quality of a specific goal related to 1) battery utilization, 2) transmission power, 3) operational efficiencies, and 4) data collection efficiency.

4.6.5.1 Provisioning the Tree Network: Discovery

It is important to note that to establish new tree network, we need a preexisting network. As described earlier, a preexisting network is required to configure a new parent–child hierarchy. Furthermore, the very first optimization of a tree network requires training data (RSSI between all possible node pairs) as well as temporary routes through which these training data are transmitted to the sink (GW) for scoring potential candidates during the exploration of an optimal tree topology. A child node needs only to know its parent, while a parent needs to know its children. The first time the relationship is provisioned algorithmically occurs during the discovery mode, in which the nodes take turns beaconing and listening for the strongest RSSI.

4.6.5.2 Data Transport: Tree Network

Figure 21 illustrates an example with one server and five clients (A, B, C, D, and E), with an update interval of 60 s. The clients are configured in a tree topology described by Figure 21(a). In this topology, clients A and C act as relay nodes, and clients B, D, and E as leaf nodes. Figure 21(b) describes the clients’ wake-up timing diagram with the different transactions at each time slot. These transactions are divided in two communication sections: forward (beacon propagation) and backward (data collection and forwarding).

Through forward communication, the server and relay nodes transmit the beacon down during precomputed time slots. In this example, the server transmits its first beacon (beacon transmit) while client A waits for it. During the next time slot, client A relays the beacon downstream (relay beacon), and clients B and C wait to synchronize with that beacon. Then, client C relays the beacon down, and clients E and D wait to synchronize with that beacon.

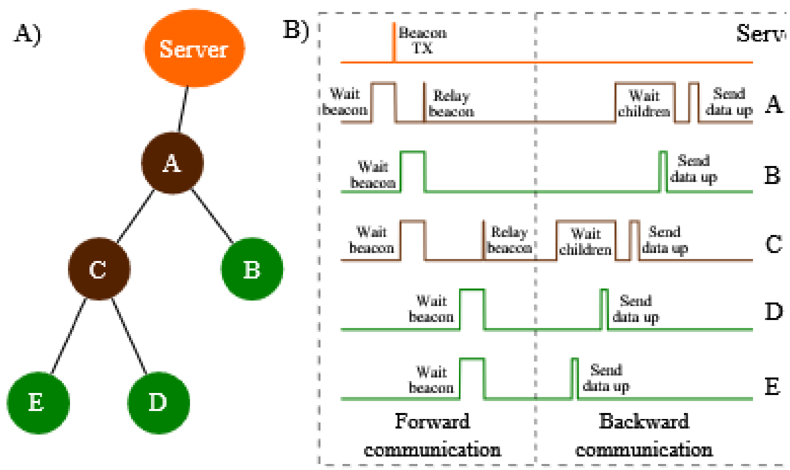
In the next phase, through backward communication, the clients packetize their data, coalesce them with their children's data, and transmit the data to the parent en route to the sink (GW). In this example, during the first and second time slots, clients E and D (children) transmit the payload data up, while client C (parent) listens. During the third and fourth time slots, clients C and B (children) transmit their payload data upstream, while the client A (parent) waits and listens to these payloads. Finally, during the last time slot, client A transmits the aggregate payload to the always-listening server.

In shipping and logistics use cases, battery consumption resulting from client placements can limit the life of the network. Depending on the physical placement and allocated hierarchy in the tree topology, clients will drain battery at different rates. This knowledge is not only essential during the establishment of optimal routes; it is also required to predict the dissolution of existing routes and the reestablishment of new routes.

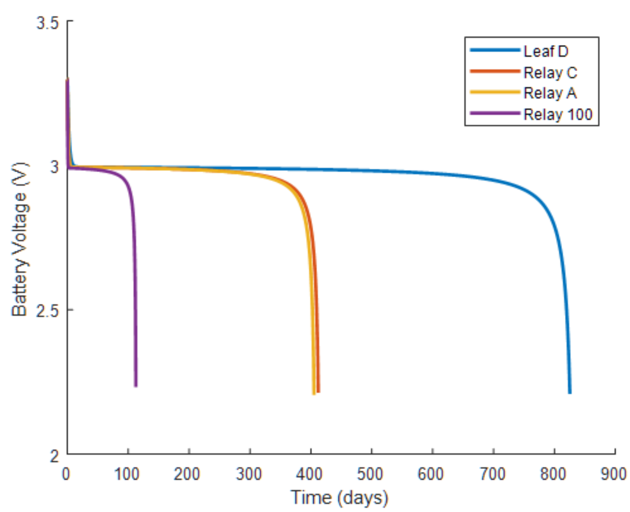
Figure 21(c) illustrates the current consumption of different clients in the network. To estimate the battery life and battery discharge curve, a battery model [290] was used to model the behavior of two coin-cell 3-V CR2450N batteries with a total capacity of 1,080 mAh. The leaf node battery life is estimated to be 824 days, while the relay node battery life is estimated to be 404 days for client A and 411 days for client B. Furthermore, the life span of a client (relay 100) with ten branches (direct children) and 100 subbranches (100 total children) is estimated to be 112 days.

These results demonstrate that the clock synchronization between the server, client relay nodes, and client leaf nodes facilitates precise custom time slots and time durations during which the device wakes up to 1) lock the beacon for synchronization, 2) transmit the beacon to its children, 3) transmit the payload data to its parent, and 4) listen to the children's payloads. A leaf node can achieve a battery life span of close to three years with a micro frame update interval of 60 s. A relay with 100 children can support communication for more than 100 days on the same battery capacity.

The results are as expected, with large disparities in the battery consumption relative to the network role, placement, and loading. This can be mitigated by periodic simulations of new (and more efficient) routes using the battery utilization models. It should be noted that current operation of the sensor network depletes the client batteries in a nonuniform manner. Current routes were established based on battery data that may



(a) A tree topology configuration and timing diagram



(b) client battery discharge curve

Figure 4.21: (a) A tree topology configuration and timing diagram, and (b) client battery discharge curve.

not be valid after a certain duration of operation. System alerts identify such conditions, where client roles may no longer be compatible with their available battery capacities. Such conditions can trigger the reconfiguration of new routes based on new training data.

4.7 Conclusions

This ultralow-power WSN design approach leverages deterministic LR-WPAN communications to satisfy the increasing demand for scalability and mobile connectivity in the IIoT, as researchers around the world attempt to discover next-generation solutions. Real implementations in complex use cases, such as LAM, depend on low-power hardware, energy-efficient architecture and operation, and power management. The engineering principles and UX synthesis described in this article can be adapted for a wide range of applications and use cases, where key tradeoffs include operating scenarios, connectivity, quality of service, mobility, cost, form factor, and energy efficiency. The applications can be categorized as (to name a few) track and trace, location estimation, anomaly detection, theft detection, and sensor monitoring.

Some more specific examples of use cases that can benefit from this approach include data center management, agriculture and farm-to-store tracking, body area networks to track human motion (fall detection and other activities involving body movement), logistics and locomotion, early detection and emergency response, and so on. For a given collection of sensor placements, connectivity constraints and energy tradeoffs drive the control loop that tunes and optimizes the topology of the WSN. The optimal topology construction can be a critical factor in which we may encounter a large search space with solutions that can lead to hidden nodes, large communication delays, or uneven energy consumption. This machine-learning technique is a promising solution that can generate optimal tradeoffs between competing objectives (energy and connectivity) to improve the life of the sensor network.

Acknowledgments We gratefully acknowledge the contributions and perspectives from other valued members of the team, including Jiejie Wang, Asif Haswarey, Laura Rumbel, Giby Raphael, Linda Schwartz, Kevin Midkiff, and Kevin Shaw.

Part II

Special Topics in Communications & Signal Proc.

Solar and RF Energy Harvesting Design Model for Sustainable Wireless Sensor Tags

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Chapter 5: Solar and RF Energy Harvesting Design Model for Sustainable Wireless Sensor Tags

Abstract: Modern society expects connectivity and autonomy amidst the internet of things (IoT) paradigm. Automation and sustainability of consumer and industrial systems is paramount to satisfy demand and transform standards. Low-power wireless sensor networks (WSNs) have proven widely successful for bridging the gap but typically depend on batteries. The next generation of devices can be batteryless or self-sustainable with energy harvesting (EH). This work presents an EH design and analysis model for a system to collect solar and radio frequency energy and store the energy until needed for WSN activities. The viability of the model is demonstrated with two micro-controller-based implementations and applied to data center monitoring.

