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Enabling Sustainable Networked Embedded Systems

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Abstract

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Networked Embedded Systems (NES) are small energy-constrained devices typically with sensors, radio and some form of energy storage. The past several years have seen a rapid growth of applications of NES, with several predictions stating billions of devices deployed in the near future. As NES are deployed at large scale, a growing challenge is to support NES for long periods of time without negatively impacting their physical or the radio environment, i.e., in a sustainable manner. In this dissertation, we identify intertwined challenges that affect the sustainability of NES systems: co-existence on the shared wireless spectrum; energy consumption; and the cost of the deployment and maintenance. We identify research directions to overcome these challenges and address them through the six research papers.

Firstly, NES have to co-exist with other wireless devices that operate on the shared wireless spectrum. A growing number of devices contending for the spectrum is challenging and leads to increased interference among them. To enable NES to co-exist with other wireless devices, we investigate the use of electronically steerable directional antennas (ESD). ESD antennas allow software-based control of the direction of maximum antenna gain on a per-packet basis and can operate within the severe energy constraints of NES. In the dissertation, we demonstrate that ESD antennas allow solutions that outperform the state-of-the-art in sensing and communication in wireless sensor networks while supporting operations on a single wireless channel reducing the contention on the shared wireless spectrum.

Secondly, we explore the emerging area of visible light sensing and communication to avoid the crowded radio frequency spectrum. Visible light can be an alternative or a complement to radio frequency for sensing and communication. We make two contributions in the dissertation to make the visible light communication a viable option for NES. We design a novel visible light sensing architecture that supports sensing and communication at tens of microwatts of power. An ultra-low power consumption can make visible light sensing systems pervasive. Our second contribution brings high-speed visible light communication to energy-constrained NES. We design a novel visible light receiver that adapts to the dynamics of changing light conditions, and the energy constraints of the host device while supporting a throughput comparable to radio frequency standards for NES. Through our contribution, we take a significant step to enable visible light-based sustainable NES.

Finally, replacing batteries on sensor nodes significantly affects the sustainability of NES. Battery-free sensors that harvest small amounts of energy from the ambient environment have a great potential to enable pervasive deployment of NES. To support wide-area deployments of battery-free sensors, we develop an ultra-low power and long-range communication mechanism. We demonstrate the ability to communicate to distances as long as a few kilometres while consuming tens of microwatts at the sensor device. Our contributions pave the way for a wide-area deployment of battery-free sustainable NES.

Through the contributions made in the dissertation, we take a significant step towards the broader goal of sustainable NES. The work included in the dissertation significantly improves the state-of-the-art in NES, in some case by orders of magnitude.

Keywords: Wireless Sensor Network; Energy harvesting; backscatter; RFID; Sensors

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In the end, I would like to thank my parents and family in India. It is challenging to live in an another country, thousands of miles away, and this thesis would not have been possible without their support, love and sacrifice.

This thesis is dedicated to my parents.

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **Ambuj Varshney**, Luca Mottola, Mats Carlsson, and Thiemo Voigt. 2015. Directional Transmissions and Receptions for High-throughput Bulk Forwarding in Wireless Sensor Networks. *In Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems (SenSys '15).* ACM, New York, NY, USA. DOI: https://doi.org/10.1145/2809695.2809720

II Bo Wei, **Ambuj Varshney**, Neal Patwari, Wen Hu, Thiemo Voigt, and Chun Tung Chou. 2015. dRTI: Directional Radio Tomographic Imaging. *In Proceedings of the 14th International Conference on Information Processing in Sensor Networks (IPSN '15).* ACM, New York, USA. DOI: http://dx.doi.org/10.1145/2737095.2737118

III **Ambuj Varshney**, Oliver Harms, Carlos Pérez-Penichet, Christian Rohner, Frederik Hermans, and Thiemo Voigt. 2017. LoRea: A Backscatter Architecture that Achieves a Long Communication Range. *In Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems (SenSys '17).* ACM, New York, USA. DOI: https://doi.org/10.1145/3131672.3131691

IV **Ambuj Varshney**, Carlos Perez Penichet, Christian Rohner, and Thiemo Voigt. 2017. Towards Wide-area Backscatter Networks. *In Proceedings of the 4th ACM Workshop on Hot Topics in Wireless (HotWireless '17) - in conjuction with ACM MOBICOM*. ACM, New York, NY, USA. DOI: https://doi.org/10.1145/3127882.3127888

V **Ambuj Varshney**, Andreas Soleiman, Luca Mottola, and Thiemo Voigt. 2017. Battery-free Visible Light Sensing. *In Proceedings of the 4th ACM Workshop on Visible Light Communication Systems (VLCS '17) - in conjuction with ACM MOBICOM*. ACM, New York, NY, USA, 3-8. DOI: https://doi.org/10.1145/3129881.3129890
(Best paper award)

VI **Ambuj Varshney**, Luca Mottola, Thiemo Voigt. 2018. Visible Light Communication for Wearable Computing. *under submission*

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List of papers not included in the dissertation

I have also authored or co-authored the following papers, posters and demonstration abstracts. These works are not included in the thesis, but still contributed to better understanding to solve the challenges discussed in the dissertation.

- Carlos-Perez Penichet, Claro Noda, Ambuj Varshney, Thiemo Voigt. 2018. Battery-free 802.15.4 Receiver.*In Proceedings of The 17th International Conference on Information Processing in Sensor Networks (IPSN)*, Portugal.

- Carlos-Perez Penichet, Claro Noda, Ambuj Varshney, Thiemo Voigt. 2018. Demo: Battery-free 802.15.4 Receiver. *In Proceedings of The 17th International Conference on Information Processing in Sensor Networks (IPSN)*, Portugal.

- Andreas Soleiman, Ambuj Varshney, and Thiemo Voigt. 2017. Poster: Battery-free Visible Light Sensing. *In Proceedings of The 23rd Annual International Conference on Mobile Computing and Networking (MobiCom '17).* ACM, New York, NY, USA, 582-584.
  DOI: https://doi.org/10.1145/3117811.3131252

- Andreas Soleiman, Ambuj Varshney, Luca Mottola, and Thiemo Voigt. 2017. Demo: Battery-free Visible Light Sensing. *In Proceedings of The 4th ACM Workshop on Visible Light Communication Systems (VLCS '17).* ACM, New York, NY, USA, 35-35.
  DOI: https://doi.org/10.1145/3129881.3129898

- Maximilian Stiefel, Elmar van Rijnswou, Carlos Perez-Penichet, Ambuj Varshney , Christian Rohner and Thiemo Voigt. 2017. Enabling Ambient Backscatter Using a Low-Cost Software Defined Radio. *In 13th Swedish National Computer Networking Workshop (SNCNW 2017)*, Halmstad, Sweden

- Ambuj Varshney, Carlos Pérez-Penichet, Christian Rohner, and Thiemo Voigt. 2017. LoRea: A Backscatter Architecture that Achieves a Long Communication Range. *In Proceedings of The 15th ACM Conference on Embedded Network Sensor Systems (SenSys '17)*, Rasit Eskicioglu (Ed.). ACM, New York, NY, USA, Article 50, 2 pages.
  DOI: https://doi.org/10.1145/3131672.3136996

- Carlos Perez-Penichet, Claro Noda, Ambuj Varshney, and Thiemo Voigt. 2017. Augmenting WSNs with Interoperable 802.15.4 Sensor Tags. *In Proceedings of The 15th ACM Conference on Embedded Network Sen-*

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- Carlos Perez-Penichet, Frederik Hermans, Ambuj Varshney, and Thiemo Voigt. 2016. Augmenting IoT networks with backscatter-enabled passive sensor tags. *In Proceedings of The 3rd Workshop on Hot Topics in Wireless (HotWireless '16)*. ACM, New York, NY, USA, 23-27. DOI: https://doi.org/10.1145/2980115.2980132

- Kasun Hewage, Ambuj Varshney, Abdalah Hilmia, and Thiemo Voigt. 2016. modBulb: a modular light bulb for visible light communication. *In Proceedings of The 3rd Workshop on Visible Light Communication Systems (VLCS '16)*. ACM, New York, NY, USA, 13-18. DOI: https://doi.org/10.1145/2981548.2981559

- Carlos Pérez-Penichet, Frederik Hermans, Ambuj Varshney, and Thiemo Voigt. 2016. Passive sensor tags: demo. *In Proceedings of The 22nd Annual International Conference on Mobile Computing and Networking (MobiCom '16)*. ACM, New York, NY, USA, 477-478. DOI: https://doi.org/10.1145/2973750.2985610

- Kasun Hewage, Ambuj Varshney, Abdalah Hilmia, and Thiemo Voigt. 2016. modBulb: a modular light bulb for visible light communication: demo. *In Proceedings of The 3rd Workshop on Visible Light Communication Systems (VLCS '16)*. ACM, New York, NY, USA, pages. DOI: https://doi.org/10.1145/2981548.3003711

- Abdalah Hilmia, Kasun Hewage, Ambuj Varshney, Christian Rohner, and Thiemo Voigt. 2016. BouKey: location-based key sharing using visible light communication: poster abstract. *In Proceedings of The 15th International Conference on Information Processing in Sensor Networks (IPSN '16)*. IEEE Press, Piscataway, NJ, USA, , Article 38 , 2 pages. DOI: https://doi.org/10.1109/IPSN.2016.7460699

- Elena Di Lascio, Ambuj Varshney, Thiemo Voigt, and Carlos Perez-Penichet. 2016. LocaLight: a battery-free passive localization system using visible light: poster abstract. *In Proceedings of The 15th International Conference on Information Processing in Sensor Networks (IPSN '16)*. IEEE Press, Piscataway, NJ, USA, , Article 60 , 2 pages. DOI: https://doi.org/10.1109/IPSN.2016.7460707

- Carlos Perez-Penichet, Ambuj Varshney, Frederik Hermans, Christian Rohner, and Thiemo Voigt. 2016. Do Multiple Bits per Symbol Increase the Throughput of Ambient Backscatter Communications?. *In Proceedings of The 2016 International Conference on Embedded Wire-*

