AGU PUBLICATIONS

Earth and Space Science

TECHNICAL REPORTS: METHODS

10.1002/2014EA000044

Toward an environmental Internet of Things

Jane K. Hart[1] **and Kirk Martinez**[2]

[1]Geography and Environment, University of Southampton, Southampton, UK, [2]Electronics and Computer Science, University of Southampton, Southampton, UK

Key Points:

- IoT technology allows a step change in monitoring environmental processes
- The types of systems, web technology, and challenges ahead are presented

Correspondence to:
J. K. Hart,
jhart@soton.ac.uk

Citation:
Hart, J. K., and K. Martinez (2015), Toward an environmental Internet of Things, *Earth and Space Science*, *2*, 194–200, doi:10.1002/2014EA000044.

Received 20 OCT 2014
Accepted 8 APR 2015
Accepted article online 14 APR 2015
Published online 15 MAY 2015

Abstract The Internet of Things is a term which has emerged to describe the increase of Internet connectivity of everyday objects. While wireless sensor networks have developed highly energy efficient designs they need a step change in their interoperability and usability to become essential tools in the study of our environment. This paper shows how Internet of Things (IoT) can be seen as a natural evolution of environmental sensing systems. We discuss the different styles and examples of IoT systems and illustrate the key technical challenges ahead. We describe a future connected world and discuss the role of environmental and Earth science sensing, web, and Internet technologies.

1. Introduction

Numerous authors have envisioned the future Internet where anything can be connected as the Internet of Things (IoT) [*Intel*, 2009; *Feki et al*., 2013]. "The Internet of Things (IoT) provides the necessary infrastructure to transparently access sensors, processes and actuators using standardized protocols regardless of hardware, operating systems or location" [*Presser et al*., 2009; *Roggen et al*., 2013]. It has been estimated that this will comprise 100 billion devices by 2020 [*Casaleggio Associati*, 2011; *Hodges et al*., 2013] and become an integrated part of our lives [*Atzori et al*., 2010, *Vilamovska et al*., 2009, *Kortuem et al*., 2007]. It will have an environmental dimension by leading to more efficient use of energy, as these devices could help to save approximately 9 Gt of CO_2 emissions (16.5% of total emissions) by 2020 [*Cullinen*, 2013] and help humanity remain within a "safe operating space" [*Rockström et al*., 2009] during a time of increasing climate change.

Most existing research into IoT systems has focused on indoor or urban applications where power is more readily available, access is relatively easy, and Internet connectivity is simpler. A current challenge facing IoT systems is sensing deployments in the environment where the reverse is the norm. The ultimate aim of environmental developments is to create a *Global Environmental Sensor Web*, driven by the scalability of the IoT. This would provide analytical tools to understand Earth system processes using near-real-time data collected from sensors (especially in situ sensor networks) combined with other mapped data sources (e.g., geology, soil type, and topography), model-based data and data sets from data fusion. Such a system would be able to provide a view of global environmental changes. Decision and support systems can be built from these, sending alerts, and influencing emergency infrastructure. Initial examples include IBM's "A Smarter Planet" [*IBM*, 2010], Hewlett Packard's (HP) "Central Nervous System for the Earth (CeNSE)" [*HP*, 2013], and Geospatial Cyberinfrastructure for Environmental Sensing project (www.geocens.ca).

Over the last 10 years there has been a rapid development of Wireless Sensor Networks (WSN) in the environment [*Delin et al*., 2005; *Martinez et al*., 2004]. These have emerged from different environmental disciplines and at different scales (e.g., habitat monitoring = *Szewczyk et al*. [2004] and *Rey-Moreno et al*. [2011], glaciers = *Martinez et al*. [2009], permafrost = *Hasler et al*. [2008], and volcanoes = *Werner-Allen et al*. [2005]) which use a similar methodology. The recent significant developments in the field of environmental sensor networks will help to build the next generation of IoT devices. This includes miniaturization, power management, communications, interoperability and standardization, robustness, scalability, management and usability, and security [*Martinez et al*., 2006; *Alcaraz et al*., 2010; *Christin et al*., 2009; *Mainetti et al*., 2011]. In this article we explain the building blocks of an environmental IoT, compare this with existing research, and outline future challenges.