5.1 Introduction

Usage complexities of sensor networks and the internet of things (IoT) are increasing demand for sustainable next-generation technologies. Many distributed use-cases deploy low-power wireless sensor networks (WSNs) with sensor tags that report to a central hub for processing and connectivity. Each device is typically small and can be non-stationary, which constrains designs to a small battery and form-factor but with the ability endure prolonged and/or harsh wireless deployments, such as industrial IoT (IIoT). The WSN design in [2] is a functional example with promise for IoT but can be improved with energy sustainability. The constraint on battery life can be reduced or eliminated with energy harvesting (EH). Alternative energy sources can drastically extend the lifespan of a duty-cycled sensor tag.

This work presents an EH design and analysis model for a system to collect solar and radio frequency (RF) energy to charge a capacitor and store the energy until needed for WSN activities. The model's versatility is demonstrated with two MCU-based implementations and applied to data center monitoring. This work is unique because it details a simple, customizable approach for multi-modal EH to support low-power sensing devices for IIoT. This directly builds on prior works to provide alternative energy and longer battery life for WSNs and IoT. This work is a primer for scalable power management of sensor tags and demonstrates its relevance to existing industry needs.

Section 6.2 details the EH design and Section 5.3 defines the analysis model with WSN platform implementations of [2]. Section 6.4 shows results of a benchmark platform and an alternate minimized setup. Section 5.5 proposes the monitoring of microclimates in data centers.

5.2 Design

5.2.1 Solar and RF Energy Harvesting

Solar EH has become a popular alternative energy supply with widely available resources. Other energy sources are gaining interest, especially those which do not impose significant additional infrastructure. Depending on implementation multi-modal techniques can be exploited to improve performance and effectiveness which offers promise for sustainable sensing devices. In complement to solar, a radio front-end can harvest ambient or regulated radio frequency exposure. RF EH can be discussed with wireless power transfer (WPT) but is research out of scope here. A sensor tag can be modified to harvest solar and RF energy with a solar cell and a 2.4GHz RF front-end (see Fig. 5.1). Solar and RF EH can contribute individually and independently, but complement each other and co-exist without significant interference. A typical RF harvester is shown in Fig. 5.2. Energy arrives at the antenna, passed to a rectifier to convert the 2.4GHz signal into low-voltage DC power, and fed to the DC-DC converter or power management IC (PMIC) [291].

5.2.2 Power Management Implementation

A typical WSN in IoT uses an ultra-low duty-cycle with low-power sleep mode to conserve energy. Short periods (ms) of activity consume the tag's energy, which may include wireless communication, sampling, processing, and more. This configuration keeps the tag in sleep 99.9% of the time [2].

Fig. 5.3 shows the EH design in configuration with a storage capacitor and battery

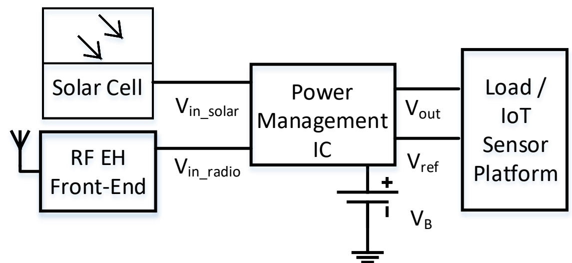

Figure 5.1: The simplified schematic contains a solar cell, RF EH front-end, DC-DC converter/power management IC, and the load.

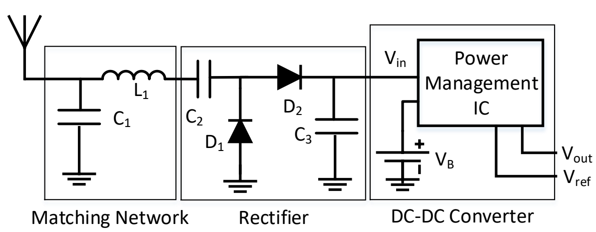

Figure 5.2: The basic RF harvester contains an antenna, matching network, rectifier, and DC-DC converter / power management IC.

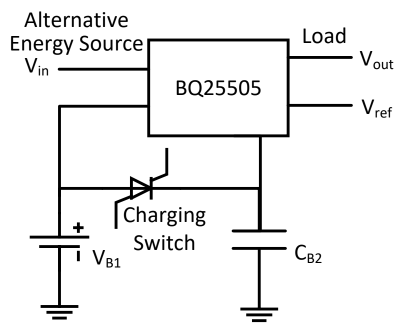

Figure 5.3: A multi-modal harvester with a switch to recharge a storage capacitor or battery.

as backup, managed by a switch and PMIC (eg BQ25505). Energy at the PMIC powers the load/tag continuously (sleep and active) with a sufficient input source (solar, RF, battery). Using the input source, the harvester charges a capacitor for temporary energy storage until needed by the load. The capacitor discharges during the short periodic high-powered tag activities. The optional charging switch recharges the battery with surplus harvested power as a backup supply.

5.3 Methods

Analysis of the HW design across several parameters was enabled by defining a mathematical system to describe expected behavior. The modeled behavior of the WSN tag is based on [2] including terminology, which varies across literature. Sensor tags are 'clients' communicating directly to a WSN coordinator called a 'server'. A micro-interval is the period of a bi-directional wireless transaction by which the server monitors the status of each client via a heartbeat or minimal response to save energy. The more informative but energy costly is a macro-interval at which each client reports all sensor data to the server for use in logs, trends, and more. The intervals are typically integer multiples of a period of many seconds or minutes, for example 2-/10- seconds micro-/macro-, respectively.

Let the power consumed by the load described using the tag's deterministic activities, where $P_o = \sum(P_a t_a f_a)$ for activities a with duration t_a and frequency f_a (cycles per second). This expands to

$$\begin{aligned} P_o = &P_{tx}(t_\mu f_\mu + t_M f_M) + P_{rx}(t_{rx\mu} f_\mu + t_{rxM} f_M) \\ &+ [P_{sl} + P_{cl} + P_{ul}] + \sum_{j=0}^{n} (P_{sj} t_{sj} f_\mu) \end{aligned} \tag{5.1}$$

where P_{tx}, P_{rx}, P_s are the power consumed while transmitting, receiving, and polling sensors for data; P_{sl}, P_{cl}, P_{ul} are leakage by the sensors, capacitor, and the microcontroller. t_μ and t_M are the transmission times, $t_{rx\mu}$ and t_{rxM} are the receiving times, and f_μ and f_M are the frequency of the micro- and macro- intervals. For simplicity, it is assumed all clients activate their radio for the same amount of time t_{rx} to receive the beacon as each other but this can vary [2]. The transmission time t_{tx} is known to vary for a given client for micro- and macro-period activities.

Next, let the power provided by the EH solution be P_i and the sufficient condition required for sustainability can be described by input-output power as $P_i \geq P_o$. The BQ25505 PMIC has an input-output efficiency of 85-95%, and imposes a higher requirement for the energy source conditions (exposure intensity and/or duration to alternative energy supply).

Another design parameter of the EH implementation is appropriate sizing of the storage capacitor. The energy stored can be expressed in terms of voltage as

$$E_C = \frac{1}{2} C (V_{OV}^2 - V_{UV}^2) \tag{5.2}$$

where the over voltage protection threshold (V_{OV}) and under voltage threshold (V_{UV}) are used to define the usable energy, limited by the input voltage range of the DC-DC converter on the client. Equation (5.2) can be used to determine the capacitance needed to store the required P_o. The capacitor charging time can be approximated by

$$T_C = \frac{E_C}{P_i - P_{sl} - P_{ul} - P_{cl}}. \tag{5.3}$$

Equations (5.2) and (5.3) were used to determine the minimum sleep time required for a given capacitor to support the load, and the maximum required capacitor size for a given sleep time interval. Using (5.2) in (5.3) yields the time required to charge the capacitor. In this way a harvester can be designed to provide sufficient power for the system in (5.1). The benchmark was the client tag power consumption with a micro-/macro-interval of 60-/120- seconds. The reference design was the multi-sensor tag in [2] equipped with temperature, humidity, accelerometer, and more. In one hour the tag consumed 0.16mWh. A 3.3V voltage source and a WT210 digital power meter were used for testing.

5.4 Results

5.4.1 Storage Capacitor

The harvester had energy usage shown in Fig. 5.4 for a $470\mu F$ and a $1000\mu F$ configuration. Efficiency of the energy collection mechanism, such as solar panels and RF front-end are out of scope for this work. The BQ25505 efficiency is considered and validated in the range of 85-95%.

Table 5.1 shows the results for an EH non-rechargeable setup. The harvester provided more than sufficient power to charge the capacitor during the tag sleep state. The capacitors successfully charged to the target 4.2V overvoltage protection limit of the PMIC allowing greater power delivery. Given a sufficiently large capacitor with appropriate time to charge during idle state, the WSN tag can be fully sustained without the battery. The battery was effectively eliminated as the primary source.