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- Ambuj Varshney, Luca Mottola, and Thiemo Voigt. 2015. Poster: Coordination of Wireless Sensor Networks using Visible Light. *In Proceedings of The 13th ACM Conference on Embedded Networked Sensor Systems (SenSys '15).* ACM, New York, NY, USA, 421-422. DOI: https://doi.org/10.1145/2809695.2817894

- Ambuj Varshney, Thiemo Voigt, and Luca Mottola. 2014. Poster abstract: directional transmissions and receptions for burst forwarding using disjoint paths. *In Proceedings of The 13th international symposium on Information processing in sensor networks (IPSN '14).* IEEE Press, Piscataway, NJ, USA, 307-308.
DOI: https://doi.org/10.1109/IPSN.2014.6846776

- Juan M Alonso, Thiemo Voigt and Ambuj Varshney. 2013. Bounds on the Lifetime of WSNs. *In Proceedings of the 5th International Workshop on Performance Control in Wireless Sensor Networks in conjunction with IEEE DCOSS*, 2013, Massachusetts, USA.
DOI: https://doi.org/10.1109/DCOSS.2013.34

- Ambuj Varshney, Thiemo Voigt, and Luca Mottola. 2013. Directional transmissions and receptions for high throughput burst forwarding. *In Proceedings of The 11th ACM Conference on Embedded Networked Sensor Systems (SenSys '13).* ACM, New York, NY, USA, Article 50, 2 pages. DOI: https://doi.org/10.1145/2517351.2517424

- Ambuj Varshney, Luca Mottola and Thiemo Voigt. 2013. Using Directional Transmissions and Receptions to reduce contention in Wireless Sensor Networks. *In Proceedings of the 5th International Workshop on Real-world Wireless Sensor Networks (REALWSN)*, Como Lake (Italy), 2013. DOI: https://doi.org/10.1007/978-3-319-03071-5_21

Contents

Part I:
Dissertation Summary

1. Introduction

The past decades have witnessed a phenomenal growth of sensor-based applications. Sensors influence every aspect of our life; they help track our daily activities [58], navigate the physical world [31, 30, 51], or maintain personal comfort by monitoring the ambient temperature [41]. Sensor-based applications are commonly implemented using embedded devices which communicate with each other or to a deployed infrastructure using radio frequency (RF) signals forming a distributed network [19, 50]. In this dissertation, we call distributed networks of embedded sensors a Networked Embedded Systems (NES). Gartner states that there were already 5 billion connected devices in 2015, and this rapid growth is going to accelerate in the future, with predictions that this number would grow to 25 billion by 2020 [22].

With NES deployed at a large scale, a significant and emerging challenge is to sustain them over long periods of time [13]. Sustaining NES is particularly tricky as the sensors are commonly deployed in large numbers, unattended and often in hard-to-reach places like embedded within the infrastructure such as bridges [8] or inside floors in a building. Further, NES operate on the shared wireless spectrum and have to co-exist with other wireless devices. A decade of experience has shown that NES even at a small scale are difficult to develop, deploy and maintain. As an example, Li et al. report difficulty to maintain a visible light sensing testbed, and report 41 damaged photodiodes in a matter of weeks [32]. In another example, Liang et al. suffer the problem of co-existence on the shared spectrum, and report significant WiFi traffic on 802.15.4 channels occupied by the NES [35]. These examples do not represent all the challenges faced by the NES when deployed for long time periods, and the literature from decades of experiences of NES [46] brings forward other difficulties faced by NES. However, to a large extent there is a consensus that there is a need to develop and deploy NES in a manner that they can function for long periods of time reliably, without increasing the cost of deployment, or the maintenance effort required after deployment, i.e., in a *sustainable* manner.

Sustainability as a concept is complex with several definitions of the term across disciplines. Sustainability in ecology refers to the ability of biological systems to remain productive and diverse for a long period of time. We adopt the definition of sustainability similar to the definition in ecology, as NES like biological systems have to remain productive for a significant period without negatively impacting their physical or the radio environment.

An important question that we ask: *What are the significant factors that influence the sustainability of NES ?*

1.1 Challenges to Sustainable Networked Embedded Systems

Based on a decade of experience with NES [35, 32, 33, 69, 36, 55, 42, 13] three crucial themes stand out which influence the sustainability of NES: energy consumption, co-existence with other wireless devices and sensors, the cost of the deployment and maintenance. The three themes are by no means independent, they influence each other and impact the overall sustainability of NES. As an example, a high energy consumption requires the sensors to operate on batteries which need to be frequently replenished affecting the cost of deployment and maintenance. Similarly, a significant interference on the shared wireless medium impacts the reliability and requires sensors to frequently re-transmit increasing the overall energy consumption.

1.1.1 Energy Consumption

Energy consumption is a critical parameter that has influenced the design of NES for more than a decade. The energy consumption impacts the choice of sensors and their resolution, the underlying communication mechanism, the physical form , the overall lifetime, and the deployment and maintenance issues. *What influences the energy consumption of NES ?*

A sensor node in its most general form consists of a radio transceiver, a computational block such as a microcontroller, one or more sensors, and an energy storage unit [19, 50]. As an energy storage unit, to keep the form factor of the sensor small and to lower the cost of the device, sensor nodes use batteries with limited capacity for energy storage such as AAA batteries. However, the particular architecture imposes two challenges: *First*, the energy cost of communication dominates the overall power consumption as radio transceivers based on the IEEE 802.15.4 standard consume mWs of power. The high power consumption requires the sensor nodes to duty cycle their transceivers and has resulted in sustained efforts to devise radio duty cycling mechanisms (RDC) [59], and associated networking mechanisms. However, despite decades of efforts, sensor nodes achieve limited battery lifetime for applications using high-bandwidth sensors such as cameras [44] or microphones [71, 56]. *Second*, the computational block increases the complexity and the power consumption of the sensor [71, 56, 61, 44]. The high energy cost for communication and processing makes battery-powered sensor nodes consume mWs of power and requires duty-cycled operation despite the fact that individual sensors are becoming exceedingly energy efficient with sensors such as microphones achieving few-μWs of power consumption [71, 56].

In summary, the disparity in energy consumption between sensing, computation and communication remains a critical bottleneck in sensor systems [61, 56, 71, 44]. The disparity in energy consumption increases the overall power consumption and requires a duty cycled operation on batteries.

1.1.2 Cost of Deployment and Maintenance

One of the factors that affect the sustainability of the NES is the cost of the deployment, and after that maintenance over the lifetime of the application. For NES deployed on a massive scale, the price of the individual sensor nodes begins to play a significant role. Traditional sensor nodes can easily cost few USD or more due to the use of sophisticated and expensive components such as MCUs/FPGAs, conventional radio transceivers [55] etc. The high cost is detrimental to the vision of ubiquitous and sustainable deployment of NES [13, 55]. Thus, an essential challenge to long-term sustainable sensing is to significantly lower the cost of the sensor nodes to enable a massive deployment at scale; a vision that was propagated by smart-dust [25].

While the cost of the individual sensor node and the cost of initial deployment is vital to sustainable NES, the price to maintain over the lifetime of the application plays a more significant role, with the task of replacing batteries on the sensor nodes dominating the overall effort. As Dutta [13] points out that even simple tasks like replacing batteries on a handful of sensors could be challenging, and to perform the function on sensors deployed at scale many of which could be in hard to reach places such as embedded in walls or under floors can be untenable. Another important aspect of reliance on batteries is the negative impact of batteries on the environment. Batteries are usually made using toxic chemicals and when disposed from a large scale NES deployment could negatively impact the environment. Hence, an essential direction to support long-term sustainable NES is to either operate NES for long periods of time such as a decade on batteries or to eliminate batteries entirely from them, with the sensors scavenging energy from the ambient environment and storing them in small capacitors for the operation [39].

1.1.3 Co-existence on Shared Wireless Spectrum

NES operate on the spectrum shared with other wireless devices. NES communicate with each other, and the deployed infrastructure using radio frequency (RF) signals. However, the shared nature of the wireless medium forces them to contend for the medium with other wireless devices such as WiFi routers that often transmit at significantly higher output power. An increasing number of devices competing for the spectrum, and operating on the same frequency band leads to increased cross-technology interference (CTI). CTI affects the reliability and the latency of the communication.

Acknowledging the challenges of the increase in CTI to the operation and scaling of the NES, the past several years have seen several approaches to mitigate the effects of CTI on low power wireless links: classify the source of the interference [23, 53], redundancy to improve reliability [37], concurrent transmissions mechanisms [17, 16, 11, 12], or the use of frequency diversity [35, 11, 12]. While all these approaches improve the ability of NES to co-exist with wireless devices that operate on the shared spectrum, however, the ever-growing number of devices make this a severe problem. Hence, a significant challenge to sustaining the rapid growth of NES is to find novel mechanisms to make efficient use of the RF spectrum or even alternatives to conventional RF communication.

1.2 Research Direction and Method

We adopt three directions to address the challenges to sustainable sensing introduced earlier. In the first research direction, we address the problem posed by the crowded RF spectrum using an ultra-low power and cost Electronically Steerable Directional (ESD) Antenna [45, 47]. In the second research direction, we explore ultra-low power sensing and communication mechanisms to enable battery-free sustainable NES. The final direction examines visible light as an alternative to RF to avoid the crowded RF spectrum.

1.2.1 Research Method

In this dissertation, we take an approach to the hardware and the software co-development to address the challenge of sustainable NES. Our approach differs from a vast majority of solutions presented over the past decade that look at the hardware or software aspects in isolation. As an example, solutions to tackle the high energy consumption of transceivers commonly devise software-based RDC mechanisms to ameliorate high power consumption [59, 14]. However, the high peak power consumption of the underlying transceiver restricts the RDC mechanisms. On the other hand, novel hardware platforms such as ESD antennas [47, 45] introduce new capabilities, however, lack higher layer software support regarding networking mechanisms to exploit them. Our approach takes inspiration from state-of-the-art systems such as Ambient Backscatter [39], Interscatter [24] or DarkLight [57] that devise new sensing and communication hardware, but also explore the higher layer aspects such as network stack, and application use case of the technology.