2. What Is the Difference Between a Sensor Network and the IoT?

The evolution from standalone data logger systems to environmental sensor networks (ESN) systems has been discussed in detail [*Hart and Martinez*, 2006]. The benefits from the change from loggers to sensor networks are

Table 1. Evolution From Logging to Environmental IoT

	Logging	Environmental Sensor Network		Environmental IoT
		Single Function	Heterogeneous	
	Increasing "smartness" →			
Sensor nodes	Normally one type per application	Normally one type	Heterogeneous, wired and wireless	Heterogeneous, wired and wireless
Communications	Usually none, IP and GSM sometimes	Always exist, mostly one way	Always exist, mostly non-IP Gateways usually IP	Always exist, IP
Communications standards	None	Custom and standard	Custom and standard e.g. Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 very few	More Standard e.g.6LoWPAN, low-power radio
Node operating system/software	Simplified or proprietary	Custom, nonstandard or TinyOS or Contiki	Custom, nonstandard or TinyOS or Contiki	More emerging or Linux
Server side software	May have, proprietary	Typically custom systems	Typically custom systems	Emerging such as Xively

expected to be further enhanced by a move toward the IoT. Data logger-based systems tend to have little or no network connectivity, and their data are often collected manually with a laptop. Nodes in a wireless sensor network typically use a specialized radio network capable of "hopping" data between nodes in order to extend range, save power, and send data to a server. They also offer some interoperability between different hardware. IoT sensor nodes use the Internet protocols in order to link directly to servers and users.

Environmental sensor networks are theoretically quiet varied in style, from a single function network (with nodes with a set of sensors, e.g., for meteorology) to a heterogeneous sensor network with a mixture of node types and functionality (Table 1). Sensor networks are designed to have "smart" behavior such as adapting to environmental conditions and power availability. However, they tend to use nonstandard radio networking where "gateways" route their data to the Internet. In an environmental IoT, nodes can have Internet connectivity allowing them to directly push data to a server and users to interact with them more easily in the field. Using a more standard network is expected to allow multivendor systems to interoperate.

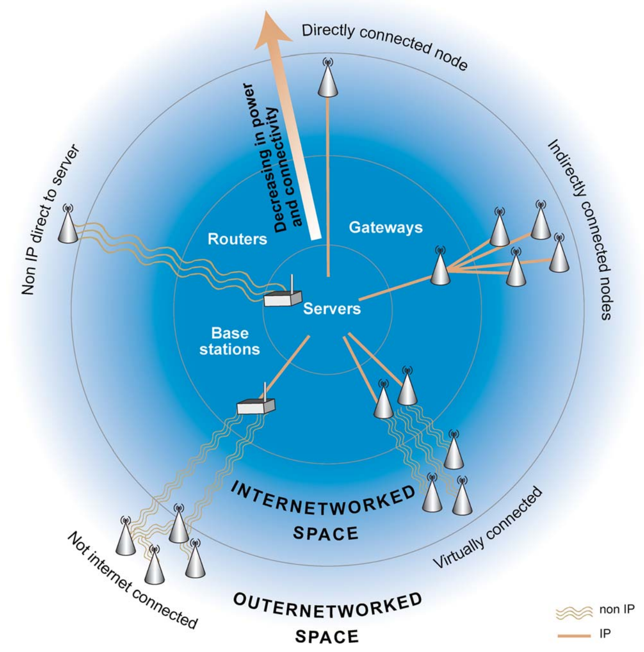

Figure 1. Schematic diagram to show the different families of IoT sensor systems. At the core there are higher connectivity and power availability, but these properties decrease toward the periphery.

IP-connected sensor networks predate the use of the term IoT but can be categorized as such in order to better understand the families of systems and architectures. As can be seen in Table 1, which shows the characteristic changes, there is a wide variation in the use of technologies, which makes the boundaries blurred on close inspection of any one particular system.