5.4.2 Alternative MCU and Minimized Setup

The power model analysis and the EH implementation is versatile and scalable. To demonstrate this an alternative minimal design was tested using a CC2650 MCU with

Table 5.1: Energy harvesting impact on battery lifespan

Harvester w/ C_{B2}	Energy Draw from Battery (mWh)	Impact (lifespan)
None	0.1644	x1
w/ $470\mu F$	0.0710	x2.3
w/ $1000\mu F$	0.0315	x5.2

Table 5.2: Power consumption by activity

Activity	Power Consumed
Standby	0.008 mW
Radio Receive	18.76mW
Radio Transmit	29.52mW
Sensor Polling	10.27mW

a LM35D analog temperature sensor and internal ADC. Power consumption by activity for this setup is shown in Table 5.2.

Using Equation (5.1) and the same reporting schedule, the average P_o of this design was $36.0\mu W$ by

$$\begin{aligned} P_o =& 29.52mW(0.005s\frac{1}{60s} + 0.005s\frac{1}{120s}) \\ &+ 18.76mW(0.05s\frac{1}{60s} + 0.05s\frac{1}{120s}) \\ &+ 10.27mW(0.01s\frac{1}{120s}) + 0.008mW \end{aligned}$$

Fig. 5.5 shows the power usage for this minimal design and the benchmark. The minimal design consumes 22% compared to the reference due to implementation and lower leakage current. The multi-sensor reference design includes some sensors that typically consume more power than others, like accelerometer. The minimal design has an analog temperature sensor and is shut off during sleep. A minimal design approach reduces the power requirements for the harvester. This setup requires $P_i \geq 36uW \geq P_o$, making sustainable sensor tags more feasible. This is advantageous for use-cases requiring only a few sensors.

5.5 Monitor Data Center Microclimates

5.5.1 Traditional Methods

Sustainable or batteryless sensor platforms would enable the widespread adoption of WSNs in transformative applications. A growing market with significant impact is data centers (DCs). No single DC management design is best, but combining recent tech-

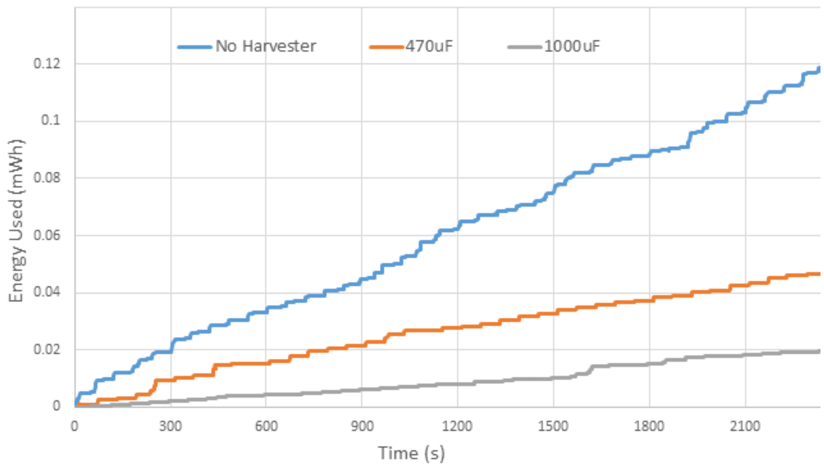

Figure 5.4: Battery consumption using different sized storage capacitors

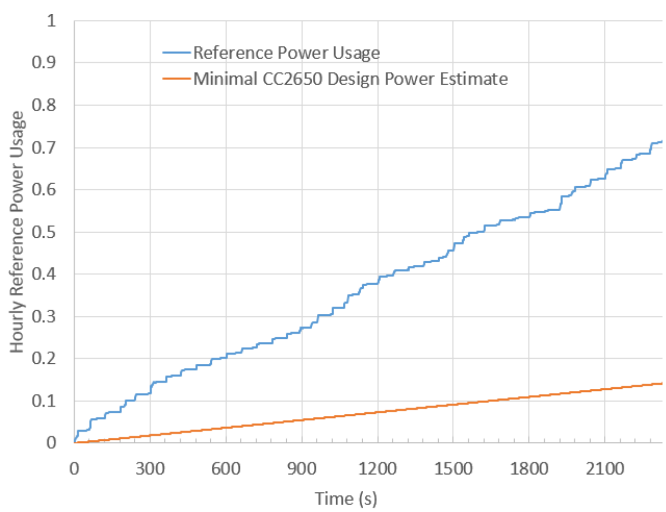

Figure 5.5: Minimal design power demand compared with the reference design

nologies can make a big impact. Climate control and resource balancing remain grand challenges. Inefficiencies cause the highly dynamic formation of costly microclimates. Participants in the Better Buildings Challenge such as the US Dept of Energy pledged to reduce 20% portfolio-wide building energy use and share best practices over the next decade. In 2013 the USA had 3 million DCs consuming approx. 100 billion kWh of electricity [292].

Airflow management facilitates climate control and response to reduce hotpsots, energy waste, and expense. The example of a typical 7-Tile-Aisle layout shown in Fig. 5.6 uses Hot-/Cold-Aisle containment, which is effective but expensive to install and maintain at large facilities. Relatively affordable, scalable, configurable systems for visibility remain sought-after.

Traditional methods include USB data loggers, but offer retrospective analysis after temporary deployment. The DC building infrastructure may be instrumented at fixed locations at large expense for install/retrofit and service. Some servers and racks may have onboard sensors but the implementation remains limiting, misrepresentative, and largely unused. If sensor data is collected it is analyzed by humans, databases, and supervisory control and data acquisition systems (SCADAs).

5.5.2 Sustainable WSN Solution

Advances in technology can leverage real-time processing for improved visibility to microclimates in such large facilities. Capturing microclimate behavior in real-time with existing infrastructure has been cumbersome and unresolved, but WSNs offer distributed, configurable sensing. Prior work in [15] presented a robust data collection protocol and network synthesis for WSNs in DCs, but the prototype needed to lower battery dependence. The solar and RF energy harvesting design in 6.2 is a strong candidate to overcome gating challenges like battery and approaches a sustainable WSN for monitoring microclimates in DCs without additional infrastructure. The data center environment can allow exploitation of solar and RF energy collection. Prior work demonstrated that microclimate visibility would directly influence key metrics such as power usage effectiveness (PUE) and infrastructure cost [15].

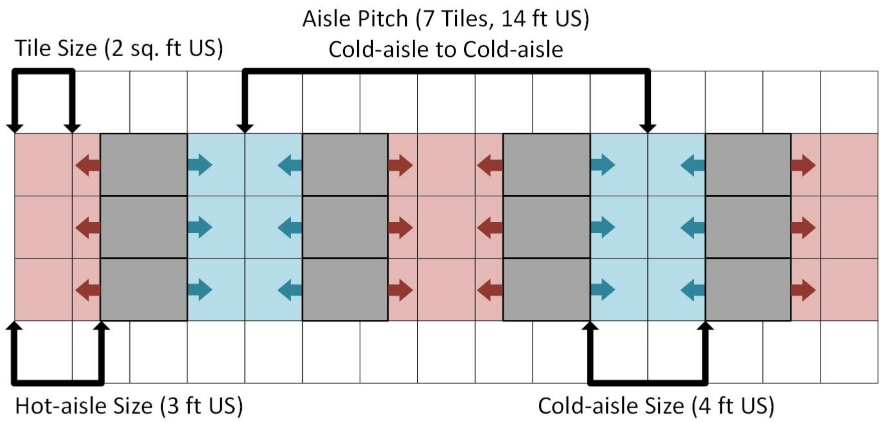

Figure 5.6: Overhead view of a data center with a typical hot-aisle/cold-aisle layout and 7-Tile aisle pitch.

5.6 Conclusion

Dependence on battery supply is a common challenge for the widespread adoption of WSNs in transformative, complex usages. This paper presents an architecture and model for solar and RF energy harvesting and power management for sustainable sensing devices. The design is aimed at low-power MCU-based IoT platforms, with a timely application to challenges in monitoring data center microclimates. This EH design architecture and power model can be leveraged for WSN and other low power devices to achieve energy sustainability with the adoption of alternative energy sources. Conclusions from this work include the importance of balancing the power usage model of the system, accounting for leakage currents, and appropriate sizing and selection of components to achieve sustainability.

Proof-of-Concept for an IoT Sensor Platform with 2.4GHz Wake-up Radio

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Chapter 6: Proof-of-Concept for an IoT Sensor Platform with 2.4GHz Wake-up Radio

Abstract: Driving the 4th Industrial Revolution and fueling the Internet of Things are billions of resource-limited devices offering computation, control, and telemetry. Designs aim to save energy yet satisfy real-time service and availability, thus necessitating power solutions. Main components typically stay in sleep modes until a wake-up event occurs, such as a timeout. Communication is often scheduled for these active periods, leaving designs susceptible to idle listening and wasted energy. An attractive approach for energy optimization and sustainability for low-power devices is wake-up radio (WUR) for the ability to wake-up devices over-the-air. This work proposes the system integration of two recent prototypes: a sensor platform for industrial IoT and a 2.4GHz WUR. Preliminary results demonstrate this proof-of-concept.