1.2.2 Directional Antennas for Sustainable Wireless Co-Existence

Directional antennas radiate or receive electromagnetic radiation at the highest signal strength only in their direction of maximum gain. Directional antennas are extensively used in wireless systems and have been a topic of active research for one-hop networks such as WiFi [40, 3] or cellular networks. State-of-the-art systems demonstrate that directional antennas can help reduce wireless contention [62], improve throughput and resilience to interference [67] and increase the communication range [73]. The directional antennas by concentrating or receiving electromagnetic radiation only from a specific direction can allow a high degree of spatial usage, and improve the ability of wireless devices to co-exist on the shared spectrum. Hence, directional antennas could be an enabler for our goal of sustainable NES.

ESD antennas allow the electronic control of the direction of maximum antenna gain, which helps NES mitigate contention on per-packet basis depending on the prevailing wireless traffic conditions [62]. However, the benefits offered by the ESD antennas remained out of reach for the low-power wireless research community for an extended period due to the lack of ESD antennas that meet the stringent energy constraints of NES.

Nilsson designed an antenna called SPIDA or Sics Parasitic Interference Detection Antenna [45, 47], one of the first ESD antenna for low-power NES. The only electronic components in the SPIDA antenna are the RF-switches, that consume few µWs of power. SPIDA has six parasitic elements surrounding a quarter wavelength monopole antenna. As a result of this design, the antenna gain varies as an offset circle from -4 to +7 dB in the horizontal plane. SPIDA offers six directional configurations, plus the omnidirectional mode. Contiki drivers allow a programmer to control the grounding or isolation of individual parasitic elements via software. In this dissertation, we use antennas with similar design and radiation pattern as SPIDA.

NES are inherently multihop in nature and offer a different challenge when compared to one-hop wireless networks where ESD antennas have been extensively studied. To investigate the benefits provided by ESD antennas for NES, we implement the first testbed of sensor nodes equipped with ESD antennas. In this dissertation, using this testbed, we develop spectrum friendly sensing and communication solutions that improve the state-of-the-art [12, 26] in wireless sensor networks (WSN), and take a step towards sustainable NES.

1.2.3 Battery-free Sustainable Networked Embedded Systems

To overcome the high power consumption and to reduce the cost of the deployment and the maintenance, we embrace the emerging direction that eliminates batteries from the design of NES [13, 39, 64, 55, 44, 56]. Battery-free sensors operate on small amounts of energy harvested from the environment such as solar, heat [6]. They commonly employ a small capacitor as the energy storage unit [39]. Battery-free sensors can be deployed at hard to reach places such as inside the floor, or deployed and maintained at scale without worrying about replacing batteries and the associated cost. Battery-free sensors are commonly intermittently powered, and operate at a stringent power budget when compared to their battery-powered counterpart. The severe power constraints prompt us to revisit the traditional sensor node architecture [19, 50].

Communication has been the most expensive operation on the traditional sensor node. The high power consumption required for radio transceiver makes it challenging to support wireless transmissions on energy harvesting sensors. Backscatter communication by reflecting or absorbing ambient RF signal enables ultra-low power wireless transmissions, and overturns the assumption that communication is the most energy expensive operation. Zhang et al. demonstrate that processing cost dominates the overall power consumption on backscatter based sensors [71]. The ultra-low power nature of backscatter makes it the mechanism of choice to support wireless transmission on battery-free sensors. Despite the suitability of backscatter for battery-free sensors, the application scenarios for backscatter-based sensors remain limited due to tens of meters of range [55], and high energy cost of the sensor node due to the use of computational blocks [56, 44, 71] in the state-of-the-art systems.

In this dissertation, we overcome the low-communication range of backscatter communication, and overturn the assumption that backscatter is a low range mechanism. Further, we identify the computational block as a bottleneck to achieve very low power consumption, and we devise an approach to eliminate it from the architecture. We believe our contributions take a major step to significantly expand the application scenarios for backscatter-based battery-free NES, and take a step towards battery-free sustainable NES.

1.2.4 Visible Light as an Alternative to RF for Sensing and Communication

Visible light is a pervasive medium that provides illumination to spaces or objects through low-cost fluorescent bulbs, light emitting diodes (LEDs) or natural light. Visible light can be used for communication or for sensing to enable applications like localisation or gesture recognition.

The concept behind Visible Light Communication (VLC) is intuitive and straightforward: The human eye cannot perceive changes in the light at a rate higher than a minimum (usually 200 Hz [31]). Encoding information in rapid changes in the light intensity (amplitude) enables transmission of information such as location data using visible light. While rapid changes in visible light are invisible to the human eye, they can be tracked by a VLC receiver to demodulate and receive information. Visible light is orthogonal to RF signals, and when used for communication avoids the crowded RF spectrum.

Visible Light Sensing (VLS) systems use visible light as a sensing medium. The VLS systems are of two categories: In the first category are systems that require modification of the lighting infrastructure to transmit beacons through VLC. Beacon-based systems often enable applications such as localisation [30] or location landmarks [51]. The passive visible light sensing systems take advantage of the fact that natural human actions such as hand gestures or movements cause a unique change in the light intensity pattern which can identify them. The systems in this category use the shadow cast on light sensors to sense. Passive VLS systems enable new applications such as human posture reconstruction [32, 33], hand gesture recognition [34] or gesture recognition [61]. Passive VLS systems can enable ubiquitous and sustainable sensing through the use of ambient light around us as a sensing medium.

In this dissertation, we take steps to enable pervasive deployment of visible light-based sensing and communication systems. We identify the commonly employed light sensing architecture as a bottleneck, and devise low power passive light sensing and communication mechanisms that take a step to make visible light an alternative to RF for NES. Our contributions help NES mitigate challenges of the crowded radio frequency spectrum, overcome high energy consumption of state-of-the-art systems [32, 33, 65, 54], and thus pave the way to sustainable visible light-based NES.

2. Research Challenges and Contributions

We adopt three interconnected directions with the broader goal to achieve our vision of sustainable NES which we discuss in this section.

Our first research direction explores ESD [45] antennas to mitigate the effects of increased contention and CTI. ESD antennas add a much needed and relatively unexplored dimension of using the directional antennas to help the NES co-exist on the shared wireless spectrum. However, the use of ESD antennas in NES, and the corresponding protocol support has been mainly missing due to lack of ESD antenna testbed. Through the contributions made in the dissertation, we address this research challenges and develop spectrum friendly sensing and communication mechanisms that improve the state-of-the-art in WSN. The direction enables NES co-exist in crowded RF spectrum.

The second research direction investigates the use of visible light as an alternative to RF in NES. Visible light avoids the crowded RF spectrum and enables NES to avoid CTI. We identify the traditional and widely used light sensing architecture as a bottleneck to widespread usage of visible light in NES. We rethink this architecture and take a step to make visible light an alternative to RF for NES enabling visible light based sustainable NES.

Finally, battery-free NES holds the potential to support sustainable NES on a large scale. RF backscatter is emerging as the mechanism of choice to support wireless transmissions from battery-free devices that operate on a minuscule amount of energy harvested from the environment. The backscatter communication faces key challenge of low communication range that limit the widespread deployment. We overturn the notion that backscatter is a short-range communication mechanism and demonstrate the ability to achieve a long communication range while consuming only tens of µWs of power. Our contributions are an enabler to wide area networks of battery free NES.

Through the above three directions, we significantly improve the state-of-the-art in NES and take steps to support our vision of sustainable NES.

2.1 Electronically Steerable Directional Antennas for Sustainable Wireless Co-Existence

ESD antennas through electronic control of the direction of the maximum gain enable NES to reduce interference and contention from sensors and wireless devices operating on the same frequency band. ESD antennas offer excellent potential to allow NES to co-exist on the shared spectrum to allow sustainable sensing and communication.

2.1.1 Research Challenges

State-of-the-art sensing and communication mechanisms in NES face challenge of CTI from wireless devices operating on the same frequency band. ESD antennas can help, but face challenge of lack of testbed and protocol support to use the ability of ESD antennas.

ESD Antenna Testbed for WSN. Testbeds such as Indriya [10], JamLab [7], FlockLab [38] allow repeatable and large-scale experiments to evaluate systems and networking issues in WSN. The testbeds employ standard WSN nodes such as Telos B [50] equipped with 802.15.4 radio, omnidirectional antenna and sensors. However, standard WSN nodes pose a problem as we cannot develop solutions that use the ability of ESD antennas to control the direction of maximum antenna gain. The lack of WSN testbeds that can support ESD antennas restricts studies related to directional communication in WSN to simulation [43], or one-hop scenarios [47, 63, 45]. Hence, there is a need to develop an ESD antenna-equipped WSN testbed to develop spectrum efficient sensing and communication solutions to enable sustainable NES.

Multihop Bulk Data Transmission. Bulk data transmission is a vital communication pattern in low-power wireless sensor networks. Hundreds of sensors monitor a phenomenon such as Volcano eruptions [66] and communicate the bulk sensor readings to a powerful base station for processing. The communication takes place through multiple hops. Transmission of bulk data requires the energy expensive radio transceiver to be switched on for extended periods of time when compared to applications that require convergecast as a traffic pattern. Hence, it is crucial that bulk transmission protocols achieve high throughput and reliability to communicate for the least possible time duration, and therefore consume the least amount of energy.

A decade of research effort has led to several bulk transmission protocols [12, 29]. State-of-the-art protocols such as P3 [12] construct disjoint path packet transmissions to transmit data at a high throughput between the sensor and the sink node. A multi-hop wireless link is affected by the interpath and intrapath interference [29]. Bulk transmission protocols such as P3 [12] and PIP [52] operate on multiple wireless channels to mitigate interpath and intrapath interference and achieve very high throughput. However, the use of several wireless channels for bulk data transmission significantly increases the wireless contention and might also increase the impact of CTI on the bulk traffic. Hence, to enable NES to co-exist on the shared spectrum with other wireless devices, it is important to devise communication solutions that use only one wireless channel for the operation.

