Here There be Dragons: The TSensors Systems Technology Roadmap

Yorgos D. Marinakis[1,2], Steven T. Walsh[1,2], Victor A. Chavez[2,3]
[1]Anderson School of Management, University of New Mexico, Albuquerque, NM- USA
[2]University of Twente, School of Management & Governance,
Dutch Institute for Knowledge Intensive Entrepreneurship (NIKOS), Enschede, the Netherlands
[3]Office of Technology Transfer, USDA Agricultural Research Service, North Atlantic Area

***Abstract*--Abundance refers to the thesis that four emerging forces, namely exponential technologies, the Do-it-yourself (DIY) innovator, Technophilanthropists, and the Rising Billion, will solve the most significant and intractable world social problems. One such exponentially growing technology is the sensor. It has been estimated that there will be a trillion sensors, or "TSensors," by 2020. These TSensors will comprise a portion of the so-called proposed Internet of Things. In the present article we construct a technology forecast for that portion of the Internet of Things that is required to support the manufacture and operation of the TSensors. We utilize the technology roadmap framework, in which we highlight the importance of consortia and provide Technology Readiness Levels for component technologies.**

I. INTRODUCTION

Abundance [1] refers to Diamandis and Kotler's thesis, as expressed in their eponymous book [1], that four emerging forces, namely exponential technologies, the Do-it-yourself (DIY) innovator, Technophilanthropists (philanthropists who made their wealth as technology entrepreneurs), and the Rising Billion (the world's poorest), will solve the most significant and intractable world social problems. Exponentially growing technologies comprise biotech and bioinformatics, medicine, nanomaterials, 3D printing and infinite computing, robotics, computational systems, artificial intelligence—and sensors. It has been estimated that there will be a trillion sensors, or "TSensors," by 2020 [2]. These TSensors will comprise a portion of the so-called proposed Internet of Things.

The proposed Internet of Things (IoT) is typically defined and discussed in terms of its technology components and their research challenges. These technology components usually comprise radio frequency identification (RFID) tags, wireless sensor networks, and identification and/or addressing schemes [3], [4]. The research challenges typically relate to: wireless sensor networks; low power and/or energy efficient sensors; energy harvesting; network security, privacy and innovation; and miniaturization [3], [4]. A more complete view of technologies such as the IoT would account for two more types of innovations, namely the products and services that will be based on the technology components, and the business infrastructure that will make technological innovation possible [5], [6], [7], [8] .

Technology forecasts for the Internet of Things have received less attention than discussions of the technologies themselves. Technological forecasting models serve a variety of purposes and come in a variety of forms. One type of technological forecasting model, the technology roadmap, addresses basic strategic questions such as "what are the major obstacles to reaching the [desired] future?" Yet structural (vis-à-vis dynamical) technological forecasting models, such as the technology roadmap, require considerable interpretation. Examples of interpretations are available, but systematic methods for interpreting structural technological forecasting models are underrepresented.

In the present article we construct a technology forecast for that portion of the Internet of Things that is required to support the manufacture and operation of the sensors, i.e., the business infrastructure that will make TSensors possible. We utilize the technological roadmapping model for disruptive [9] and emerging [10] technologies. In our roadmap we identify critical dimensions and boundary conditions that must be satisfied by emerging technologies relating to the TSensors Systems. We identify candidate technologies and evaluate their Technology Readiness Levels. We then offer a method for systematic interpretation by applying trends in technology supply-side and market-side market behavior and technology evolution.

The present work will be of interest to researchers and practitioners in the topics of Abundance, the Internet of Things, sensors, and technological forecasting and evolution. We contribute to the practice of technological roadmapping by rationalizing the third generation roadmap [10] and by providing a method for roadmap interpretation. The present article can also be utilized as an example case study in technological roadmapping.

II. THEORETICAL BACKGROUND

We begin our discussion of the theoretical background by addressing key definitions. We then address technological roadmapping. In that discussion we present the theory underlying our method for interpreting structural technological roadmaps.