6.1 Introduction

The internet of things (IoT) conceptualizes that everything everywhere be connected for real-time remote visibility and control of data and things. Fueling IoT and driving the 4th Industrial Revolution are billions of electronics forming low-power wireless sensor networks (WSNs) and similar technology. Yet sensing, processing, and telemetry deplete limited energy supply. Such devices rely on limited resources to collect data and transmit to a nearby gateway for cloud services. Designs aim to reduce dependence on energy supply while preserving service and availability. Energy consumption is often reduced by duty-cycling and low-power sleep modes triggered by wake-up events like timers. Always-on always-sensing (AOAS) techniques extend functionality in sleep at low energy-cost, such as wake-on-motion. An opportunity to save energy during active times is the radio. The transceiver consumes more power when active, and is active more, than other components in a typical WSN [2]. Wake-up radio (WUR) can offload radio frequency (RF) event detection with AOAS to trigger rendezvous. Depending on implementation WUR can reduce idle listening and collisions, mitigate drift, enable on-demand time-division-multiple-access (TDMA), and more.

This work proposes the system integration of two recent designs to achieve a sustainable IoT platform: the low-power WSN in [2, 3] and a 2.4GHz WUR-based overlay with the wake-up receiver (WURx) in [293]. Sections 6.2-6.4 describe the design, methods, and results.

6.2 Design

This proof-of-concept (PoC) unites system implementations in [3, 293] for a WSN and WUR as an overlay. Each was designed independently in a modular approach with bounded inputs and outputs but the system interface needed to be defined. This section details the design at the sensor tag platform level with minor modification to existing solutions. The initial goal is to reduce idle listening to improve energy supply lifespan.

6.2.1 Idle Listening Use-Case

An example of idle listening appears in [3] with a centralized WSN using IEEE 802.15.4 on 2.4GHz to collect sensor samples across a wireless personal area network (WPAN). Each device calculates time based on its local oscillator, which is inherently susceptible to error from quality, time elapsed, temperature, and other factors. Stability is achieved with a beacon period (i.e every 60 seconds) and a listening phase (B in Fig. 6.1).

Ultra-low-power WUR offers AOAS and offload potential idle listening. WUR can listen for a wake-up call (WUC) indicating beacon arrival despite drift, and trigger a pulse to wake the main radio/MCU for rendezvous. In this way, WUR acts as an air-

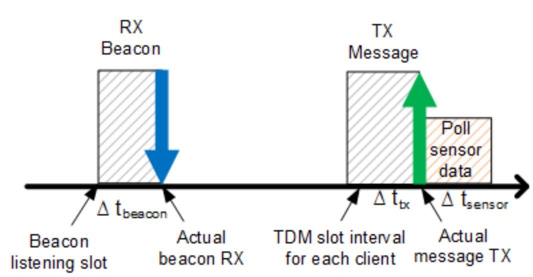

Figure 6.1: Example of sensor tag radio activity and worst-case beacon drift

clock or synchronization mechanism for simplified payloads. This can be described as transmitter-initiated WUR (TI-WUR) whereby a transmitter sends a WUC indicating a beacon, the WUR-based tag wakes up to the WUC, and the main radio receives the beacon with commands.

Initial system integration needs two main functionalities for WUR-based rendezvous: (1) the WUR detects a wireless wakeup signal and wakes up the tag; and (2) the tag's main radio transmits a detectable WUC, allowing tags to wake each other up. Incorporating the designs to a unified architecture can facilitate mesh networking, multi-hop schemes, etc.

6.2.2 Architecture

Fig. 6.2 shows the high-level device architecture. The WURx sniffs the radio for a specific sequence to trigger a pulse by wire to wake-up the primary system. Each WSN tag would have a WURx module and have a way to transmit a WUC to another WUR tag. The basic interface toggles power to the MCU or main radio. Yet, toggling power supply to the MCU is not viable in this use-case, as with many MCU-based primary systems, because of the need to preserve sleep mode for volatile memory, critical timers, etc. Adding a switch or trace results in current leakage and loss of signal integrity. The WURx output signal is low power and toggled with the clock which can be missed by the MCU. Thus, practical implementation is dual-antenna and includes a level shifter to boost the voltage of the WURx output to a detectable level for standard GPIOs shown in Fig. 6.3, and a low-power D-Flip-Flop as an SR-latch to hold the WURx output event until cleared by the MCU to avoid missing the brief wakeup signal. The interface is shown for the level-shifter and latch in Figs. 6.4 and 6.5.

6.2.3 Theory of Operation

The desired WUC exhibits a low-data-rate bit period (50us) with transmission for bit-value of '1' and idle for '0' to generate an on-off-keying (OOK) when mixed with the 2.4GHz signal [293]. In Fig. 6.6 the WURx RF front-end (FE) receives and detects the envelope of the RF signal, feeds it to a logic-level correlator and, if the OOK sequence is satisfied, then the Wake-up Enable signal is generated. The wakeup signal sets the latch

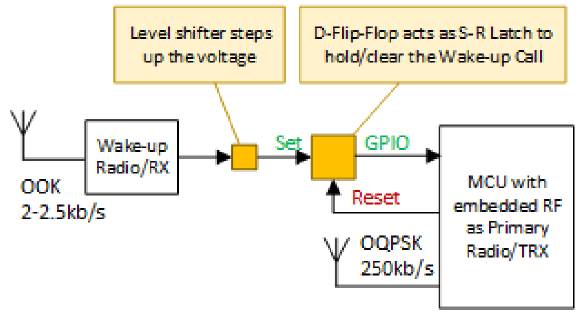

Figure 6.2: Proposed WUR Architecture using multi-antenna technique for AOAS, with level-shifter and SR-latch

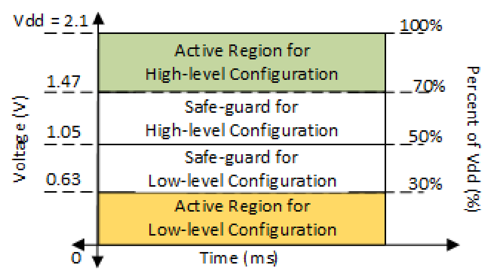

Figure 6.3: Sample active regions for a standard GPIO pin

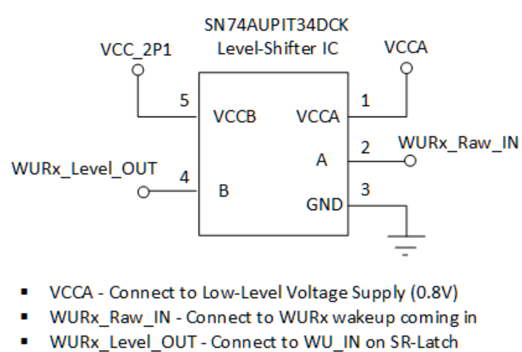

Figure 6.4: Sample pinout for the level shifter to boost the WURx output to trigger a standard GPIO

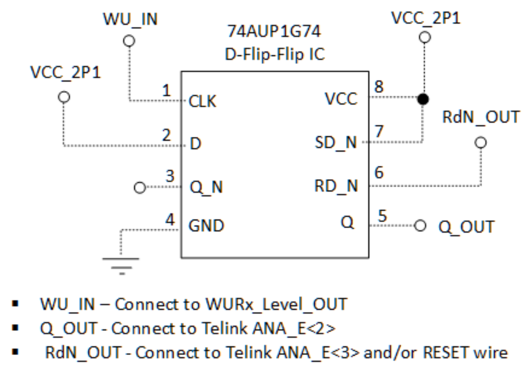

Figure 6.5: Sample pinout of a D-Flip-Flop as a Set-Reset Latch

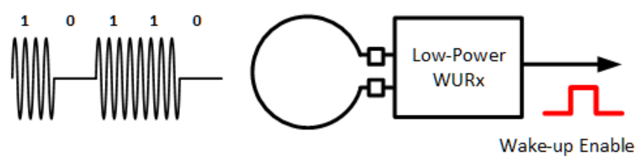

Figure 6.6: Example of arbitrary source on-off-Keying (OOK) transmission to trigger the WURx pulse out to the 1ry system

which is held until the MCU reads and clears the pin. The MCU awakens to resume programatically, preparing the main transceiver (TRx) for WSN rendezvous and resume sleep until the next wakeup event. The power profile is depicted in Fig. 6.7 with a blue dashed area for energy savings of the sensor tag with WUR (red) compared to the tag without WUR (black) for a typical reporting cycle of 60s.