Figure 1 illustrates the variety of network styles emphasizing the communications and networks differences. Data and Web services are a common layer across the different types of architecture so have been integrated with the center of the diagram (server). Some nodes are outside current "internetworked space" because they use legacy hardware, require too much power (to transmit the data), or are too remote (in distance or the nature of the material). Over time the number of Internet connected things will grow as low-power products and standards are implemented. Each technological step from logging through to an IoT system reflects a step change in the impact for environmental sensing.

3. Emerging Environmental Sensor IoT Systems

Table 1 shows the evolution from nonstandard, custom communications and software to more standard IoT versions. The original internet protocols (IPv4), although used in some high powered sensors and gadgets is not optimized for low-power radio networks (approximately < 20 mW). WiFi (IEEE 802.11.x which uses IPv4 or IPv6), is designed to use around 100 mW of radio power to achieve high data rates (Mb s^{-1}) compared to typical WSN radio of 10 mW and 50–250 kb s^{-1}. Where there is sufficient power availability WiFi (especially high power versions over 500 mW) has been used successfully over large areas and brings considerable convenience. 6LoWPAN [*Shelby and Bormann*, 2009] is a specialized version of the next generation internet protocol (IPv6) for low-power wireless networks (or Personal Area Networks). It is designed for low data rates, power consumption, and costs, with automatic configuration and flexible topologies (e.g., "self-healing" mesh networking). A router device, which links 6LowPAN devices to the rest of the Internet, is required, but these are becoming off-the-shelf products. Using IP allows advances in usability for nonspecialists, because once standards emerge, systems with hardware from multiple vendors can be integrated. These emerging IoT systems are more easily enhanced with Internet and web technologies and facilitate the use of advanced sensing systems. An example of the evolution of sensing systems is the High Performance Wireless Research and Education Network (http://hpwren.ucsd.edu/), which now comprises heterogeneous sensors and cameras using a high power IP radio backbone.

The different connectivity systems are illustrated in Figure 1, and here we discuss some examples. The simplest system would comprise a *non-Internet Protocol direct to the server*; for example, sea buoys with a radio modem link to a server [*Tateson et al.*, 2005].

A typical *non-Internet connected system*, where nodes are connected to each other by a non-IP radio network and to a Base Station connected to the Internet, would be the environmental sensor network systems developed in the 2000s [*Hart and Martinez*, 2006; *Corke et al.,* 2010].

Virtually connected nodes use a technique which allows nodes to appear to be connected to the Internet but use a "private" non-IP local radio network and a gateway to link it to the Internet. This includes

Zigbee [*ZigBee Alliance*, 2009] (non-IP, wireless networking standard) wireless sensors for agricultural applications [*Moorthy et al*., 2013], and the instrumented city "Smart Santander" [*Sanchez et al*., 2014].

Indirectly connected nodes also use a gateway to transparently link them to the Internet, but the nodes actually use IP so can be accessed directly if necessary. This includes WiFi routers, or 6LoWPAN compliant gateways. MEMSIC's telosB motes and Zolertia's Z1 nodes are examples of low-cost commercially available nodes which can use 6LoWPAN. Deployments include greenhouse monitoring [*Ahonen et al*., 2008], habitat sensing in the Amazon [*Cama et al*., 2013], monitoring flood levels in breeding areas of migratory water birds [*Larios et al*., 2013], and the environmental monitoring of Cairngorms, Scotland (http://www.mountainsensing.com). It is also possible to use mobile IP (LoWMob [*Bag et al*., 2009]) which has many potential applications including animal tracking.

Alternatively, nodes can be *directly connected to the Internet*;—for example, nodes connected to a building such as cameras or temperature sensors. GSM (mobile phone) systems are often used in order to send data to a server; however, this uses more power and relies on network availability. Examples include mobile radiation detectors (POKEGA) used at Fukushima, Japan, connected to a smart phone [*Ishigaki et al*., 2013], and farm vehicles sending back sensor data via satellite or GPRS (general packet radio service) as part of smart agriculture systems [*Yan-e*, 2011]. To a user, the last two types are almost indistinguishable but rely on different infrastructure.