A. Definitions

Abundance [1] is the hypothesis that technological advances will resolve the world's most intractable problems by 2050. Abundance comprises the four pillars of abundant health care, abundant food, abundant energy and an abundant "green" environment [1]. The specific origins of Abundance are obscure but can be placed in the Twentieth Century attitude of optimism about science and then about technology [11]. There is an equally long tradition of skepticism about technology [12], [13], [14], due perhaps to the atrocities of mechanized war seen in World War I [15], [16: 27]. Within that skeptical tradition, Abundance has been criticized as an example of techno-utopianism [17]. Abundance would likely be ushered in by the Internet of Things.

The Internet-of-Things (IoT) refers to a futurist vision in which items such as household objects are endowed with Internet connectivity [18]. The IoT is typically defined as “a Network of interconnected objects that not only harvests information from the environment (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analytics, applications, and communications” [4: 1646]. The European Commission Information Society similarly defined the IoT as “Interconnected objects having an active role in what might be called the Future Internet” [19]. It is believed that the IoT will comprise (i) smart devices and sensors; (ii) an Internet-based network that will connect the smart devices and sensors, and (iii) the ensemble of applications and services leveraging such technologies to open new business and market opportunities [3]. Because up to a trillion sensors are forecast by 2020, we refer to these smart devices and sensors collectively as TSensors.

We define TSensors Systems as that portion of the Internet of Things that is required to support the manufacture and operation of the sensors, i.e., the business infrastructure that will make TSensors possible. Per our discussions with experts, TSensors Systems comprise technology for: manufacturing the sensors and networks and their respective components; sensor and network energy harvesting and storage; hardware and software at the edge of the networks; ultralow power wireless; network protocols, standards, architectures and algorithms; Operating Systems; and analytics. These will be defined in their corresponding sections below.

B. Constructing and Interpreting Technological Roadmaps

Technological roadmapping [9], [10], [20] is likely a useful tool for navigating the path to Abundance: Abundance is a technology transition, and technology roadmaps are increasingly being recognized as useful tools for managing or navigating technological transitions [21]. In addition, components of technology roadmaps (e.g., consortia [22]) are also independently individually being recognized as useful for managing transitions. The purposes of technology roadmaps are various and are widely reviewed [23], [24]. The technology roadmap has been defined as a consensus articulation of scientifically informed vision of attractive technology futures [25]. There are varieties of technology roadmaps [9], [10], [20] and most at their core address the state of maturity of the technology.

In the present student we utilize the third generation technological roadmap or technology landscape [10]. The third generation roadmap is a roadmap of roadmaps. It is a meta-roadmap. This particular version of roadmap was designed for use with contemporary technological systems that comprise “multiple root technologies” [10: 195] i.e., a plurality of emerging technologies, often from disparate and remote technology sectors. In the best case, the technology landscape comprises roadmaps of these multiple root technologies, combined with a plan for integrating these multiple root technologies into a system or systems. We expect that more often the technology landscape, like the present example, will be more preliminary. It will likely comprise an identification of the relevant component technologies, along with examples of these component technologies that represent their current states of maturity. We expect most third generation roadmaps will be of the preliminary type because roadmaps for these component emerging technologies are not commonly available to independent forecasters and these component roadmaps are hard to construct. Integrating these groups of emerging technologies into specific example systems is even harder. The preliminary type of third generation roadmap, however, is not an inferior or deficient product. It has the benefit of enabling and facilitating the identification of areas in these component technologies in need of development. Therefore it enables recommendations that would advance or accelerate technological development. These preliminary roadmaps can also raise the awareness in firms that are developing these component technologies. Such awareness could result in collaboration between firms that would not otherwise take place. This collaboration could take the form of consortia development.

The third generation technology roadmap utilizes the Technology Readiness Level (TRL) [10] to assess the state of maturity of the technology. Originally developed by NASA for use in the space program, TRLs have been appropriated by technology forecasting for any and all contexts. TRLs implicitly assume that the technology fits the task at hand. We assign TRLs to each technology component of the roadmap. There are now several TRL rubrics, but they all range from basic research through operations, and steps in between.