6.2.4 Wake-up Call Implementation

Without adding RF circuitry, software defined radio using the MCU was the next available option. A script was written to implement the on-off-keying sequence to toggle the existing WSN transmission of the MCU using onboard timers according to a bit sequence. However, the application layer calls low-level firmware to execute the transmission, which requires the service to finish full payload before returning to the timer-based loop for 50us per bit. However, leveraging the multi-standard support of the MCU with embedded communications module was practical and required minimal modification. The

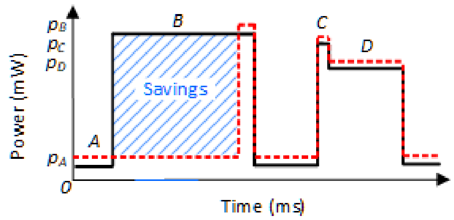

Figure 6.7: Example power profile of a sensor tag without WUR (black) vs. with WUR (red) with energy savings (blue) in a typical 60s report cycle.

Bluetooth Low Energy (BLE) advertising (AD) beacon is capable of short transmission on 2.4 GHz similar to the desired bit-period and is sufficient for this PoC and readily supported by the hardware and software implementation. The transmission of each AD beacon represents a bit period and frequency estimated by Eqs. 6.1 and 6.2, which informs calibration of the WURx for future tests to receive this waveform,

$$8(7+6+1)/10^6 = 112us \tag{6.1}$$

$$f = 1/T = 1/(112us + 112us) = .224Hz. \tag{6.2}$$

At this time, the WURx in [293] only receives and detects the OOK but later designs may incorporate transmission as a transceiver (WUTRx). However, the MCU-based sensor tag is already equipped to transmit multi-standard IEEE 802.15.4 including ZigBee, BLE, etc. and can be connected to standard 2.4 GHz 50 Ohm antenna. For the tags to wake-up each other (each equipped with WURx) with existing implementations, the MCU must transmit an OOK WUC to trigger a neighboring tag's WUR.

6.3 Methods

The PoC composed of two initial experiments to determine feasibility for: (1) the MCU responds to the wake-up trigger and controls the latch; and (2) the MCU generates a WUC to be detected by another WURx. The WURx is reasonably tunable. Testbeds defined for the WUR device-under-test (DUT) are outlined in Table 6.1 and depicted in Figs. 6.8 and 6.9. In Testbed 1 (Fig. 6.6) the known signal is the WUC generated to invoke the WURx wakeup signal output and wake the sensor tag. A known method

Table 6.1: Testbed Components

Testbed	**Purpose**
1 - Generate a Known Signal	Test MCU Response/Control
Signal Generator	Generate OOK
Arbitrary Waveform Generator	Mix OOK and RF
2.4GHz Antenna	Transmit
WURx EVB	Receive
WSN EVK (Telink TLSR8267)	1ry MCU
2 - Measure the DUT Signal	Test MCU Generate WUC
Power Sensor (U2042XA),	Pulse detect and analyze
or Signal Analyzer (N9020B), etc.	
2.4GHz Antenna or RF Probe	Receive
WSN EVK (Telink TLSR8267)	1ry MCU, Transmit

for generating a successful WUC for the WURx is a signal generator and waveform generator [293]. Testbed 2 measured the unknown DUTs (MCU-based tag) generation of the desired signal (WUC). An EVK board with an RF switch mounted to the 2.4GHz transmission path was connected to an RF probe and fed to a Power Sensor (U2042XA).

6.4 Results and Discussion

Successful experiments in [293] generated a known signal to which the WURx EVB responded as designed. The WURx detected the WUC from the transmitter (waveform generator and antenna) and invoked the wakeup signal observed on an oscilloscope. The testbed was replicated here and the wakeup signal output fed to the level shifter, which set the latch and the sensor tag read and cleared the latch. The behavior was as expected for the tag to respond to the wakeup signal and use the trigger to implement controlled behavior (clearing the latch). Next, successful OOK behavior from the tag was observed, with minor modification and within tolerance of the desired WuC for the WuRx. This was accomplished by employing the BLE Advertising (AD) beacon using the built-in multi-standard support from the MCU's embedded communications module. The BLE

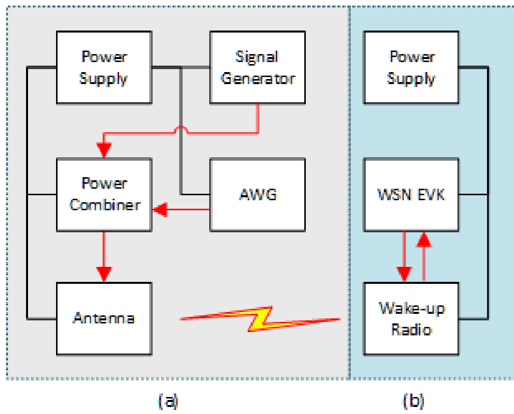

Figure 6.8: Testbed 1 block diagram

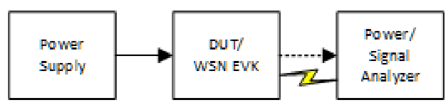

Figure 6.9: Testbed 2 block diagram

AD beacon is defined as a minimum 80us pulse width, and in this experiment 112us ON and 85us OFF was observed (Fig. 6.10) and is sufficient for PoC. This design is in prototyping phase at this time and restricted to laboratory testing for consistency and control of ESD and 2.4GHz wireless activity. A grand challenge in uniting these prototypes is a robust interface on a hybrid printed circuit board (PCB). The sensor tag PCBs are constructed with layers of standard FR4, but the high frequency WUR FE requires a hybrid of Rogers and FR4. From an operational perspective the design must also address the definition/modification of the MAC protocol for shared channel configurations. This TDMA approach is sufficient PoC but can benefit from protocol designs for ultra-low power wake-up systems such as [294].

Additional features can offer the ability to tune and uniquely address nodes [293]. WUR is also typically dual-antenna and sub-GHz, but recent research has demonstrated feasibility at higher frequencies such as 2.4GHz. Offloading MAC tasks to an intermediary between WUR and main radio is being explored for error checking and ignoring irrelevant messages. Another added capability with WUR FE is to harvest the ambient RF energy irradiating at the antenna during idle periods. This PoC can leverage recent

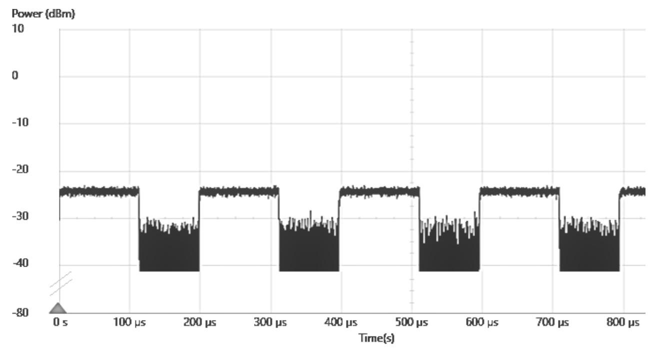

Figure 6.10: Observed DUT output was the 2.4GHz WUC (OOK) using Testbed 2 and BLE Advertising Beacon

designs in energy harvesting (EH) and wireless information and power transfer (WIPT), like using WiFi to power networks of connected devices [291].

Furthermore, the system integration PoC demonstrated here can be applied to diverse usages, such as large-scale building/office space monitoring or data centers to assist in airflow management. Equipping facilities with this unique architecture of WSNs with WUR offers visibility and connectivity without excess wires to achieve real-time monitoring and reduced energy consumption.

6.5 Conclusion

System integration was defined and implemented with preliminary results sufficient for PoC. The MCU successfully responded to the WURx wake-up pulse and generated a wake-up call sufficient to trigger a WUR module, satisfying initial system integration tests. Next steps will determine the interoperability between equipped tags with WUR. Research remains in the capabilities, cost, complexity, and usages to extend lifespan.

Acknowledgments

The authors sincerely appreciate key contributors: Arun Natarajan, Kamala Sadagopan, Giby Raphael, Linda Schwartz, Chris Carlson, and Paul Gohlke.

Part III

Special Topic in Agriculture LAM with Final Remarks

Farm-to-Fork Computing: Sensor Networks in Agriculture's Coldchain

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17-20 October 2019

Chapter 7: Farm-to-Fork Computing: Sensor Networks in Agriculture's Coldchain

Abstract: Growing concern among consumers and stakeholders in food safety, security, traceability, and sustainability is driving innovation of track-and-trace technologies. Wireless sensor networks (WSNs) can offer visibility and traceability in agriculture's supply chain from farm-to-fork (F2F). This effort enables realistic multi-scale deployment and industry transformation. This application-driven design requires a balance of technical expertise and use-case expert knowledge of operations, infrastructure, trends, limitations, and user experience 'on the floor'. A WSN architecture, implementation, and real-world experimental results are presented for the 1st major leg of the F2F journey. This preliminary study tracks blueberries from harvest to the distribution site. Broader impacts of this agricultural technology include reducing food loss and waste (FLW), improving response time, availability, forecasting, and more.