Most real world systems will contain different communication elements depending on the application. The Glacsweb project [*Martinez et al*., 2012] deployment at Skálafellsjökull to monitor glacial processes used *non-Internet connected* probes and geophone nodes (radio links), *indirectly connected* nodes (via a gateway and Wifi IPv6), and a *directly connected* camera node. The subglacial sensor nodes used an evolution of a custom radio protocol to save energy, while the surface nodes integrated IP networking in order to explore IoT designs on higher-power hardware. Thus, the system moved from a heterogeneous environmental sensor network toward an environmental IoT (Table 1) as the hardware became powerful enough to support IP. In addition, due to rapidly advancing technologies, systems need to constantly evolve. This was demonstrated in a study of badger behavior by *Dyo et al*. [2010], where they showed how an improved radio range, increased data storage capacity, and reduced power consumption led to significant system performance.

There are some disadvantages of an IoT approach compared to traditional sensor networks. The use of an IP protocol is less energy efficient, so more power may be required on the nodes. It is also possible to misconfigure a system so that people can breach the security of the nodes themselves. Security technology is more advanced for IP systems and needs to be implemented with care. In practice, secure connections (secure shell and secure web, HTTPS) and proper use of firewalls can make an IoT system as secure as any other Internet connected system [*Medaglia and Serbanati,* 2010; *Suo et al*., 2012].

4. Web and Internet Technologies

One of the main benefits of networks based on IP protocols is the use of web and Internet technologies. These will help drive the production of new data and make "harvesting" data easier. Internet services which are useful include time servers (NTP) which can be used to set an accurate time and date on systems (within the bounds of Internet latency). Flexible naming schemes (Domain Name System) also allow data sinks to be moved easily (e.g., the domain name "mydata.org" can initially point to a small server then be moved to a virtual cloud server later). "Big" and "linked" data are active areas of research which bring benefits to the access and distribution of the data collected. This is a key element of the "Fourth Paradigm of Science" [*Hey et al*., 2009], where data exploration (from the "capture, curation, and analysis of large data") allows a new inductive approach to science. It has been argued that the challenges for big data are volume, velocity, variety, value, and veracity [*Hitzler and Janowicz*, 2013] and that specific disciplines prioritize these differently. We argue that these are all vital to an environmental IoT being successful.

Cloud-based information systems are seen as a way to simplify the storage, management, and access to data. There have been various web-based systems developed which build on the early systems which provided a generic data repository and map/access (e.g., sensormap [*Nath et al*., 2007]). In the Glacsweb project the base station node pushed data directly to a cloud-based store via the best available IP network on each day [*Martinez et al.,* 2012]. Cloud-based services for IoT are evolving rapidly (e.g., http://Xively.com) as they can provide a scalable repository for data and provide common standard interfaces to upload/download data.

Web technologies also help with increasing the standardization and usability of the systems. Low-power devices cannot be expected to deliver web pages on demand, however, as they are expected to have a limited communications time slot to save power. Simple interactions can be built into nodes using web pages and a normal browser rather than a custom protocol and client software, for example. This allows initial configuration and maintenance to be carried out using a standard web browser. The actual data send or fetch mechanisms do not involve web pages but a more suitable data encapsulation. Within the system, nodes can use well-developed web techniques to “post” data to servers and “get” information from the web, thus avoiding more nonstandard protocols. Web protocols such as HTTP are less energy efficient than state of the art WSN techniques, but a small trade-off of battery use to utility may be beneficial. This is because HTTP is more easily debugged, standard web browsers can be used and there is a large community of Web programmers which helps with the challenge of maintainability. Emerging standards such as the Constrained Application Protocol (CoAP: RFC 7252, http://coap.technology/spec.html) have been developed specifically for low-power IP networks and are more energy efficient than HTTP [*Colitti et al*., 2011].

5. A Future Connected World

A connected world has many foreseeable advantages, and IoT technologies have the potential to make a significant improvement to environmental monitoring and hazard warnings. Many basic properties of the Earth are currently very poorly monitored. One example is how current global warming is melting the permafrost which produces carbon dioxide and methane [*Wickland et al*., 2006], and although the additional greenhouse gases are well mixed throughout the global troposphere [*Serreze and Barry*, 2011], this is one factor that contributes to Arctic amplification (preferentially warm Arctic) [*Manabe and Stouffer*, 1980; *Miller et al*., 2010]. This in turn has led to many current changes in the Arctic including the melting of sea ice, which has affected the position of the jet stream and may account for the recent extreme weather events seen recently in Europe and North America (e.g., UK wet summer 2012 and late spring 2013) [*Francis and Vavrus*, 2012]. There are very few in situ monitoring stations measuring carbon dioxide and methane production in the Arctic.