Third generation technological roadmaps reflect and depict the complex nature of the contemporary environment by considering multiple root technologies, multiple unit cells, multiple critical dimensions, strict boundary conditions constraining innovations and products; and by giving a heightened importance to drivers and consortia [10]. Technology roadmaps began widespread use at the same time that the technology paradigm framework [26] began to be developed, and there appears to be considerable overlap or resonance in their core concepts. A technology paradigm is a set of specific patterns of solution to selected techno-economic problems. It comprises a specific body of practice, an ensemble of artifacts, a distinct notion of a design of desired artifacts, and a specific body of understanding shared among professionals in a field. A paradigm is driven by a solution to the multiple critical dimensions (qualitative descriptions of the technical parameters that must be met by the component emerging technologies) and boundary conditions (non-technical environmental constraints that must be met by the system as a whole). The dominant specific body of practices in contemporary supply-side technology evolution [8] comprises technology convergence [20], [27], [28], distributed computing [29] and miniaturization [30]. The ensemble of artifacts comprises the multiple root technologies, and the desired artifacts are future versions of those technologies that satisfy the multiple critical dimensions and boundary conditions. The progressive refinement and improvement in the supply responses to user demand requirements is called the technology trajectory [26].

To forecast a technology, the roadmap (and implicitly, the technology paradigm and trajectory) must be interpreted in light of patterns in market behavior. In the contemporary technology sector, the dominant pattern in technology market-side behavior [31], [32] is the network effect [33], [34], comprising increasing returns (winner-take-all-or-most) [35], [36], [37], [38]; and switching costs [37]. These two phenomena determine the size and stability of the installed (customer) base, and singly or together they can lead to lock-in on the market side [37] and path dependency on the supply side [37].

III. METHODS

We began with structured interviews of experts in the emerging technologies of the Internet of Things. In these interviews we identified the critical dimensions, boundary conditions, market drivers, and components of the TSensors Systems. We then performed literature searches on each of these subjects, focusing on articles that were relevant to IoT. These searches validated the expert opinions and provided data on the state of development of the technology components. We focused on emerging technologies that satisfied the critical dimensions and the boundary conditions. We then classified the components according to the Technology Readiness Level. We organized the results in the visual fashion of the technology landscape [10], which we then interpreted for both market-side behavior, and market-side and supply-side evolution.

IV. RESULTS

As stated above, a technology paradigm comprises a specific body of practice, an ensemble of artifacts, a distinct notion of a design of desired artifacts, and a specific body of understanding shared among professionals in a field [26]. According to our interviews of experts, the specific body of practice comprises miniaturization, convergence (in part through software), and distributed computing. Miniaturization is evidenced by the research in MEMS and nanotechnologies for 3D printing, and energy harvesting and storage. Convergence is evidenced by emerging network protocols that accommodate ultralow operating power and energy harvesting. The use of similar miniature technologies for energy harvesting and energy storage also suggests convergence. Distributed computing is evidenced by Operating Systems designed for 10^12 simultaneously networked low-memory devices, analytics at the edge of the swarm, and proposed data-centric architectures.

The specific body of understanding regarding TSensors Systems is that it will be implemented as part of the Internet of Things using a modified cloud interface and simple printed, self-powered wireless sensors; and that it must satisfy the enumerated multiple critical dimensions and as the strict boundary conditions. The amount of data that can be streamed in wired and wireless networks, as well as the likely sensor capabilities for data transmission, storage and processing, suggests a distributed cloud-based architecture. The need to minimize sensor manufacturing costs and to optimize sensor energy storage capacity suggests a solution using printed sensors.

The ensemble of artifacts is set out below as the components of the roadmap. The desired artifacts are future versions of the ensemble of artifacts that satisfy the specific body of understanding. The development of future versions is subject to the dominant supply-side and market-side forces.

A. *Multiple critical dimensions*

The critical dimensions are qualitative descriptions of the technical parameters that must be met by the component emerging technologies. Their identification comprises an early stage step towards developing technical specifications for the component technologies. These critical dimensions will set the direction for concerted technological development.