7.1 Introduction

World leaders recognized the growing need for sustainability across the agricultural supply chain, ranking Agriculture and Food Security as Sustainable Development Goal 2 (SDG2) on the 2030 Agenda for Sustainable Development [295]. This goal encompasses food scarcity, accessibility, affordability, traceability, sustainability, loss, waste, and more. Food loss and waste (FLW) occurs with perishables and typically involves refrigerated storage, processing, and distribution. Each year approx. 1.3 Billion tons of food is lost or wasted globally, which can almost feed half the world's population [296]. Consumers and distributors contribute to high FLW, offering many areas of opportunity to improve from farm-to-fork (F2F). Each stage can have significant impact directly and indirectly.

Detecting damage, contamination, inefficiencies, inconsistencies, etc. is key to drive awareness and change, but non-trivial at scale. Visibility to widespread real-time data on food quality along the supply chain is a grand challenge and technology can help. Sensor devices have proven useful for collecting in-situ critical temperature and humidity data needed for response and risk management. Electronics are more usable, affordable, and prolific than ever but not yet at an agricultural scale. Sensor technologies have enabled real-time monitoring of climate-controlled facilities and shipping containers yielding valuable microclimate data. Detecting and monitoring adverse microclimates for perishables in F2F translates to reduced FLW and more food reaching the hungry. Yet, widespread adoption of technology is hindered due to dependence on connectivity, energy, cost, and demand for real-world experiments demonstrating the use-case viability. A conflicting reality is that 'the convenience of wasting food often outweighs the cost' [297].

In response, this work presents a real-world design and application of wireless sensor networks (WSNs) in F2F to improve quality and safety with traceability at package-level. The full F2F journey is a complex, dynamic design challenge that can be considered in stages and combined in many ways to reach a consumer. This preliminary study is a work in progress that tracked blueberries from harvest to the 1st distribution site using ground transportation as seen in Fig. 7.1.

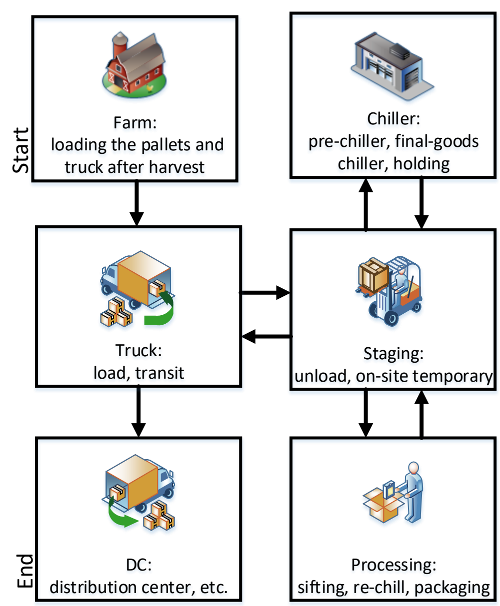

Figure 7.1: The F2F journey is a complex design challenge with dynamic flow from the farm to the distribution center (DC).

7.2 Design

7.2.1 Design Context

F2F sets many unique requirements and constraints significantly impacting WSN design and implementation, including:

- Real-time visibility of sensor data
- Stationary and/or mobile
- Dynamic reporting schedules
- Avoid wires or invasive infrastructure
- Ideally battery-/maintenance-free
- Endure harsh, dynamic environments
- Foodsafe materials and process integration
- Globally accepted, understood, and adoptable
- Variability, maturity of industry trends and standards
- Multi-level stakeholders, agreements, ownership

Several transportation modes (see Fig. 7.2) are used for various freight types including perishables, capital goods, pharma. Technology has the potential to transform complex industrial use-cases such as logistics and asset management (LAM) [2, 3]. A division of LAM uses the coldchain method of refrigerated-/frozen- freight, but varies in implementation. Coldchain is used in agriculture (e.g. perishables) and any electronics introduced for monitoring are exposed to harsh, dynamic, non-stationary scenarios. The electronics are rated to tolerate such conditions but are typically not designed to do so for long periods. Research is still needed for extended subfreezing usages but is out-of-scope here.

Perishable food must be kept refrigerated within standardized specific temperature ranges and exposure duration tolerances, maintaining 'safety zones' and avoiding 'danger zones' for (1) safety and (2) quality/shelf-life, ranges and risk vary depending on

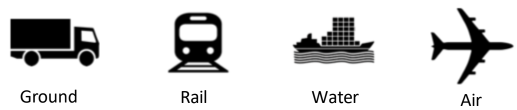

Figure 7.2: Example transportation modes include ground (road), rail, water (shipping), air, and more that can be combined worldwide for various freight.

product, processing stage, and more. Existing solutions are limited, expensive to scale, require infrastructure, maintenance, and data retrieval for monitoring perishables along the F2F journey. Today many facilities typically rely on investing in the appropriate air conditioning system, best practices and trainings, ad-hoc dataloggers, and on-the-spot sensor probe values recorded manually on paper. Consistency and response is critical, only a few hours out of the safety zone can result in exponential bacteria/mold growth, drastically reducing quality or risking safety, and food waste and lost profits. With the amount of equipment, pallets, produce, people, and vehicles quickly moving around the facility, tracking one pallet, let alone one tray of berries can be extremely challenging, dangerous, and time consuming. Typically, ad-hoc and/or manual log processes are implemented to some extent and merged with the inventory management systems. This is time-/labor-intensive and ROI can be improved with a mobile WSN with E2E visibility to the pallet-level data.

The WSN must move seamlessly with the product (e.g. fruit) from the farm to the processing site(s) to the distribution center(s), and finally the end consumer/store. With various stages of storing and packaging, cables and large batteries are not feasible and large equipment occupies space that could hold product (food/profit). Furthermore, the agricultural supply chain experiences dynamic schedules and environments hourly, potentially exposing the perishables to undesired or critical conditions (food safety or shelf-life).

7.2.2 Selected F2F Example

The WSN is applied to a real-world fruit use-case in collaboration with a local distributor. Blueberries were selected for their local availability and popularity at the time of study. Oregon is the leading producer in the USA with production at 131 million pounds in 2018's preliminary crop reports [298]. Blueberries exhibit a minimal processing flow that is similar and scalable to other fruit/vegetables despite unique schedules and requirements. The distributor routinely monitored temperature, humidity, duration in/out of safety zones, and more across various locations (truck, chillers, processing floor, etc.). Consider the typical flow for blueberries from harvest, to processing, to distribution center (DC). Fig. 7.3 shows an example 3-day schedule for blueberry processing.

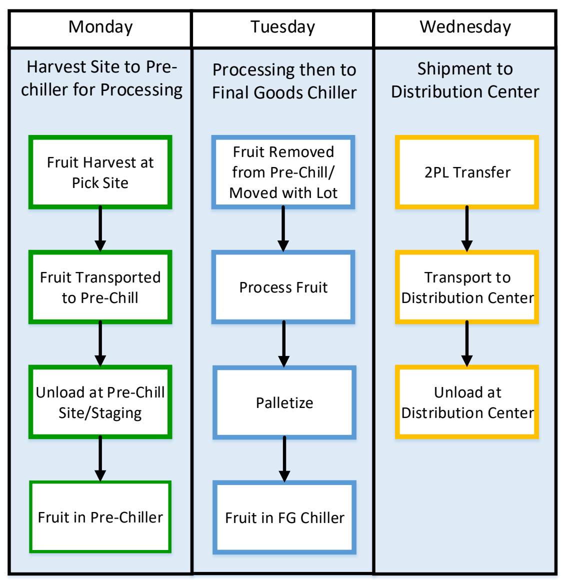

Figure 7.3: Example schedule for blueberries from harvest, to processing, to distribution center takes 3 days depending on fruit readiness, seasonality, market demand, etc.

Fig. 7.4 illustrates the flow at the processing facility. The raw blueberries are loaded in trays onto pallets at the farm, pre-chilled overnight to harden for processing, undergo minimal processing (sifting, chill/re-harden, then packaged), and palletized as outbound orders. The pallets may sit in the final goods chiller for a few days or weeks depending on season/market.