Radio Tomographic Imaging. Radio Tomographic Imaging (RTI) is a device-free localisation system which enables localisation of person or object indoors. In a typical scenario a large number of low-power wireless sensor nodes are deployed in the area of interest to collect link statistics. By observing changes in statistics of radio links, an object or person of interest is localised. In an RTI

Figure 2.1. ESD antenna testbed environment. We set up the testbed in a 32 sqm office environment in our institution's building. The office environment features a complex radio setting, with metallic objects in the corners and the ceiling.

application, due to a large deployment of sensors which periodically transmit probe messages, it is vital to mitigate interference from the RTI to other coexisting wireless networks. This is particularly challenging, as state-of-the-art RTI systems often leverage channel diversity to improve the accuracy [26]. However, using several channels for frequent probe messages negatively impacts the prospect of coexistence of RTI systems with other wireless networks.

2.1.2 Research Contributions

We make several contributions that use the ability of ESD antennas to support spectrum-friendly solutions for battery-operated NES.

Multihop ESD Antenna Testbed. We develop a testbed of WSN nodes equipped with an electronically steerable directional antenna (ESD) - SPIDA [45, 47]. The testbed overcomes the limitation of WSN testbeds [7, 38, 10] in that it allows the electronic control of the direction of maximum antenna gain on the sensor nodes. Due to the constraints of limited space and the availability of low-power sensor nodes in the university, we developed a small testbed using 15 TelosB sensor nodes [50]. We set up the testbed in a 32 sqm office environment in our institution's building. The office environment features a complex radio setting, with metallic objects in the corners and the ceiling, as shown in Figure 2.1. Other interfering wireless networks are also abundantly present. We reprogram and communicate with individual sensor nodes using external USB cables.

High-throughput Bulk Transmissions using ESD Antennas. Our first contribution is a high-throughput bulk data transmission protocol that we call Directional Pipelined Transmission (DPT). In Paper I, we introduce DPT that achieves the highest demonstrated throughput over low-power 802.15.4 multihop wireless links peaking at 214 kbit/s in the settings we test. As opposed to state-of-the-art bulk transmission protocols such as PIP [52] or P3 [12] that

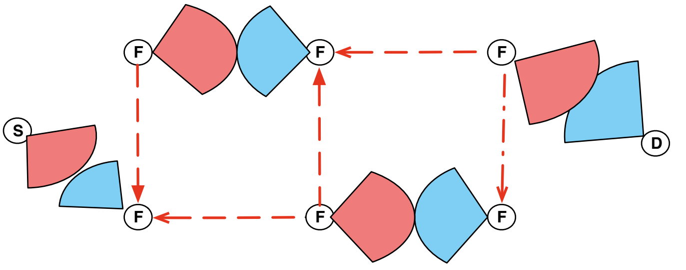

Figure 2.2. DPT transmissions occur in parallel over the two paths at non-interfering links. The nodes change antenna orientation based on which of the two paths is active. S indicates the source node, D indicates the sink, and F nodes are forwarding. Dashed arrows indicate possible interference at the receiving end. Darker (red) arcs indicate directional transmissions, lighter arcs (blue) are directional receptions.

use several wireless channels to reduce interpath and intrapath interference, DPT achieves high throughput while operating only on one wireless channel. As bulk data transmissions occupy the wireless channel for an extended period when compared to the typical WSN traffic pattern, the ability of DPT to operate on a single wireless channel reduces contention substantially and helps sensor nodes co-exist with other wireless devices, and hence supports our vision of sustainable NES.

Directional Radio Tomographic Imaging. Our second contribution is to develop a device-free passive localisation system based on RTI. In Paper II, we develop a system that we call Directional Radio Tomographic Imaging (dRTI) that uses the ability of ESD antennas to improve the accuracy of RTI. dRTI when compared to the state-of-the-art solution that uses several wireless channels for operation [26], requires only a single wireless channel. dRTI by supporting passive device-free localisation, and using a single wireless channel supports vision of sustainable NES.

2.2 Battery-free Sustainable Networked Embedded Systems

Backscatter communication has been in existence for more than half a century. The earliest example of a device using backscatter communication was a surveillance device gifted by the Russians to the US Embassy that transmitted audio signals called "the great seal bug" [1]. Backscatter communiction due to the ultra-low power nature is emerging as a mechanism of choice to support wireless transmissions on battery-free sensors. Backscatter is a key enabler to our vision of battery-free sustainable NES. However, the adoption of backscatter communication in NES has been limited.

2.2.1 Research Challenges

Backscatter communication faces key research challenges - low communication range, expensive reader infrastructure, and lack of system support for large-scale operations that limit the application scenarios of the technology and restrict our vision of sustainable battery-free NES.

Low Communication Range. Backscatter communication has been widely used in RFID and related systems as a low-power transmission mechanism for a decade, with the perception that backscatter is a low communication range mechanism. As an example, the widely used passive RFID systems can communicate only up to a distance of 18 m [21]. On the other hand, state-of-the-art backscatter systems such as HitchHike [70], Interscatter [24], BackFi [5] Passive WiFi [28], BLE Backscatter [15], WiFi Backscatter [27] demonstrate a maximum communication range of tens of meters.

The low communication range of the state-of-the-art backscatter systems are due to two key factors: these systems reflect commodity wireless protocols such as WiFi [27, 28, 24] or BLE [15] that operate at high bitrates and consequently, occupy a large bandwidth. As the sensitivity for reception decreases with higher bandwidth, systems that backscatter commodity protocols achieve a short communication range. Another reason for the low communication range is that many backscatter systems such as BackFi [5] transmit information at the same frequency as the excitation (carrier) signal which causes severe self-interference restricting the achievable communication range. The low communication range negatively impacts the possible application scenarios for backscatter based battery-free NES.

Infrastructure for Backscatter Reception. A significant constraint that has restricted the widespread use of backscatter systems is the requirement of an expensive reader device to receive the weak backscatter reflections. RFID, Computational RFIDs [49], and systems such as BackFi [5] require specialised equipment to power the passive backscatter tags, provide the excitation signal, and receive backscatter reflections. However, an RFID reader can cost around USD 1000 [55]. Further, the reader also consumes a significant amount of power (4 W), which can make many application scenarios that need mobile backscatter readers challenging.

What are the main reasons that cause the backscatter reader to be expensive and consume high power? Conventional backscatter tags transmit at the same frequency as the excitation signal. However, as the backscatter reflections are inherently weak, the strong carrier overwhelms the weak backscatter reflection. Readers employ complex mechanisms and self-interference cancellation techniques to receive backscatter transmissions in the presence of the carrier signal which increases the cost and power consumption of the reader [5]. A second important aspect is the need to generate the strong carrier signal. The backscatter readers generate a strong carrier signal that is typically 4 W which increases the power consumption and complexity of the backscatter reader. To enable backscatter based battery-free NES a significant research challenge is to lower the cost of the carrier generation, and the reader device required to receive backscatter transmissions.

System Support for Large-scale Deployment. A large-scale deployment of backscatter-based and battery-free NES is challenging and requires us to solve essential research challenges. It is not difficult to imagine that if we have a large number of sensors deployed, many of these could communicate at the same time. Hence, there is a need to support simultaneous transmissions from many sensors at the same time. There exists systems that devises mechanisms to support simultaneous transmissions for backscatter sensors [20, 48]. However, the tags in these systems transmit at the same frequency and require significant processing at the reader device to recover information from collided transmissions which significantly increases the complexity and the cost of the reader. A high price for the reader, as discussed earlier negatively impacts the sustainability of large-scale deployment.

Another critical challenge is the reliability of the link between the sensor and the reader device. Large-scale deployments of sensors require the backscatter sensors to communicate to distances of hundreds of meters. Receptions at large distances is challenging, as systems such as LoRea [60] and LoRa backscatter [55] use commodity radio transceivers with high sensitivity to achieve a long communication range. Receptions at very low sensitivity make backscatter tags prone to interference from wireless devices operating on the same spectrum, and also from the carrier signal. Hence, an essential challenge to a battery-free sustainable NES is to develop system support for large-scale deployment and operation.

2.2.2 Research Contributions

We overcome the low communication range of backscatter communication, and present our vision of wide-area networks of battery-free sustainable NES.

Long-Range Backscatter Communication. To improve the communication range of the backscatter transmissions, in this dissertation, we take a step to overturn the long-standing assumption that backscatter is a short-range communication mechanism. We present a backscatter architecture that we call LoRea (Paper III) that achieves the highest demonstrated range with backscatter communication. LoRea achieves a range of 3.4 km while only consuming 70 μW at the backscatter tag. The architecture consists of multiple carrier generators, a low-cost reader, and a backscatter tag, as shown in Figure 2.3.

LoRea overcomes the cost limitations of existing RFID and CRFID systems building on insights from Zhang et al. that backscatter is a mixing process [72], which allows us to keep the backscatter transmissions and the carrier signal apart in frequency. Separation in frequency for the backscatter signal and the carrier signal enables LoRea to reduce the self-interference without

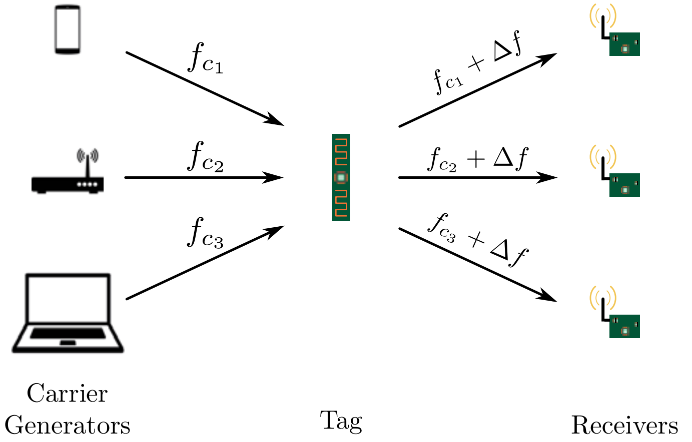

Figure 2.3. Overview of LoRea architecture. One or more devices (sensor nodes, WiFi access points, etc.) provide the carrier signal that the backscatter tag reflects to transmit. The backscattered signal is received by one or more receivers.

using complex techniques and methods employed on existing RFID readers, and to use low-cost commodity transceivers as a receiver helping to significantly lower the cost of the reader (70 USD). To improve the communication range, we build on the key idea that receiver sensitivity improves with lower bandwidth. In our architecture, we generate narrow bandwidth transmissions to significantly improve receiver sensitivity, and achieve orders of magnitude higher range when compared to state-of-the-art systems [70, 28, 24]. To improve the scalability of the architecture, lower the cost and power consumption of the reader, LoRea uses a bistatic configuration [28] and enables wireless devices such as WiFi routers and sensor nodes to provide the carrier signal. LoRea takes a step to improve the range and expand the application scenarios for backscatter-based sensors towards battery-free sustainable NES.