1. Amount of data that can be streamed in wired and wireless networks.
2. Sensor manufacturing costs.
3. Sensor capabilities for data transmission, storage and processing.
4. Sensor energy storage capacity.

B. *Strict boundary conditions constraining innovations and products*

Boundary conditions are non-technical environmental constraints that must be met by the system as a whole. These are concerns and frameworks that comprise the socio-legal context in which the proposed emerging technological system will operate. In the case of TSensors Systems, these are primarily privacy and security.

Privacy is a non-technical boundary condition for TSensors Systems because the Internet of Things, of which TSensors are a part, envisions ubiquitous sensors [39]. Trends in data privacy laws can be determined by analyzing proposed laws and new laws, such as: the EU draft General Data Protection Regulation [40], [41], [42]; proposed changes to United States communications law [43]; and the new Singapore Personal Data Protection Act [44]. Privacy is a particularly fluid area, since on October 6th, 2015, the European Court of Justice (ECJ) struck down the year 2000 safe harbor privacy pact between the European Union and America [45], [46], [47]. The ECJ decision destabilized (if not democratized) the issue by giving EU member state data protection authorities the power to determine whether Europe-wide deals have sufficient safeguards. The holding also specifies that these data protection authorities can litigate these Europe-wide deals national courts, and these national courts can then refer the case to the ECJ.

Security is also a non-technical boundary condition for TSensors Systems due to the distributed computing model of the IoT [48]. Highly invasive, ubiquitous sensors will require both security in both cyberspace and physical space. One current example is the hacking of a Jeep Cherokee [49], which prompted US Senators Markey and Blumenthal to introduce the SPY Car Act to promulgate federal standards for automobile cybersecurity [50].

C. Drivers of the TSensors Systems Technology Roadmap

The drivers of technology change for TSensors Systems are more specific and more technological than the drivers for the TSensors. TSensor drivers comprise policy issues like hunger. TSensors Systems drivers in contrast relate more specifically to the technological requirements of the infrastructure and network operations. Some of these drivers are initiatives by single corporations, e.g., Hewlett-Packard, and IBM.

The TSensors Systems drivers comprise:

- *TSensors* – The TSensors themselves are the one and only primary driver for TSensors Systems. All other TSensors Systems drivers are derivative of the TSensors.
- *Internet of Things (IoT)* –The IoT comprises IP-enabled (Internet protocol) devices, RFID tags, wireless sensor networks, machine-to-machine (M2M) communications, mobile devices and apps, white space TV spectrum and cloud computing. It connects these devices and entities through new network architectures to enable low latency control.
- *Mobile Market* – This market is transitioning to an unPad infrastructure in which the (key)Pad/mobile device goes away but its functionality remains. It will be implemented by opportunistically interconnecting sensors and actuators.
- *Wearable Market* - The four end-user segments of the wearable technology products comprise: fitness and wellness, Infotainment, healthcare and medical, and industrial and military.
- *Digital Health* - Improving health diagnostics and therapeutics while reducing cost.
- *Context Computing* - Deriving information about us (such as feelings) and around us.
- *CeNSE (Central Nervous System for the Earth)* - Building global environment monitoring. Sponsored by Hewlett-Packard Corporation.
- *5-in-5* - Five senses for computers in five years. Sponsored by IBM.

D. Consortia of the TSensors Systems Technology Roadmap

In the contemporary environment of technology development, consortia play a prominent role because they consolidate the major parties behind competing technologies. This is particularly important in the cases of technology platforms such as protocols and standards, because these are usually winner-take-all-or-most competitions [36], [51]. Open Standards reduce transaction costs and foster specialization and entrepreneurship; and conversely, entrepreneurship encourages the adoption of Open Standards [52].

The first IoT protocol was AllJoyn. It was developed by Qualcomm in 2011 and was given to the Linux Foundation in December 2013. Despite Qualcomm's statement that they would not monetize their contributions to AllJoyn [53], a mistrust of Qualcomm and dissatisfaction with AllJoyn contributed to the formation of the Open Interconnect Consortium [54]. Not to be outdone by Qualcomm, in July 2014 Alphabet's (formerly Google Inc's) Nest Labs introduced the Thread Group. Thread Group's purpose was to promote Thread, an IPv6 networking protocol built on open standards and designed for low-power 802.15.4 mesh networks. Seeking a niche in the industrial IoT, in March 2014, Intel, Cisco, AT&T, GE, and IBM announced the Industrial Internet Consortium.