Currently there are a number of sensor network systems (of different scales and in different stages of development) which may provide hazard warnings (e.g., tsunamis warning system [*Meinig et al*., 2005], forest fires [*Yu et al.,* 2005], and lightning detection [*Betz et al.*, 2009]). IoT can bring benefits in terms of easier rapid deployment and data integration.

Environmental sensor data brought to the general public can also provide education and engagement, e.g., volcanic activity (http://volcanoes.usgs.gov), cherry blossom forecast and observation (www.tenki.ja/sakura/expection.html), and glacial environments (www.glacsweb.org/glacier-explorer/). IoT sensors are expected to be low cost and simple to use, becoming common gadgets at home which contribute crowd-sourced data (e.g., www.wunderground.com). IoT technology does not necessarily provide better data integration globally as there are web technologies (linked data and semantic web) which are also required. It is still possible to make IoT sensing systems produce “data silos” which are separate and provide no data exchange interfaces.

There are also some disadvantages to the spread of devices. An increase in devices could increase our use of energy and resources. However, as mentioned in section 1, using IoT sensing could reduce greenhouse gases by improved efficiencies for vital resources (agriculture, power, and transport). These embedded systems may have a short life and quickly become obsolete. Technologies such as smart dust (nanoscale nodes = *Buettner et al*. [2008]) could become pollutants, so small they become difficult to remove from the environment.

6. Conclusions

Environmental sensor networks have the potential to transform environmental and Earth science, but there has been a slow uptake of the technology from the laboratory to the field. This is because most of the systems rely on bespoke nonstandard elements which require specialized expertise. The logical next step is the use of IoT systems where elements are more standardized, easier to use, and link with other web resources. The IoT concept provides the opportunity for Earth and environmental scientists to have a seamless data stream from the field to the web. It should be possible to replace a sensor node with one from another manufacturer without needing to replace the radio communications, data server, and management software. Whether this happens with internet protocols everywhere, open standards and reuse of other IoT hardware depends on take-up of the technologies in Earth science. What is clear is that the wave of IoT development can make a significant contribution to sensing through the use of appropriate new technologies.

Acknowledgments
We wish to thank Glacier-Jeeps Iceland for fieldwork assistance and hosting our gateway station, Guðrún Guðmundsdóttir and Magnús Guðjónsson, in Holmur for hosting the "farm" gateway. Also, the fieldwork team: Philip Basford, Graeme Bragg, Alex Clayton, Jeff Gough, Dirk De Jager, Kathryn Rose, Sarah Stock, Andrew Turner, Richard Waller, and Tyler Ward, and Lyn Ertl, Geography and Environment, for cartographic services. The data for this paper are available at www.glacsweb.org.

References

Ahonen, T., R. Virrankoski, and M. Elmusrati (2008), Greenhouse monitoring with wireless sensor network, in *IEEE/ASME International Conference on Mechtronic and Embedded Systems and Applications, 2008. MESA 2008*, pp. 403–408, IEEE, Xi'an, China, doi:10.1109/MESA.2008.4735744, 12–15 Oct.

Alcaraz, C., P. Najera, J. Lopez, and R. Roman (2010), Wireless sensor networks and the Internet of Things: Do we need a complete integration?, in *The Internet of Things: A Survey*, Comput. Networks, vol. 54, edited by L. Atzori, A. Lera, and G. Morabito, pp. 2787–2805. [Available at https://www.nics.uma.es/system/files/AlcarazNajeraLopezRoman2010.pdf, accessed on February 2015].

Atzori, L., A. Lera, and G. Morabito (2010), The Internet of Things: A survey, *Comput. Networks*, *54*, 2787–2805.