Wide-area Backscatter Networks. Achieving hundreds of meters of communication range with ultra-low power backscatter communication can be a crucial enabler for a wide-area networks of battery-free backscatter tags. Our work in Paper IV, takes a step to develop system support for large-scale deployments of the backscatter tags. We demonstrate that unlike other existing systems which require complex processing at the reader to receive information from simultaneous transmitting tags, we can use the mixing property to implement a scheme similar to FDMA to support multiple transmitting backscatter tags. To improve the reliability of the long distance backscatter links, we explore spread spectrum and error correction mechanisms at the backscatter tag and demonstrate that they can be implemented within the constraints of the backscatter tag to improve the reliability of backscatter links. Finally, we also investigate the effects of filter bandwidth on commodity transceivers to reject the interband and intraband interference. Our work gives a direction to develop

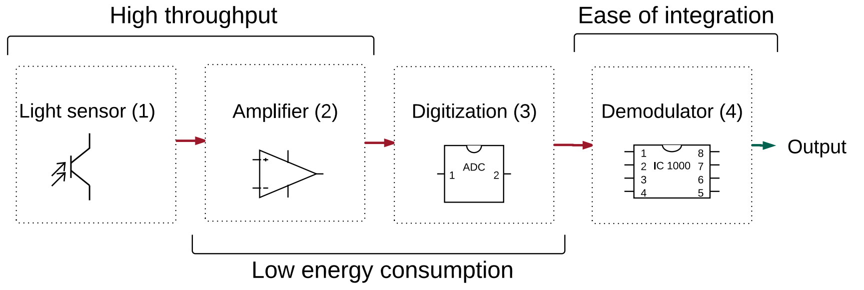

Figure 2.4. Abstract architecture of a VLC receiver.

system support for wide-area networks of battery-free and backscatter-based sustainable NES.

2.3 Visible Light as an Alternative to RF for Sensing and Communication

Visible light can be used for sensing and communication as an alternative to RF signals, as state-of-the-art systems have demonstrated [32, 33, 57, 65]. However, several challenges hinder visible light as an alternative to RF on NES, which we discuss and address next.

2.3.1 Research Challenges

State-of-the-art VLC/VLS systems suffer from issues such as high power consumption, low throughput, a requirement of retrofitting the lighting infrastructure and the inability to operate under diverse light conditions.

Visible Light Receiver Power Consumption. The visible light receiver is an important component of the VLC or VLS system. A large majority of the state-of-the-art systems use the traditional light sensing architecture [32, 33, 51, 65] shown in Figure 2.4. In this architecture, the light signal is received by a light sensor such as a photodiode, amplified using a transimpedance amplifier, digitised using an ADC, and finally demodulated and received using a computational block such as MCU/FPGA. However, the conventional light receiver architecture prohibitively increases the power consumption of the receiver for NES - due to the use of the energy-expensive components such as transimpedance amplifiers, high-speed ADCs and energy expensive processing blocks. An important research challenge is to design low-power light receivers to enable sustainable VLC/VLS systems.

VLC Throughput. VLC holds great potential as a high-speed communication medium. Over the past decade, state-of-the-art VLC systems demonstrate a

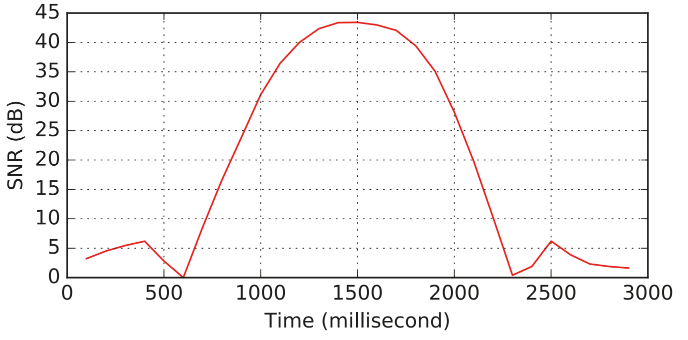

Figure 2.5. Change in signal-to-noise (SNR) ratio under mobility. *Mobility induces rapid changes in the SNR in a time span of hundreds of milliseconds. No single VLC receiver design can provide efficient performance across the whole range.*

throughput as high as Gigabit/s [4]. However, the high-speed VLC systems optimize for throughput, and hence often overlook the energy consumption required for reception. The high-speed VLC systems use energy-expensive components such as high-speed ADCs, large gain trans-impedance amplifiers and complex modulation schemes to achieve high throughput [4] which makes them prohibitive for the energy-constrained NES.

On the other hand, VLC systems optimized for embedded systems achieve a significantly lower throughput, and their per bit energy cost is significantly higher than those of modern RF transceivers which limits the practical usage of VLC for NES.

Visible Light Sensing Infrastructure. Leveraging the ubiquitous nature of the visible light is essential to lower the cost of the deployment and hence the maintenance, and is crucial for sustainability of VLS systems. State-of-the-art VLS systems [32, 33, 34] fail to take advantage of the ubiquitous nature of the visible light. They also require the lighting infrastructure to be fitted with specialised circuitry to send optical beacons which need significant effort to replace an already deployed infrastructure. Further, the infrastructure itself has to be maintained over time which also increases the cost and negatively impacts the sustainability of the system.

Another essential element that affects the sustainability of the VLS infrastructure is the light sensor. State-of-the-art systems passively track a shadow cast on an array of conventional photodiode based light sensors. The photodiodes are sampled using an ADC, and after performing some local processing, the sensed values are transferred using cables or wireless radios such as WiFi to a powerful end-device for further processing. However, such an architecture negatively impacts the sustainability of the light sensing infrastructure: Photodiodes can get easily damaged [32], the light sensor design increases the power consumption and the cost and requires the sensor to be battery or ex-

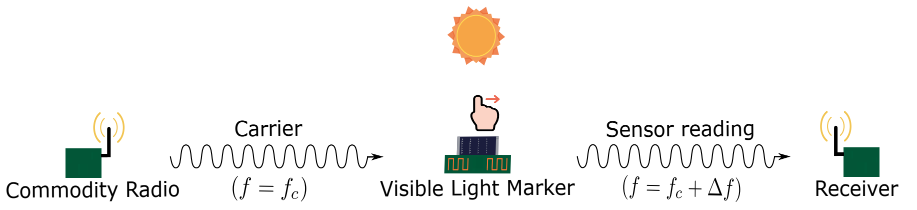

Figure 2.6. Shadow sensing at µWs *of power.* We can detect and communicate shadow events by reflecting ambient RF signals at a total power consumption of 20 µWs.

ternally powered. Thus, a significant research challenge is to lower the cost of deploying and maintaining a VLS infrastructure.

Dynamics of Visible Light Links. A significant challenge that a VLC and VLS system has to tackle is the dynamics of changing light conditions. A visible light link can be affected by several elements in the environment such as the shadow cast on the light sensor, reflections from the surfaces, ambient light such as natural light or artificial lights. The changes in the VLC links are drastic when compared to RF links, and can change by as much as 10 dB to 15 dB within the span of few hundred milliseconds [68]. Further, the VLC links can suffer a significant change in the signal-to-noise-ratio (SNR) due to the mobility of the light sensor or the modulating light. As an example, Figure 2.5, which we experimentally obtained by checking the light conditions on a person's chest when *walking* in a university building, demonstrate that the SNR may change by tens of dB in a few hundreds of milliseconds. Hence, the dynamics of rapidly chaining light conditions present a significant challenge to conventional light sensors.

A conventional light sensor amplifies the signal from a photodiode using a transimpedance amplifier, that usually has a fixed amplification gain. The fixed gain results in the light sensor operating within a defined light intensity region. The amplifier gets saturated when the light levels are high, and fails to amplify the signal sufficiently when the levels are too low. However, such a design is detrimental to practical deployment of light sensing systems, as due to dynamics of changing light conditions they often encounter situations where the light levels fall outside their region of operation. Hence, a significant challenge is to design light sensors that can operate under diverse light conditions and can tackle the dynamics of changing visible light links.

2.3.2 Research Contributions

We overcome the challenges to enable a visible light-based sustainable NES through two contributions made in the dissertation.

Battery-free Visible Light Sensing. To enable pervasive and sustainable visible light sensing, in Paper V, we introduce a novel sensing architecture that can

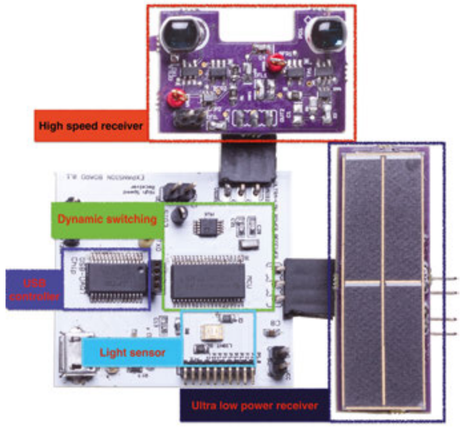

Figure 2.7. VLC receiver for wearable devices. Combing three receiver designs helps to tackle rapid changes in light intensity due to mobility. At the lowest power state, the receiver consumes sub-μW of power for reception.

detect changes in the light, and communicate them at a peak power consumption of 20 μWs. Our architecture represents three orders of magnitude lower power consumption when compared to the state-of-the-art light sensing systems [32, 33]. Also, as opposed to state-of-the-art [32, 33] that often requires retrofitting lighting infrastructure with beaconing circuits, our architecture can use unmodulated ambient light for sensing and requires no modifications to existing light infrastructures. Further, in our architecture, the light sensors are inexpensive and are composed of a handful of inexpensive components. The low power consumption enables our architecture to operate on small amounts of harvested energy eliminating the use of batteries, and together with very low-cost light sensors and the use of unmodulated ambient light reduce the cost of deployment and maintenance of the light sensing infrastructure.