Because the IoT sensor technologies relating to these protocols are still relatively new, the protocols remain relatively untested. We assign them TRL = 4 (Table 1).

TABLE 1A. 3D PRINTING (ADDITIVE MANUFACTURING) CONSORTIUM.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
3MF Consortium	3MF	Dassault Systèmes S.A.; FIT AG/netfabb GmbH; Microsoft Corporation; HP; Shapeways, Inc.; SLM Solutions Group AG; and Autodesk Inc.	TBS	The 3MF 3D printing format will allow design applications to send full-fidelity 3D models to a mix of other applications, platforms, services and printers.

TABLE 1B. ENERGY HARVESTING CONSORTIUM.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
Energy Harvesting Consortium in Japan	N/A	12 companies	Now 32 companies.	Aim to incubate and accelerate new ventures embarked upon by our members as well as stimulate the relevant markets in collaboration with the government of Japan.

TABLE 1C. ENERGY STORAGE CONSORTIA.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
UK Energy Storage Consortium	N/A	Engineering and Physical Sciences Research Council	Eight professors.	Lithium ion, flow and supercapacitors.
Energy Storage System Evaluation & Safety Consortium (EssEs)	N/A	TBD	TBD	Provides test data from member-selected sets of battery cells.
New York Battery and Energy Storage Technology (NY-BEST™) Consortium	N/A	New York State	150 members	Expert resource to energy storage-related companies and organizations seeking assistance to grow their businesses in New York State.

TABLE 1D. ULTRALOW POWER WIRELESS CONSORTIUM.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
Wireless Power Consortium	Qi [low and medium power]	ConvenientPower Limited, Fulton Innovation LLC, Logitech SA, National Semiconductor Corporation, Royal Philips Electronics N.V., Sanyo Electric Co. Ltd., Shenzhen Sang Fei Consumer Communications Co. Ltd. and Texas Instruments Incorporated.	Nokia, Huawei and Visteon.	Aims to create a global standard for inductive charging technology.

TABLE 1E. NETWORK PROTOCOL/STANDARD CONSORTIA.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
Thread Group	IPv6 over Low power Wireless Personal Area Networks (6LoWPAN)	Nest (Google, Alphabet)	Samsung Electronics, ARM Holdings, Freescale Semiconductor, Silicon Labs, Big Ass Fans, Yale (locks)	6LoWPAN will involve mesh networks that "scale to hundreds of devices with no single point of failure" and which feature "banking-class encryption."
Allseen Alliance	AllJoyn	Qualcomm and The Linux Foundation	Cisco, Microsoft, LG, and HTC	Device, OS, and network agnostic, so it shouldn't become obsolete when newer technologies come along.
Open Interconnect Consortium	None yet.	Intel	Atmel, Dell, Broadcom, Samsung, and Wind River	The protocol would be created as part of a collaborative process between all of the members.
Industrial Internet Consortium	None yet.	Intel, Cisco, AT&T, GE, and IBM	Microsoft	Focuses on industrial IoT.

TABLE 1F. OPERATING SYSTEMS CONSORTIUM.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
None.	N/A	N/A	N/A	N/A

TABLE 1G. ANALYTICS CONSORTIUM.

Consortium	Protocol	Founder(s)	Other players	Differentiating Factor(s)
None.	N/A	N/A	N/A	N/A

E. Components of the TSensors Systems Technology Roadmap and their Technology Readiness Levels

Unlike earlier technological advances that comprised a single unit cell or root technology, many contemporary technological advances comprise multiple root technologies, e.g., as in emerging technologies in the pharmaceutical industry [10]. In accordance with our definition of TSensors Systems, we have identified multiple root technologies and consolidated them into six categories: Additive manufacturing; Energy harvesting; Energy Storage; Ultralow power wireless; Network innovation; Operating Systems; and Analytics. We now discuss these in turn.