Bag, G., M. T. Raza, K.-H. Kim, and S.-W. Yoo (2009), LoWMob: Intra-PAN mobility support schemes for 6LoWPAN, *Sensors*, *9*, 5844–5877.

Betz, H. B., K. Schmidt, P. Laroche, P. Blanchet, W. P. Oettinger, E. Defer, Z. Dziewit, and J. Konarski (2009), LINET—An international lightning detection network in Europe, *Atmos. Res.*, *91*, 564–573, doi:10.1016/j.atmosres.2008.06.012.

Buettner, M., B. Greenstein, A. Sample, J. R. Smith, and D. Wetherall (2008), Revisiting smart dust with RFID sensor networks, Proceedings of ACM HotNets 2008, Calgary, Canada.

Cama, A., F. G. Montoya, J. Gómez, J. L. De La Cruz, and F. Manzano-Agugliaro (2013), Integration of communication technologies in sensor networks to monitor the Amazon environment, *J. Cleaner Prod.*, *59*, 32–42, doi:10.1016/j.jclepro.2013.06.041.

Casaleggio Associati (2011), The evolution of internet of things. [Available at http://www.casaleggio.it/pubblicazioni/Focus_internet_of_things_v1.81%20-%20eng.pdf, accessed on February 2015.]

Christin, D., A. Reinhardt, P. S. Mogre, and R. Steinmetz (2009), Wireless sensor networks and the Internet of Things: Selected challenges. [Available http://www.ti5.tuhh.de/events/fgsn09/proceedings/fgsn_031.pdf, accessed on February 2015].

Colitti, W., K. Steenhaut, N. De Caro, B. Buta, and V. Dobrota (2011), Evaluation of constrained application protocol for wireless sensor networks, in *18th IEEE Workshop on Local & Metropolitan Area Networks (LANMAN)*, pp. 1–6, IEEE, Chapel Hill, N. C.

Corke, P., T. Wark, R. Jurdak, W. Hu, P. Valencia, and D. Moore (2010), Environmental wireless sensor networks, *Proc. IEEE*, *98*, 1903–1917, doi:10.1109/JPROC.2010.206853.

Cullinen, M. (2013), Machine to machine technologies: Unlocking the potential of a $1 trillion industry, Carbon War room Research report. [Available at http://www.grahampeacedesignmail.com/cwr/cwr_m2m_down_singles.pdf, accessed on February 2015.]

Delin, K. A., et al. (2005), Environmental studies with the SensorWeb: Principles and practice, *Sensors*, *5*, 103–117.

Dyo, V., S. A. Ellwood, D. W. Macdonald, A. Markham, C. Mascolo, B. Pásztor, S. Scellato, N. Trigoni, R. Wohlers, and K. Yousef (2010), Evolution and sustainability of a wildlife monitoring sensor network, in *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys '10)*, pp. 127–140, ACM, New York, doi:10.1145/1869983.1869997.

Feki, M. A., F. Kawsar, M. Boussard, and L. Trappeniers (2013), The Internet of Things: The next technological revolution, *Computer*, *46*, 24–25, doi:10.1109/MC.2013.63.

Francis, J. A., and S. J. Vavrus (2012), Evidence linking Arctic amplification to extreme weather in mid-latitudes, *Geophys. Res. Lett.*, *39*, L06801, doi:10.1029/2012GL051000.

Hart, J. K., and K. Martinez (2006), Environmental sensor networks: A revolution in the Earth system science?, *Earth Sci. Rev.*, *78*, 177–191.

Hasler, A., I. Talzi, J. Beutel, C. Tschudin, and S. Gruber (2008), Wireless sensor networks in permafrost research: Concept, requirements, implementation, and challenges, in *9th International Conference on Permafrost, Fairbanks, US*, pp. 669–674, Institute of Northern Engineering, Fairbanks.

Hey, A. J., S. Tansley, and K. M. Tolle (2009), *The Fourth Paradigm: Data-Intensive Scientific Discovery*, Microsoft Research, Redmond, Wash.

Hitzler, P., and K. Janowicz (2013), Linked data, big data, and the 4th paradigm, *Semantic Web*, *4*, 233–235, doi:10.3233/SW-130117.