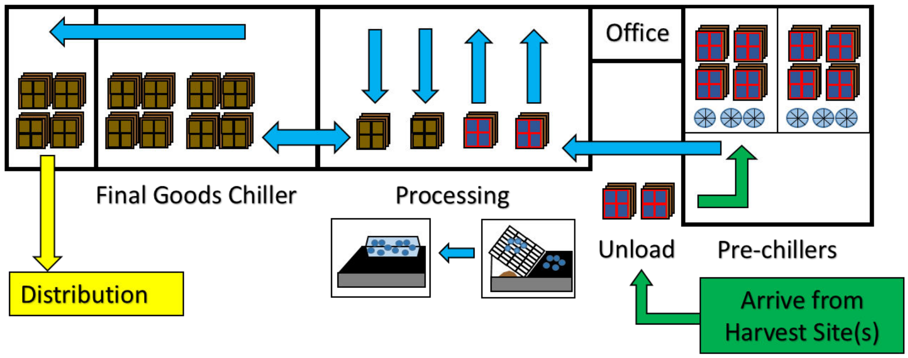

Figure 7.4: Raw blueberries arrive in trays on pallets at the processing site, pre-chill overnight to harden, undergo minimal processing (sifting, chill/re-harden, packaged), and palletized for DC.

7.2.3 New, Prolific, Actionable Data

The primary reasons to (densely) distribute sensor tags among the trays and pallets throughout F2F is to ensure (1) safety and (2) quality/shelf-life. This design focuses on 'actionable data' toward proactive computing to monitor, detect, and act/correct [299]. For example, temperature and humidity are indicators that someone/something needs to take action and correct the situation or trend, which in the agricultural industry translates to significant financial expense, food waste, lost time, etc. Existing methods of managing and reporting for regulatory compliance includes sampling of temperature, humidity, time, and place that are typically manual, ad-hoc, and localized throughout the F2F journey.

This work demonstrates a system to monitor and detect, along with the datapipe and mechanisms to achieve act/correct. Automating and scaling the coverage area of this sensor data collection with set-and-forget wireless devices yields:

- Sensor tag paired to pallet IDs, time, temperature, humidity, etc.
- In-situ monitoring with a mobile MCU-based WSN, gateway, and cloud services
- Real-time and historical data available on cloud database with analytic tools

The sensor tags must be mobile and continuously monitoring for real-time traceability of critical environmental metrics to inform operations, quality control, efficiency, and more. Most facilities can benefit from an E2E solution to study processes, exposure times, thermal control, etc. Visibility to trends and ability to respond real-time at the pallet-level throughout the facility and F2F journey allows for insights and optimizations. Areas of interest to optimize include minimum pre-chiller duration, pallet layout, refrigeration methods, inventory management, and more.

Automatic data collection with WSNs is feasible, yet successful designs can still struggle with real-world usability, sustainability, integration with infrastructure, computational interpretation, and meaningful presentation [299]. IoT and WSNs proliferate the Big Data Challenge with highly diverse data and stakeholders. The vast data needs to be presented in an easily navigable interpretation for those who need to use it (such as facility operators, etc.) toward better understanding, improving, and forecasting. The trends and alerts of threshold breach, such as rotting fruit or inadequate cooling. Visualizing the data with an E2E solution with WSNs enables facility managers to improve cold storage methods, leading to industry transformation and approaching the new-norm. The amount of computation and/or interpretation applied to the data for presentation and use remains open in research, first appearing in the vineyard computing context in 2004 [299]. No one-size-fits-all design exists and should take an ethnographic approach whenever possible. This depends on the use-case, amount and type of data, purpose of investigation (trends, event, etc.), expense, etc. However, the data must be easily readable, understandable, and informative without being overwhelming or off-putting.

7.2.4 System Architecture & Operation

This work used the WSN and E2E solution detailed in [3] and consists of a gateway device, sensor tags, on-boarding tool (OBT), and cloud services. The high level E2E system architecture is illustrated in Fig. 7.5 demonstrating connectivity from cloud to the gateway device to the sensor tags (WSN). The gateway device is akin to a smartphone with WiFi/cellular for cloud connectivity, embedded processing, and on-board memory storage. A larger internal battery supports deployment and smaller display screen helps reduce unnecessary cost, size, computing, and power consumption since the focus is to sense, process (minimimally), and transmit/receive. Also part of the gateway is a low-power WSN server module that uses short-range radio to wirelessly collect sensor data from the nearby assigned sensor devices (‘tags’). Each tag hosts a micro-

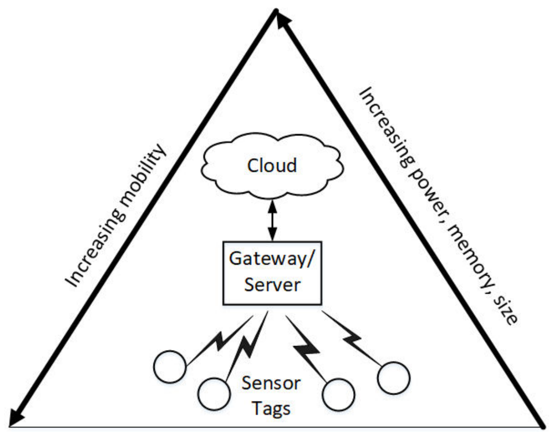

Figure 7.5: A typical high-level E2E system architecture has sensor node(s) with short-range communication and a gateway with long-range for cloud services. Mobility tends to be inversely related to the power, memory, and size.

controller (MCU)-based low-power sensing platform for environmental data collection and has an embedded communications module. This WSN is a set of devices forming a low-rate wireless personal area network (LR-WPAN) for short-range 2.4GHz communication using the IEEE 802.15.4 standard. A star network topology is sufficient for this introductory study and can modified to support other topologies. The tags wirelessly transmit to/receive from the server module of the gateway, which is processed by the gateway main module, stored, and sent to the cloud database at next connection to WiFi/cellular. In this way, the gateway collects the WSN data and sends it to the cloud for storage and processing, taking advantage of the gateway's greater connectivity and battery.

The OBT is used at the dock to assign ('provision') the gateway and sensor tags with the pallets and form a 'shipment' for tracking in the web interface. This information is exchanged between the WSN, OBT, and cloud services for complete visibility. After provisioning, the sensor data exchange on the E2E system occurs at configurable intervals (such as 60 seconds, 15 minutes, etc.). If the gateway does not have WiFi/cellular/etc. connectivity, then it will store the information from its assigned short-range WSN and push the stored data upon reconnection. In this use-case, the reporting schedule preference depends on the phase, for example the reporting interval should be faster for periods of transit or processing, but slower for periods of storage. The WSN and gateway can also operate as a mobile datalogging solution. At the end of the ‘shipment’ the gateway and tags are ‘de-instrumented’ at the dock using the OBT and can be reused for the next shipment. Future designs using non-OBT solutions could improve the network scheme with features like self-organization and self-healing.

Also considered during this design was the concept of human touchpoints as introduced by [299] regarding user interaction with pervasive computing systems. In this case, the WSN and E2E system become ’portals’ connecting an individual with the underlying system infrastructure:

- WSN, Gateway, OBT
- Cloud services

7.3 Methods

7.3.1 Approach and Guidelines

This work takes ethnographic research approach placing importance on the use-case, usability, and user-experience in light of the challenge to adoption of technology in agriculture with its scale and existing infrastructure. There is variation in methods, equipment, investments, and regulations around the globe adding to the complexity. Technology can be seen by some as disruptive to operations or return on investment (ROI), but risk is mitigated with co-design for cross-domain expertise. Studying the ‘flow on the floor’ has direct implications for designing WSNs in these use-cases, yielding a better understanding of the needs and priorities of the people operating the facility or business [299]. The guidelines adopted for this experiment included:

1. Aim for sufficient topology and coverage for meeting the goal - tradeoffs to over-designing, define baseline upon which to improve performance
2. Adapt to market and environmental dependencies - supply/demand effect on economics and shipments; harvest is seasonal, and systems are non-stationary without maintenance in harsh environments
3. Refine the approach - the environment can be dangerous for testing with extra people/equipment and can be invasive to existing infrastructure and flow, translating

to lost profits

The success criteria for real-world systems guiding this experiment are shown shown in Table 7.1, which can be described in three major categories:

- Technology Performance
- User Experience and Usability
- Business Value

Table 7.1: Success Criteria for Real-World PoC

SUCCESS CRITERIA
Hardware Health
End-to-End Data Collection from Field to DC
Data Accuracy/Integrity
Sensor accuracy
Creation of Lot & Tag IDs
Accuracy of Lot Process Steps
Data Visualization on UI
User Experience
Business Value

7.3.2 Special Considerations

Special considerations at field deployment also included: clean/sanitized devices, food-safe packaging, cold-tolerant batteries, and manually following the equipment in the processing flow. Until all aspects can be incorporated the systems were manually placed on the pallets at the harvest site before loading onto the truck. The GWs were placed on top and several tags distributed on the same pallet and surrounding pallets, tags placed between the handle-gaps of the blueberry trays stacked on the pallets. A 12-inch strip of food-safe ribbon was attached to each device for visual aid during the PoC. The devices were placed between the trays, avoiding the perimeter's exposure to extremely chaotic, harsh forklift/pallet-stacking. Identifying a fully integrated product solution is beyond the scope of this experiment. The devices at this early stage of integration cannot pass through the processing machinery so the devices were manually removed from the pallet at the start of the processing line and replaced on the re-formed pallet at the end of the processing line, preserving the pallet-level pairing of the sensor data. This experiment ensured WiFi/Cellular connectivity and 1:1 pallet of raw blueberry trays to pallet of processed/packaged blueberry boxes. This assumption is appropriate but variations can occur in practice.