1) Additive manufacturing (3D printing) for manufacturing sensors and sensor components. TRL 4.

While the popular press focuses on high-value, low-volume usages such as printing houses and bridges [55], the TSensors Systems effort focuses on 3D printing of sensors. Additive printing will be needed to make low-cost sensors. The main technological challenges for TSensors Systems arise from the need to print very small devices such as sensors at the nano-scale.

This area has a TRL of 4 (Table 2).

TABLE 2. 3D PRINTING FOR MANUFACTURING SENSORS AND SENSOR COMPONENTS.

Source	Technology Description	Technology Readiness Level
[56]	Direct printing of PDMS (polydimethylsiloxane) on glass lab-on-a-chip (LOC) devices implemented by micro stereo lithography.	TRL 4
[57], [58]	The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is printing electronic components and sensors.	TRL 4
[59]	GE Global Research is developing Direct Write to print 3D sensors that can withstand 2,000 degrees Fahrenheit and handle high mechanical forces.	TRL 4
[60]	IBM Research in Zurich developed a microscopic 3D printer capable of writing nanometer resolution patterns into a soft polymer.	TRL 4
[61]	Experimentally investigate the 3D printing of nanoscale objects by depositing electrospun polymer nanofibers.	TRL 1
[62]	Microcapillary (Microfluidic) Interface Fabrication using 3D printing; 3D printing allows for direct generation of complex, three-dimensional structures that are otherwise only achievable using multiple processing steps and at significantly higher costs.	TRL 3
[63]	Embedded 3D printing of a carbon-based resistive ink within an elastomeric matrix, for creating soft functional devices for wearable electronics, human/machine interfaces, soft robotics, etc.	TRL 4

2) Energy harvesting for operating sensors. TRL 4.

Energy harvesting technologies scavenge energy from the ambient environment. They convert heat, strain, vibration, sun and sound into electricity. The central challenge is to miniature these technologies to the level of the sensors themselves.

In the area of energy harvesting, there are ample analyses of requirements and model systems, but there are fewer reported prototypes and forecasts. A baseline for existing energy harvesting technologies for Wireless Sensor Networks (WSNs) is available [64], and can be used a benchmark to measure progress. Some of these power densities and strength-weakness assessments will change as the technologies are further developed. Our emphasis is on new developments and new capabilities in those technologies.

One of the most promising emerging energy harvesting technology is piezoelectrics. Piezoelectric devices create electricity from strain-, vibrational- and acoustic-based [65] sources. With piezoelectric energy the main technological challenge is purportedly harvested energy density [66]. The main design issue, however, is beam shape [67]. Much of the recent research relates to cantilever beams (and their transducers, e.g., [68]), such as optimal piezoelectric shape and configuration [69], [70]. Rectangular beams are favored because they have lower resonance frequencies and higher strain for a given force input, but trapezoidal cantilever beams produce more power per unit area because the distribution of strain is uniform [67]. Some researchers are investigating designs other than cantilevers such as stacked configurations [71], though research from the last ten years also considers shells, spirals and zigzags [67]. For greater energy requirements, multiple sources in piezoelectric energy harvesting may be required, and three harvesting interface circuits have been proposed for enabling the use of multiple sources [72].

Though some of these technologies are mature, in terms of IoT needs this area has an overall TRL of 4 (Table 3).

TABLE 3. ENERGY HARVESTING FOR OPERATING SENSORS.

Source	Technology Description	Technology Readiness Level
[69]	Piezoelectric device comprising a MEMS cantilever mechanical resonator for scavenging energy from ambient vibrations.	TRL 4
[70]	Three different MEMS cantilever structures for power density and bandwidth.	TRL 9
[67]	A triangular cantilever beam harvests more energy than rectangular comb-shaped cantilever beam.	TRL 4
[73]	Highly-efficient, flexible piezoelectric PZT thin film nanogenerator that generates power from regular bending motions.	TRL 4
[68]	Cymbal-shaped transducers for piezoelectric rectangular beam.	TRL 2
[71]	Multilayer piezoelectric stack.	TRL 2
[74]	Piezoelectric ceramic nanowires in strain-driven nanogenerators (NGs), polymers for stress-driven NGs.	TRL 7
[75]	Piezo-electrochemical effect in Li intercalated carbon fibers.	TRL 2
Cypress	Chips that can harvest their own energy from the sun, vibration or heat.	TRL 9
EnOcean GmbH	Energy converters that can harvest their own energy using motion, heat and solar energy.	TRL 9

3) Energy storage for operating sensors. TRL 4.