In our visible light sensing architecture, shown in Figure 2.6, we make several technical contributions over state-of-the-art [32, 33]. We design a novel mechanism that uses solar cells to achieve a sub-μW power consumption for sensing. Solar cells eliminate energy and expensive photodiodes and transimpedance amplifiers. Further, we devise an ultra-low power transmission mechanism that uses RF backscatter to transmit sensor readings and avoids the processing and computational overhead of existing sensor systems which reduces power consumption and cost. Our results show the ability to detect and transmit hand gestures or the presence of people up to distances of 330 m, at a peak power of 20 μWs. Further, we demonstrate that our system can operate in diverse light conditions (100 lx to 80 klx) where existing VLS designs fail due to saturation of the transimpedance amplifier.

Visible Light Communication for NES. Our final contribution is to enable VLC on embedded and energy harvesting devices. In Paper VI, we introduce the design of a new VLC receiver that brings high-speed VLC to embedded and energy harvesting devices such as those used in wearable computing. The receiver achieves orders of magnitude higher throughput when compared to state-of-the-art VLC systems designed for embedded devices [65, 54, 57] at an energy cost lower than many RF standards. At the smallest power state, the receiver achieves sub-μW power consumption which is comparable to passive envelope detectors employed on energy-harvesting backscatter tags [27, 39].

A novel feature of the receiver is that it can operate under diverse light conditions. We observe that visible light communication suffers from *unpredictable drastic changes* in light conditions, for example, due to reflective surfaces and obstacles casting shadows, or mobility. We experimentally demonstrate that such changes are so extreme that no single design of a VLC receiver can provide efficient performance across the board. Based on these observations, we present three different designs of VLC receivers that *i)* are individually orders of magnitude more efficient than the state-of-the-art in a subset of the possible conditions, and *ii)* can be combined in a single unit that dynamically switches to the best performing receiver based on the light conditions, as shown in Figure 2.7. Our evaluation indicates that dynamic switching incurs minimal overhead, that we can obtain throughput in the order of MBit/s as opposed to the few KBit/s of existing VLC receivers designed for embedded devices, even when light conditions change drastically.

3. Summary of the Papers

3.1 Paper I - Directional Transmissions and Receptions for High-throughput Bulk Forwarding in Wireless Sensor Networks

Ambuj Varshney, Luca Mottola, Mats Carlsson, and Thiemo Voigt. 2015. Directional Transmissions and Receptions for High-throughput Bulk Forwarding in Wireless Sensor Networks. *In Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems (SenSys '15)*. ACM, New York, NY, USA, 351-364. DOI: https://doi.org/10.1145/2809695.2809720

3.1.1 Summary

This paper introduces a bulk data transmission protocol that we call DPT or Directional Pipelined Transmission. DPT leverages the ability of the ESD antenna to electronically control the direction of maximum antenna gain to support high throughput bulk data transmission. As opposed to the state-of-the-art protocols that operate on several wireless channels, DPT by using the ability of ESD antennas to reduce wireless contention supports high-throughput bulk data transmissions on a single wireless channel. The DPT protocol operates in three phases: In the first phase, while the network is quiescent, DPT collects link metrics across all antenna configurations. This information allows us to formulate a constraint satisfaction problem that enables us to find *two multi-hop disjoint paths* connecting source and sink, along with the corresponding antenna configurations. We inject these configurations back into the network. During the actual bulk transfer, the source funnels data through the two paths by quickly alternating between them. Our results, obtained in a real testbed using 802.15.4-compliant radios and custom SPIDA antennas, indicate that DPT achieves the maximum throughput supported by the link layer, peaking at 214 kbit/s in the settings we test.

3.1.2 Reflections

This paper was our attempt to explore the advantage offered by ESD antennas in the multihop environment of WSN. We began our efforts by trying to understand the ability of ESD antennas to reduce interpath and intrapath interference which resulted in a preliminary workshop publication [62]. We identified bulk data transmission as a traffic pattern that could benefit the most from ESD antennas and decided to pursue the research direction. It took significant effort to build the testbed as all the antennas in the testbed were handmade, which also meant that we could only create a small testbed of around 15 nodes. In the DPT protocol, we found the most challenging and surprising aspect was the complexity of the problem to find the disjoint path. The time to find the solution grew significantly as the number of nodes in the network.

3.1.3 My Contribution

I am the lead author of the work. I came up with the idea to leverage reduced contention offered by ESD antennas for bulk forwarding. I did most of the implementation which includes writing the protocol and building the testbed of TelosB nodes with SPIDA antennas. I performed all the experiments and contributed significantly to the writing of the paper. I wrote the initial optimisation framework to find disjoint paths using integer linear programming (ILP). However, we found that it took significant time to construct paths as the number of nodes increased. We approached Mats Carlsson, who wrote the optimisation framework using constraint programming.

3.2 Paper II - dRTI: Directional Radio Tomographic Imaging

Bo Wei, **Ambuj Varshney**, Neal Patwari, Wen Hu, Thiemo Voigt, and Chun Tung Chou. 2015. dRTI: Directional Radio Tomographic Imaging. *In Proceedings of the 14th International Conference on Information Processing in Sensor Networks (IPSN '15).* ACM, New York, NY, USA, 166-177.
DOI:http://dx.doi.org/10.1145/2737095.2737118

3.2.1 Summary

In this paper, we develop a device-free localisation system based on Radio Tomographic Imaging (RTI). RTI is based on the concept that when an object blocks a radio frequency link, the blockage can cause changes in the statistics of radio signals. However, the accuracy of RTI suffers from complicated multipath propagation inherent to radio links. An electronically steerable directional (ESD) can improve the quality of the radio link, and improve the localisation accuracy of the RTI. We implemented a device-free localisation system called directional RTI (dRTI) and demonstrated that dRTI significantly outperforms the state-of-the-art RTI localisation methods that operate on multiple wireless channels using omnidirectional antennas.

3.2.2 Reflections

This paper was a result of collaboration with Bo Wei who was visiting SICS from Australia. We performed an initial experiment to investigate the directional links for tomographic imaging, and we were encouraged by the results. It was also an exciting experience for me as a researcher, as it was one of the first works where I collaborated on a research idea. Similar to bulk forwarding, a significant research challenge in using ESD antennas was to identify the best performing antenna configuration. The paper also introduced me to the area of device-free localisation, which provided a good foundation for the visible light sensing work conducted during the latter half of my PhD program.

3.2.3 My Contribution

I am the second author of the work. I did the preliminary experiment to understand the impact of link blockage when operating with an omnidirectional antenna and the SPIDA antenna. The idea was further developed together with Bo Wei and other co-authors. I performed most of the experiments in the paper. I also built and maintained the ESD antenna testbed which was used in the work. I contributed to the writing of the paper.

3.3 Paper III - LoRea: A Backscatter Architecture that Achieves a Long Communication Range

Ambuj Varshney, Oliver Harms, Carlos Pérez-Penichet, Christian Rohner, Frederik Hermans, and Thiemo Voigt. 2017. LoRea: A Backscatter Architecture that Achieves a Long Communication Range. *In Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems (SenSys '17).* ACM, New York, USA. DOI: https://doi.org/10.1145/3131672.3131691

3.3.1 Summary

In this paper, we present an architecture called LoRea that overturns the long standing assumption that backscatter is a short range mechanism. We demonstrate that it is possible to communicate to distances as high as few kilometers while consuming tens of µWs of power at the backscatter tag. LoRea achieves a high communication range by generating narrow bandwidth backscatter transmissions which allows the use of highly sensitive receivers for reception. LoRea overcomes the limitation of high cost for the reader of traditional backscatter systems such as Computational Radio Frequency Identification (CRFID) by using inexpensive commodity transceivers for reception. An off-the-shelf implementation of LoRea costs 70 USD, a drastic reduction in price considering that commercial RFID readers can cost upward of 2000 USD. LoRea's range scales with the carrier strength, and proximity to the carrier source and achieves a maximum range of 3.4 km when the tag is located at 1 m distance from a 28 dBm carrier source while consuming 70 µW at the tag.

3.3.2 Reflections

Our initial attempts to explore backscatter communication started in 2015 with the WISP 5.0 platform from the University of Washington, Seattle. We received several WISP platforms to work on a battery-free passive localisation system [9]. We were disappointed with the constraints of the WISP platform: it required us to buy an expensive RFID reader (2000 USD) and achieved a very short communication range of a few meters. To overcome the limitations of the WISP platform, we started the project LoRea with the objective to lower the cost of the reader required for receiving backscatter receptions. When we started the project, we never expected to get a range as high as kilometres. At each stage of the project, we were surprised with how much we could improve the range. Performing experiments that achieved such a long communication range were also very challenging to perform, as we had difficulty to find a line-of-sight environment with kilometres of open space. Further, we had practical challenges like wind toppling the carrier generator which required us to walk kilometres.

3.3.3 My Contribution

I am the lead author of the work. I came up with the idea of the architecture, backscatter tag, and using narrow bandwidth transceivers to improve range. I did most of the implementation in the paper with some help for the 2.4 GHz architecture from Oliver Harms (a student under my supervision). I did most of the experiments together with the other co-authors. I wrote a significant part of the paper.