7.4 Results & Discussion

7.4.1 Temperature Example

Fig. 7.6 shows the truckload of blueberries arriving from harvest, loading the pre-chiller, line start and stop in processing, final goods with tag tails, and loading the truck to the DC. The results shown in Fig. 7.7 demonstrate distinguishable variations in temperature through the phases of the supply chain. The temperature curve exhibits distinct behavior in and transitions between major phases, including fruit loading at the harvest site, placement overnight in cold storage, and during processing. The segmented behavior are the focus rather than the accuracy of the hardware in this study. From left to right, the stages include: harvest; pre-chiller; processing; chiller and storage; and distribution, ignoring the grey (left-/right-most) setup/padding data. The tags were provisioned to the sensor network and assigned to pallets of berries at the harvest site and removed at the DC handoff. These results demonstrate the viability of the WSN in the agricultural supply chain for visibility to the real-time environmental conditions and trends over time. This preliminary experiment successfully tracked blueberries from harvest to the 1st distribution site.

7.4.2 Continued Research

Work still remains in large-scale affordability, deployment, stakeholder agreements, and tracking the full F2F journey. A secondary benefit of this digital transformation can improve workplace safety, allowing workers to focus on the job-at-hand and the machinery,

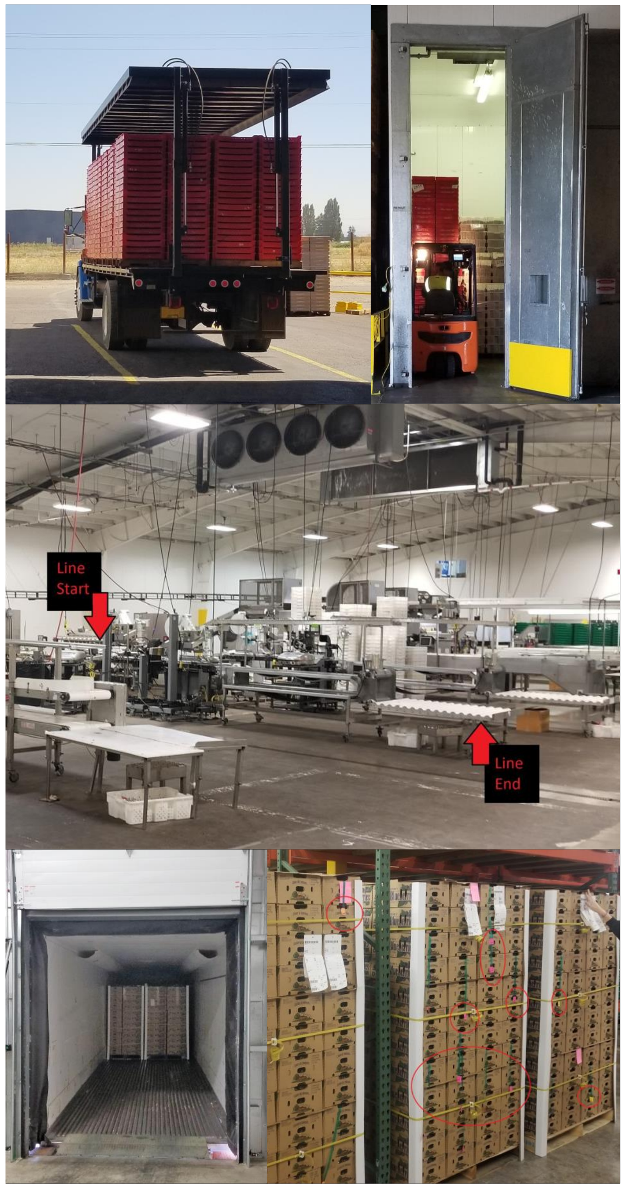

Figure 7.6: Truckload of blueberries arriving from harvest, loading the pre-chiller, line start and stop in processing, final goods with tag tails, and loading the truck to the DC (left to right)

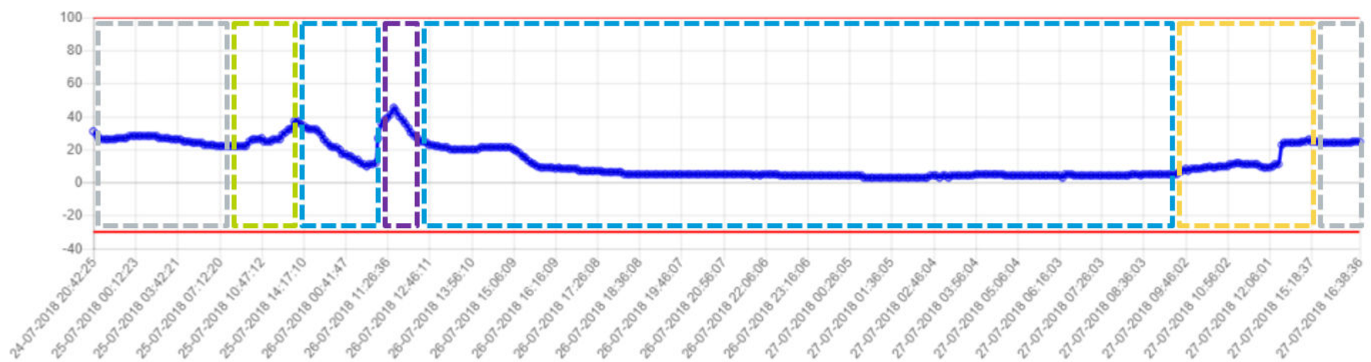

Figure 7.7: Temperature traceability for the 3 day test from harvest to distribution. (This sample data is to demonstrate the F2F stages not analyze device accuracy.)

rather than pen and paper. For the F2F and coldchain use-case, value is further added by pairing the data with on-site physical location and inventory management systems and displaying this with a SCADA (supervisory control and data acquisition system used for industrial facilities, such as data centers). Other extensions to this research in WSNs, IoT, LAM, and related topics include:

- Proactive computing and cyber-physical systems for automated control and response
- Cloud-based analytics and sensor network synthesis
- Integration with multi-level stakeholders, owners, etc.
- Combination with pre-harvest monitoring techniques

Furthermore, this work opens a big data pipeline for AI and ML to address some of societies major pain points. Recent research in IoT and agriculture explore the value of IoT sensor technology, contents of transaction payloads, and how/when/to whom data is shared. These are yet to be defined by the industry, consumers, and stakeholders. Sensors and blockchain is a research area as a solution for traceability, trustworthy exchange, and digital ledger. Trace-Forward techniques in LAM can be enabled by WSNs and blockchain technology, significantly reducing response time compared to trace-backward with paper trails across the supply chain. Continued research of T&T technologies holds promise in agriculture's supply chain for new opportunities. The WSN-enabled traceability can help reduce FLW, improve forecasting, shorten response time, improve trust, and more.

7.5 Conclusion

This work identified a WSN architecture, implementation, and real-world experimental results tracking perishables for the 1st major leg in F2F. As a work in progress, this preliminary study tracks blueberries from harvest to the distribution site. This work employed a balance of technical expertise and domain-specific knowledge of the use-case for flow of operations, infrastructure, trends, gaps, and usability. This application of WSNs in IoT demonstrated visibility and traceability of food quality indicators in F2F toward improving coldchain methods. This work enables further research in optimization and control, forecasting and risk management, and other techniques to reduce FLW, improve availability and connection, and more.

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Chapter 8: Conclusion

The Internet of Things (IoT) paradigm brought ever-increasing demand for device connectivity and lifespan, largely driven by applications of sensor systems in consumer and industrial use-cases. This collection of works evolved through the central theme of low-power wireless sensor networks (WSNs) in the IoT, with contributions ranging from an IoT literature review to enabling densely-scalable WSNs for logistics & asset management (LAM) in IIoT. Also proposed was to leverage wake-up radio (WUR) and energy harvesting (EH) toward battery-free WSNs. Lastly, this work proposed and demonstrated WSNs can improve visibility and control of airflow management in IoT applications such as data centers and farm-to-fork agriculture.

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