Energy storage technologies are being developed at spatial scales that are appropriate for the emerging nano-scale energy harvesting technologies. These include nanowires [76], nanotubes [77], and nano-scale 3D electrodes. In addition, technology has been developed to wirelessly power micro-scale devices implanted in deep tissue, a microimplant (2 mm, 70 mg) capable of closed-chest wireless control of the heart [78].

These individual technologies generally have a TRL of 4. This area has a TRL of 4 (Table 4).

4) Ultralow power wireless. TRL 4.

Wireless sensor networks (WSNs) are relevant to TSensors Systems because the primary goal of a WSN is to enable wireless communication from and between sensors at low operating power. Low operating power is achieved at the device level by low transmit power [80] and/or low circuit power [81], [82]. In this section we discuss device-level innovations.

This area has a TRL of 4 (Table 5).

5) Network innovations. TRL 4.

Networking protocols are rules and conventions for how networked electronic devices identify each other, make connections with each other, and send and receive data [84]. Network standards set the boundary conditions for network protocols. Protocols and/or standards can be hierarchically layered, as in the widely-used Open Systems Interconnection Model (OSI) [85]. These layers comprise the network architecture. Emerging architectures have been designed for ubiquitous wireless applications [86], for wireless network management and control [87], and for spectrally efficient with power consumption awareness [18].

Though several wireless network protocols are currently in use [88], we are concerned here with emerging innovations for a post-IP network in the areas of protocols, standards, architectures and algorithms. The attributes of this post-IP network will flow from the nature of the major terminals, just as the architecture for the Internet was determined by PCs and the architecture of telephony networks was determined by the need for stable voice communications [86]. These new major terminals will likely be low power, small devices such as passive or active radio frequency identification (RFID) tags and wireless sensors.

Emerging network protocols (and/or standards) are integrating the IoT technologies by accommodating emerging functionalities and by providing new functionalities. In particular, emerging network protocols are designed to work with and/or enable the low power consumption of connected devices [86], [88] and to provide heightened network-level security [89]. These emerging protocols are thereby enabling technology convergence at the physical level, as in the convergence of energy harvesting, cognitive spectrum access and mobile cloud computing technologies [18]. Commercial protocols have also been issued by Apple and Google as part of their IoT Operating Systems.

This area has a TRL of 4 (Table 6).

TABLE 4. ENERGY STORAGE FOR OPERATING SENSORS.

Source	Technology Description	Technology Readiness Level
[79]	Formation from beach sand of an interconnected 3D network of nano-silicon with a thickness of 8-10 nm.	TRL 4
[78]	Wirelessly charge micro-scale (2 mm) devices implanted inside the body.	TRL 4
[76]	Flexible electronic devices and storage using nanowires.	TRL 4
[77]	Fiber-like supercapacitors, assembled from graphene/carbon nanotube fibers, having both high power density and high energy density that can be woven into clothing and thus can power devices for the wearable market.	TRL 4

TABLE 5. ULTRALOW POWER WIRELESS.

Source	Technology Description	Technology Readiness Level
[80]	Differential frequency shift keying (DFSK), a particular variant of the conventional binary frequency shift keying (BFSK), where the transmit RF carrier is deliberately allowed to vary.	TRL 2
[83]	Active RFID tag for attaching to pallets. The tag has a 10 year battery life, costs $5-7, and possesses a 300m non-line-of-sight (NLOS) range.	TRL 6-7
[81], [82]	Flexible passive organic and MEMS RFID tags.	TRL 4
Linear Technology	Dust Networks has more than 30,000 networks installed in 120 countries.	TRL 9
EM Microelectronic	Bluetooth low energy based circuits and modules; Ultra-Low power, 2.45GHz transceivers and circuits for custom protocol applications; COiN Bluetooth beacon.	TRL 9

TABLE 6. NETWORK INNOVATIONS.