3.4 Paper IV - Towards Wide-area Backscatter Networks

Ambuj Varshney, Carlos Perez Penichet, Christian Rohner, and Thiemo Voigt. 2017. Towards Wide-area Backscatter Networks. *In Proceedings of the 4th ACM Workshop on Hot Topics in Wireless (HotWireless '17) - in conjuction with ACM MOBICOM*. ACM, New York, NY, USA, 49-53.
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3.4.1 Summary

In this paper, we present our work to develop system support for wide-area networks of battery-free backscatter based sensors. The system builds on LoRea, that demonstrates that backscatter communication can achieve a significantly longer range reaching up to a few kms when the tag is co-located with the carrier source. In our vision, such a large range could be a key enabler to develop wide-area networks of battery-free sensors. In this paper, we identify improving the reliability of weak backscatter links, increasing the range and supporting the operation of multiple tags as the critical challenge to our vision, and present our preliminary efforts to address them.

3.4.2 Reflections

As we were working on LoRea, there was a significant research interest to allow wide-area networks with conventional and energy-expensive radios such as LoRa. Wide-area networks almost exclusively rely on large batteries as a source of power due to the high current draw of transceivers based on protocols like LoRa [55]. Long range wireless networks with battery-powered sensors are challenging due to the logistics of replacing batteries at scale. In this paper, we envisioned the long range as a critical enabler for wide-area networks of backscatter tags. This article introduces essential building blocks necessary to support our vision. As we were working on this idea, a parallel work, LoRa backscatter [55] was made available as a preprint. LoRa backscatter tackled similar issues to what we were addressing.

3.4.3 My Contribution

I am the lead author of the work. I came up with the idea and developed the idea with other co-authors. I performed all the implementation, and performed most of the experiments with the help of co-authors. I wrote most of the paper.

3.5 Paper V - Battery-free Visible Light Sensing

Ambuj Varshney, Andreas Soleiman, Luca Mottola, and Thiemo Voigt. 2017. Battery-free Visible Light Sensing. *In Proceedings of the 4th ACM Workshop on Visible Light Communication Systems (VLCS '17) - in conjuction with ACM MOBICOM*. ACM, New York, NY, USA, 3-8.
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(Best paper award)

3.5.1 Summary

In this paper, we design the first Visible Light Sensing system that consumes only tens of µWs of power to sense and communicate. The light sensing system leverages ambient and unmodulated light for sensing, and hence overcomes the limitation of state-of-the-art systems that require modification to the lighting infrastructure to transmit optical beacons. Our system achieves very low power consumption through a novel light sensing mechanism that uses a solar cell to achieve sub-µWs power consumption for sensing. The architecture eliminates the computational block and instead uses RF-backscatter to transmit sensor readings directly from the light sensor. Our results demonstrate the ability to communicate hand gestures to distances of 330 m, at a peak power of 20 µWs.

3.5.2 Reflections

We began our efforts to devise a battery-free and passive visible light sensing system called LocaLight [9] using the WISP 5.0 CRFID platform together with a photodiode as a light sensor. The constraints of the WISP 5 platform limited us to a very small communication range (3 m), and high cost for the reader. However, the more severe constraints to the system were that the accuracy of LocaLight suffered due to the duty cycled nature of the WISP 5 platform, which was due to the need to perform the frequent energy-expensive ADC operations and the high power consumption of the microcontroller.

We observed that the state-of-the-art passive VLS systems perform very little local processing [32, 33], and instead transferred the sensor readings to a powerful device for further processing. Based on the observation, we designed a very simple light sensor that could sense changes in the visible light and transmit them without performing any computation or energy expensive computational block. To achieve very low power consumption, we decided to build on our experience from the LoRea project and leverage RF backscatter communication. Concurrent with our efforts, battery-free cellphone [56] also advocated eliminating computational blocks from sensors to achieve very low power consumption. However, our design significantly improved the design presented by battery-free cellphone as we could transmit sensor readings without computational blocks and also keep them apart from the carrier signal which significantly improved the communication range.

3.5.3 My Contribution

I am the lead author of the work and came up with the initial idea of the architecture. The concept of using solar-cell together with thresholding circuit was developed in discussion with Thiemo and Luca. All the experiments and implementation in the paper was done along with Andreas (a student under my supervision). I wrote most of the paper.

3.6 Paper VI - Visible Light Communication for Wearable Computing

Ambuj Varshney, Luca Mottola, and Thiemo Voigt. Visible Light Communication for Wearable Computing. *Under submission*.

3.6.1 Summary

In this paper, we introduce the design of a novel VLC receiver for wearable computing. Enabling VLC in wearable computing, however, is challenging because mobility induces *unpredictable drastic changes* in light conditions. We experimentally demonstrate that such changes are so extreme that no single design of a VLC receiver can provide efficient performance across the board. The diversity found in current wearable devices complicates matters. Based on these observations, we present three different designs of VLC receivers that *i)* are individually orders of magnitude more efficient than the state-of-the-art in a subset of the possible conditions, and *ii)* can be be combined in a single unit that dynamically switches to the best performing receiver based on the light conditions. Our evaluation indicates that dynamic switching incurs minimal overhead, that we can obtain throughput in the order of MBit/s, and at energy costs lower than many RF devices.

3.6.2 Reflections

When we started our efforts to explore the emerging area of VLC, we were constrained due to lack of open-source designs of VLC transmitters and receivers. We began our efforts to design receiver and transmitter to support VLC on NES. Our first effort resulted in a VLC transmitter called modBulb [18]. Concurrently, we started to develop the receiver with the objective to support high throughput on NES which resulted in this work.

3.6.3 My Contribution

I am the lead author of the work and came up with the initial idea. The concept of using a solar-cell together with a thresholding circuit, integration receiver and the dual gain highspeed receiver was developed in discussion with Thiemo and Luca. All the experiments and implementation in the paper were done by me. I wrote most of the paper with contributions from the co-authors.

4. Future Work and Conclusions

4.1 Conclusions

The past several years have seen a rapid growth of NES with predictions of billions of devices deployed over the coming decade. The rapid growth in NES introduces the challenge to develop, deploy and maintain them in a sustainable manner. In this dissertation, we identify three problems that are going to impact the sustainability of NES in the future: the high energy consumption, co-existence on the shared wireless spectrum, and the high cost required for the deployment and the maintenance. We adopt a three-pronged approach to deal challenges to sustainable sensing.

Our first approach explores the use of low-cost and low-power electronically steerable directional (ESD) antennas to reduce the contention on the shared wireless spectrum. We develop the first testbed of WSN with ESD antennas. We demonstrate that reduced contention due to the use of ESD antennas helps us devise spectrum friendly sensing and communication mechanisms for WSN that operate on a single wireless channel and achieve similar or better performance compared to state-of-the-art that uses several wireless channels. In the dissertation, we explore ESD antennas for battery-powered WSN. ESD antennas also hold great potential for the emerging area of batter-free sensors. Our results in this dissertation demonstrate that ESD antennas enable NES to co-exist on the shared spectrum through spectrum-friendly sensing and communication mechanisms, a step towards sustainable NES.

The second approach we adopt in the dissertation is to explore the use of visible light as an alternative to radio frequency for sensing and communication. Visible light communication avoids the crowded radio frequency spectrum and holds a great potential to enable NES to co-exist on the crowded spectrum. In this dissertation, we make two significant contributions that improve the state-of-the-art in visible light sensing and communication. We devise a novel and ultra-low-power light sensing architecture that can sense changes in light intensity levels caused due to the human motion to detect hand gesture. A vital contribution of the architecture is the design of a very low power light sensor that consumes a peak power of 20 µW, which represents two order of improvement in power consumption over the state-of-the-art. The architecture, can be a key enabler to the ubiquitous use of the VLS systems. Our second contribution takes a step to bring high-speed VLC to energy constrained NES. We design a VLC receiver that can tackle the dynamics of visible light, and achieves a throughput comparable to RF standards such

ZigBee or Bluetooth Low Energy used in NES. Together the two contributions improve the state-of-the-art in VLC and VLS by orders of magnitude, and take a significant step to enable visible light based sustainable NES.

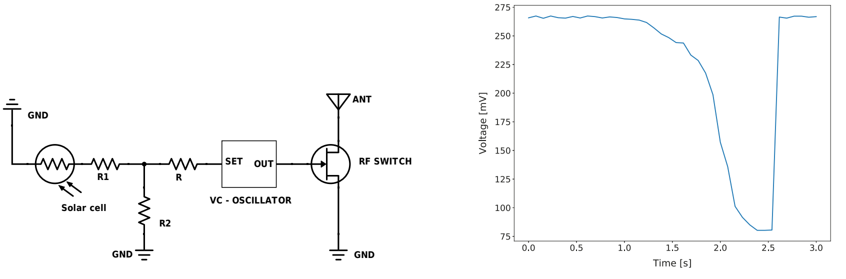
Finally, Battery-free sensors can be deployed at scale, in hard to reach places and do not have the cost or the maintenance overhead of replacing batteries. Battery-free sensors operate on small amounts of energy harvested from the ambient environment and can enable sustainable NES. Battery-free sensors are severely constrained regarding their energy budget and require the development of new sensing and communication mechanisms that can operate within the energy harvesting constraints. Backscatter or communication through reflections of ambient wireless signals enables wireless transmissions at tens of µWs of power consumption and is the mechanism of choice to support wireless transmissions on energy harvesting sensors. In this dissertation, we overcome one constraint that has limited the application scenarios of backscatter based battery-free sensors: low communication range. Through our contributions, we overturn the notion that backscatter is a short-range communication mechanism, and we believe our work lays the vision for a wide-area network of reliable backscatter based battery-free NES.

4.2 Future Work

In this section, we present possible research directions based on the work performed in this dissertation. We also provide a high-level overview of some of the results that we have already obtained for these research directions.