Hodges, S., S. Taylor, N. Villar, J. Scott, D. Bial, and T. B. Fischer (2013), Prototyping connected devices for the Internet of Things, *Computer*, *46*, 26–34, doi:10.1109/MC.2012.394.

HP (2013), Central Nervous System for the Earth (CeNSE). [Available at http://www8.hp.com/us/en/hp-information/environment/cense.html?jumpid=reg_r1002_usen_c-001_title_r0001#.UVLHXldIVCM, accessed on February 2015.]

IBM (2010), A Smarter Planet. [Available at http://www.ibm.com/smarterplanet/.]

Intel (2009), The rise of the Embedded Internet. Intel embedded processes white paper. [Available at http://download.intel.com/embedded/15billion/applications/pdf/322202.pdf, accessed on February 2015.]

Ishigaki, Y., Y. Matsumoto, R. Ichimiya, and K. Tanaka (2013), Development of mobile radiation monitoring system utilizing smartphone and its field tests in Fukushima, *IEEE Sens. J.*, *13*, 3520–3526, doi:10.1109/JSEN.2013.2272734.

Kortuem, G., N. Davies, C. Efstratiou, K. Kinder, M. I. White, R. Hooper, J. Finney, L. Ball, J. Busby, and D. Alford (2007), Sensor networks or smart artifacts? An exploration of organizational issues of an industrial health and safety monitoring system, in *Proceedings of International Conference, Ubiquitous Computing (Ubicomp 07)*, pp. 465–482, IEEE, Innsbruck, Austria.

Larios, D. F., J. M. Mora-Merchan, E. Personal, J. Barbancho, and C. León (2013), Implementing a distributed WSN based on IPv6 for ambient monitoring, *Int. J. Distrib. Sens. Networks*, *2013*, 328747, doi:10.1155/2013/328747.

Mainetti, L., L. Patrono, and A. Vilei (2011), Evolution of wireless sensor networks towards the Internet of Things: A survey, in *2011 19th International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, pp. 1–6, IEEE, Dalmatia.

Manabe, S., and R. J. Stouffer (1980), Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. *J. Geophys. Res.*, *85*, 5529–5554, doi:10.1029/JC085iC10p05529.

Martinez, K., J. K. Hart, and R. Ong (2004), Environmental Sensor Networks, *IEEE Comput.*, *37*, 50–56.

Martinez, K., P. Padhy, A. Elsaify, G. Zou, A. Riddoch, J. K. Hart, and H. L. R. Ong (2006), Deploying a sensor network in an extreme environment, in *Sensor Networks, Ubiquitous and Trustworthy Computing, 05–07 Jun 2006*, pp. 186–193, IEEE Computer Society, Taichung,Taiwan.

Martinez, K., J. K. Hart, and R. Ong (2009), Deploying a wireless sensor network in Iceland, in *Proceedings of Geosensor Networks*, Lect. Notes in Comput. Sci., vol. 5659, pp. 131–137, Springer, U. K.

Martinez, K., P. J. Basford, D. De Jager, and J. K. Hart (2012), A wireless sensor network system deployment for detecting stick slip motion in glaciers, in *IET International Conference on Wireless Sensor Systems 2012*, pp. 1–3, IET, London, 18–19 Jun.

Medaglia, C. M., and A. Serbanati (2010), An overview of privacy and security issues in the Internet of Things, in *The Internet of Things*, pp. 389–395, Springer, New York.

Meinig, C., S. E. Stalin, A. I. Nakamura, and H. B. Milburn (2005), Real-time deep-ocean tsunami measuring, monitoring, and reporting system: The NOAA DART II description and disclosure.

Miller, G. H., R. B. Alley, J. Brigham-Grette, J. J. Fitzpatrick, L. Polyak, M. C. Serreze, and J. W. C. White (2010), Arctic amplification: Can the past constrain the future?, *Quat. Sci. Rev.*, *32*, 1779–1790.

Moorthy, G. K., C. Yaashuwanth, and K. Venkatesh (2013), A wireless remote monitoring of agriculture using Zigbee, *Int. J. Eng. Innovative Technol. (IJEIT)*, *2*, 72–74.