ESD Antennas for Backscatter Communication. In this dissertation, we leverage reduced contention offered by the ESD antennas to improve sensing and communication mechanisms on WSN. The SPIDA antenna consumes a few µWs of power and is compatible with the ultra-low power constraints of the battery-free and energy harvesting sensors. An exciting research direction could explore the use of ESD antennas on the backscatter tag leading to several potential benefits. The backscatter tags operate on the shared spectrum, and the ESD antennas could improve co-existence with other wireless devices. Another possible use of the ESD antennas at the backscatter tag could be to direct the backscatter reflections to improve the communication range while consuming only a few µWs of power. The advantage of ESD antennas on backscatter systems is not just limited to the tag, but they could help the carrier generator by directing the unmodulated carrier signal towards the backscatter tag to reduce interference to other co-existing devices.

Battery-free Visible Light Sensing. In Paper V, we introduced the first visible light sensing architecture that consumes only tens of µWs of power for sensing and communication of shadow events. The VLS architecture encounters several challenges that limit the application scenarios. In our architecture, we use a thresholding circuit to digitise the light readings. The thresholding



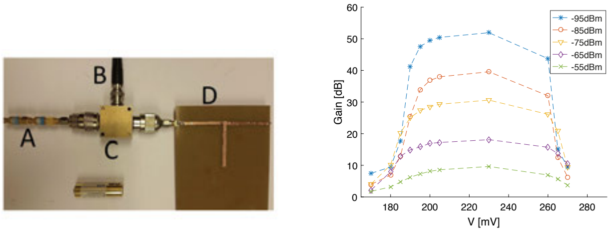
(a) Analog Backscatter Schematic (b) Received Gesture Signal

Figure 4.1. Analog Backscatter Design. Transforming analog signal to corresponding change in the frequency of the backscatter signal enables transmitting of analog information at µWs of peak power consumption.

circuit acts as a 1-bit ADC and hence provides binary information about the changes in the light conditions that are further backscattered using our *Scatterlight* mechanism. The binary changes mean that essential data such as light intensity levels is lost in the process and impacts the ability to detect complex gestures [32, 33, 34]. The VLS architecture uses backscatter communication to achieve ultra-low power wireless transmissions. Backscatter transmissions require the presence of an ambient RF signal which the tag reflects. In our architecture, we generate a carrier signal using a dedicated device which increases the complexity of the deployment.

Our work in progress overcomes some of these limitations. We eliminate the thresholding circuit and improve *Scatterlight* using the analog backscatter design presented in Figure 4.1(a). The design instead of digitising the analog signal using a thresholding circuit instead maps analog values to different frequencies. We achieve this by connecting the output of a solar cell to an ultra-low power voltage-controlled oscillator. The voltage-controlled oscillator generates a digital signal with a frequency corresponding to the analog input signal. The end-device reconstructs the analog signals by identifying the frequencies in the received backscattered transmissions, as we show in Figure 4.1(b). We also overcome the need to generate the carrier signal, as our analog backscatter design can use FM bands and ambient FM signals [64] for backscatter transmissions. Our VLS design by using such ambient wireless signals avoids the crowded license-free band and by supporting ultra-low power and battery-free operation supports the vision of a pervasive and sustainable visible light sensing system.

Long Range Backscatter Transmissions. We introduced an ultra-low power backscatter tag in our system LoRea (Paper III). However, like other state-of-the-art backscatter systems [24, 28, 70, 39, 64], our tag does not transmit with amplification. Amato et al. [2] demonstrated that tunnel diodes can create a



(a) Reflection Amplifier Tag (b) Gain

Figure 4.2. Reflection amplifier backscatter tag. Negative resistance device tunnel diode enables large gain while backscattering ambient signals.

reflection-amplifier to achieve a gain as high as 34 dB at the backscatter tag when operating at a frequency of 5 GHz and power consumption of 45 µW. Introducing reflection amplifiers at the tag could enable us to improve the range significantly, especially in scenarios where the backscatter tag is not in proximity of the carrier source. Our initial results demonstrate the exciting potential of the research direction. In Figure 4.2(a) we show a prototype reflection amplifier that we have fabricated using an AL301A tunnel diode. Figure 4.2(b) reflects the relationship between the reflection gain and the bias voltage obtained using a vector network analyser (VNA). We observe a gain as high as 50 dB for a power consumption of approximately 300 µWs. As future work, we will integrate the tunnel diode reflection amplifier in the LoRea backscatter tag to improve the communication range when LoRea is not in proximity of the carrier generator, a key enabler to our vision of a sustainable wide-area networks of battery-free NES.

A significant challenge to our vision of wide-area networks of NES is to coordinate carrier generators. Existing backscatter systems including LoRea generate a strong carrier signal which is often the maximum permissible in the license-free ISM band to maximise communication range. However, strong carrier signals could negatively impact other co-existing wireless networks, especially in scenarios where multiple carrier generating devices are present. A possible solution could be to coordinate the carrier generators such that they transmit carrier signals only periodically, where the tag could sense the presence of a carrier signal to initiate transmissions. The carrier generators could communicate among themselves to coordinate transmissions of the carrier signal to mitigate interference on other wireless networks.

5. Summary in Swedish

Under senare tid har vi sett en markant ökning av trådlöst sammankopplade inbyggda system vilka förutspås uppnå miljarder utplacerade enheter under det kommande decenniet. Den hastiga ökningen av dessa system introducerar utmaningar i att utveckla och placera ut dem på ett hållbart sätt. I denna doktorsavhandling identifierar vi tre problem som kommer att påverka hållbarheten av dessa system: hög energikonsumption, samexistens i ett delat trådlöst spektrum, och den höga kostnaden som krävs för att placera och underhålla systemen. Vi antar tre olika tillvägagångssätt för att hantera de ovan nämnda utmaningarna i hållbar sensor-igenkänning.

Vårt första tillvägagångssätt utforskar användningen av låg-pris och låg-energikonsumerande elektroniskt riktningsbara antenner för att reducera effekterna av kollision i det delade trådlösa spektrumet. Vi utvecklar den första testbädden av trådlösa sensornätverk med riktningsbara antenner. Vi demonstrerar att en reduktion i kollision med hjälp av riktningsbara antenner hjälper oss att skapa spektrum-vänliga sensor -och kommunikationsmekanismer för trådlösa sensornätverk som opererar i en enskild trådlös kanal. Dessa uppnår liknande eller bättre prestanda jämfört med toppmoderna system som ockuperar flera trådlösa kanaler. I denna doktorsavhandling utforskar vi användningen av elektroniskt riktningsbara antenner för batteridrivna trådlösa sensornätverk. Användningen av dessa antenner har också en hög potential för det framväxande området batterifria sensorer. Våra resultat demonstrerar att elektroniskt riktningsbara antenner möjliggör för trådlösa inbyggda system att samexistera i ett delat spektrum; ett steg mot hållbara inbyggda system.

Det andra tillvägagångssättet innefattar att utforska användningen av synligt ljus som ett alternativ till radiofrekvens för igenkänning och kommunikation. Kommunikation av synligt ljus undviker det trånga radiofrekvensspektrumet och har en stor potential till att göra det möjligt för trådlösa inbyggda system att samexistera. I denna doktorsavhandling gör vi två signifikanta bidrag som förbättrar toppmoderna system inom igenkänning och kommunikation av synligt ljus. Vi tar fram en arkitektur för ljusigenkänning som kan detektera ändringar i ljusintensitet orsakat av mänsklig rörelse, i form av handgester. Ett avgörande bidrag till denna arkitektur är designen av en ljussensor som konsumerar väldigt lite energi - den konsumerar en maxeffekt på 20 µW. Detta representerar en förbättring på två storleksordningar i energikonsumtion jämfört med toppmoderna system. Denna arkitektur kan vara en nyckel till ubikvitär användning av ljusigenkänningssystem. Vårt andra bidrag tar ett steg till att bringa höghastighets-kommunikation med synligt ljus till energibegränsade trådlösa inbyggda system. Vi designar en mottagare som kan tackla dynamiken av synligt ljus och uppnå en genomströmning som är jämförbar med radiofrekvens-standarder som ZigBee eller låg-energi Bluetooth. Tillsammans utgör dessa två bidrag förbättringar till toppmoderna kommunikationssystem och igenkänningssystem av synligt ljus med två storleksordningar. Med detta tar vi ett viktigt steg framåt för att göra det möjligt för inbyggda system att kommunicera med synligt ljus på ett hållbart sätt.

Slutligen så kan batterifria sensorer vara utplacerade i stor skala, på svåråtkomliga platser och som inte har underhållningskostnader likt sensorer som behöver byta batterier. Batterifria sensorer operarar på en liten mängd energi som är skördad av omgivande energikällor. Av denna anledning har batterifria sensorer potentialen att bädda för hållbara trådlösa inbyggda system. Batterifria sensorer är väldigt begränsade gällande deras energi-budget och kräver därför en utveckling av nya sensor -och kommunikationsmekanismer som kan fungera inom begränsningen av mängden energi som kan skördas från omgivande källor. Backscatter - eller kommunikation genom reflektioner av omgivande trådlösa signaler skapar möjligheter för trådlös kommunikation i tiotals µWs effekt. Detta är mekanismen som ofta väljs för att stödja trådlös transmission på energiskördande sensorer. I denna doktorsavhandling överkommer vi en restriktion som har begränsat applikations-scenarion av backscatter-baserade batterifria sensorer: kort kommunikationsräckvidd. Genom våra bidrag omstörtar vi idén om att backscatter är en kommunikationsmekanism med kort räckvidd. Vi tror att vårt arbete lägger fundamentet för en vidsträckt nätverk av backscatter-baserade batterifria inbyggda system.

Den markanta ökningen av trådlöst sammankopplade inbyggda system innebär att vi möter en stor utmaning för att uppnå en hållbar utveckling av dessa system. Vi har gjort en ansträngning för att identifiera några av problemen och vi har identifierat tre tillvägagångssätt för att mildra dem. Våra resultat demonstrerar att vi kan ta ett steg mot hållbara trådlösa inbyggda system. Vi tror att det finns en utmärkt potential för framtida arbete inom området som identifieras i denna doktorsavhandling. Vi kommer att fortsätta att bedriva forskning inom dessa tre riktningar för att möjliggöra visionen av hållbara trådlösa inbyggda system.

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