Nath, S., J. Liu, and F. Zhao (2007), SensorMap for wide-area sensor webs, *Computer*, *40*, 90–93, doi:10.1109/MC.2007.250.

Presser, M., M. Eurich, C. Villalonga, and P. M. Barnaghi (2009), The SENSEI project: Integrating the physical with the digital world of the network of the future, *IEEE Commun. Mag.*, *47*, 1–4.

Rockström, J., et al. (2009), A safe operating space for humanity, *Nature*, *461*, 472–475.

Rey-Moreno, C., I. Bebea-Gonzalez, I. Foche-Perez, R. Quispe-Tacas, L. Liñán Benitez, and J. Simo-Reigadas (2011), A telemedicine WiFi network optimized for long distances in the Amazonian jungle of Peru, in *Proceedings of the 3rd Extreme Conference on Communication: The Amazon Expedition, ExtremeCom '11*, pp. 1–9, ACM, New York, doi:10.1145/2414393.2414402.

Roggen, D., G. Tröster, P. Lukowicz, A. Ferscha, J. Millán, and R. Chavarriaga (2013), Opportunistic human activity and context recognition, *Computer*, *46*, 36–45, doi:10.1109/MC.2012.393.

Sanchez, L., et al. (2014), SmartSantander: IoT experimentation over a smart city testbed, *Comput. Networks*, *61*, 217–238, doi:10.1016/j.bjp.2013.12.020.

Serreze, M. C., and R. G. Barry (2011), Processes and impacts of Arctic amplification: A research synthesis, *Global Planet. Change*, *77*, 85–96, doi:10.1016/j.gloplacha.2011.03.004.

Shelby, Z., and C. Bormann (2009), *6LoWPAN: The Wireless Embedded Internet*, vol. 43, John Wiley, West Sussex, U. K.

Suo, H., J. Wan, C. Zou, and J. Liu (2012), Security in the Internet of Things: A review, in *2012 IEEE International Conference on Computer Science and Electronics Engineering (ICCSEE)*, vol. 3, 648–651, IEEE, Hanzhou, China.

Szewczyk, R., E. Osterweil, J. Polastre, M. Hamilton, A. Mainwaring, and D. Estrin (2004), Habitat monitoring with sensor networks, *Commun. ACM*, *47*, 34–40.

Tateson, J., C. Roadknight, A. Gonzalez, T. Khan, S. Fitz, I. Henning, N. Boyd, C. Vincent, and I. Marshall (2005), Real world issues in deploying a wireless sensor network for oceanography, paper presented at Workshop on real-world wireless sensor networks REALWSN'05, Stockholm, Sweden.

Vilamovska, A. M., E. Hattziandreu, R. Van Schindler, C. De Oranje H. Vries, and J. Krapelse (2009), RFID application in healthcare—Scoping and identifying areas for RFID deployment in healthcare delivery, RAND Europe.

Werner-Allen, G., J. Johnson, M. Ruiz, J. M. Lees, and M. Welsh (2005), Monitoring volcanic eruptions with a wireless sensor network, paper #1568945184 presented at Proc. European Workshop on Sensor Networks (EWSN'05).

Wickland, K. P., R. G. Striegl, J. C. Neff, and T. Sachs (2006), Effects of permafrost melting on CO_2 and CH_4 exchange of a poorly drained black spruce lowland, *J. Geophys. Res.*, *111*, G02011, doi:10.1029/2005JG000099.

Yan-e, D. (2011), Design of intelligent agriculture management information system based on IoT, in *4th International Conference on Intelligent Computation Technology and Automation*, vol. 1, pp. 1045–1049, IEEE, Shenzhen, China, doi:10.1109/ICICTA.2011.262.

Yu, L., N. Wang, and X. Meng (2005), Real-time forest fire detection with wireless sensor networks, in *International Conference on Wireless Communications, Networking and Mobile Computing*, vol. 2, pp. 1214–1217, IEEE, Wuhan, China.

ZigBee Alliance (2009), IEEE 802.15. 4, ZigBee standard. [Available at http://www. zigbee.org.]