Source	Technology Description	Technology Readiness Level
[18]	IoT architecture comprising spectrum and energy management engines for maximizing the spectral and energy efficiencies.	TRL 2
Alljoyn (Open Source)	Protocol that allows devices to communicate with other devices around them.	TRL 4
Apple	HomeKit protocol	TRL 8-9
EnOcean GmbH [88]	Wireless standard “for sustainable buildings” (optimized for solutions with ultra-low power consumption and energy harvesting; ISO/IEC 14543-3-10).	TRL 9
[90]	A cooperative energy harvesting medium access control (CEH)-MAC, that adapts its operation to the energy harvesting (EH) conditions in wireless body area networks (WBANs) by setting idle time that allows the relay nodes to charge their batteries.	TRL 2
Google	Weave protocol	TRL 8-9
[86]	Post-IP network architecture.	TRL 2
IEEE	802.11af and ah standards provides extended range Wi-Fi networks and lower energy consumption.	TRL 7
IETF 6TSCH Working Group; [91]	IETF standardization group “6TSCH” aims to significantly improve IoT data flows over IEEE802.15.4e TSCH and IETF 6LoWPAN/ROLL enabled technologies.	TRL 2
[87]	An integrated network management framework comprising sensor localization, routing, data scheduling, and data aggregation for a large-scale WSN.	TRL 2
[92]	Modified IEEE 802.11 PSM for the M2M communications network deployed with numerous energy-harvesting devices.	TRL 2
Linear Technology	Dust Networks’ WirelessHART (IEC 62591) standard.	TRL 9
Thread Group	IPv6 networking protocol built on open standards and designed for low-power 802.15.4 mesh networks, such that existing popular application protocols and IoT platforms can run over Thread networks.	TRL 4

6) Operating Systems. TRL 4.

Operating systems are being designed to optimally operate in IoT environments, that is, with innumerable, tiny low power sensors and high data rates. These include the open source Contiki Operating System, RIOT, TINY and Berkeley’s Swarm Lab’s Tesselation 2.0 and Swarm OS. Commercial IoT OS have been introduced by Google. These exemplify distributed computing vis-à-vis decentralized architectures. Distributed computing has been emerging as a dominant paradigm for the Internet of Things [48].

This area has a TRL of 4 (Table 7).

TABLE 7. OPERATING SYSTEMS.

Source	Technology Description	Technology Readiness Level
Contiki (Open Source)	Contiki; connects tiny low-cost, low-power microcontrollers to the Internet. It supports IPv6 and IPv4, as well as the recent low-power wireless standards 6lowpan, RPL, CoAP.	TRL 9
RIOT (Open Source); originally developed by FU Berlin, INRIA and the HAW Hamburg	RIOT OS; based on a microkernel architecture, originally developed for sensors.	TRL 4
Swarm Lab, UC Berkeley (http://swarmlab.eecs.berkeley.edu/research/distributed-swarm-infrastructure)	Swarm-OS, Tesselation 2.0: OS’s that can simultaneously support real-time, responsive, and high-throughput parallel applications.	TRL 4
TINY OS Alliance (Open Source); originally UC Berkeley, Intel Research and Crossbow Technology	TINY OS targeting wireless sensor networks.	TRL 4
Apple	HomeKit home automation platform	TRL 8-9
Google	Devices that use Brillo OS (stripped down Android) can communicate through the Weave protocol.	TRL 8-9

TABLE 8. ANALYTICS.

Source	Technology Description	Technology Readiness Level
[93]	Proximity sensing RFID tags.	4
[94]	Model suggests platform strategies will win in the IoT world.	2
[95]	Architecture comprising a federated system of VM-based cloudlets that perform video analytics at the edge of the Internet.	2
[37]	Architecture for a decentralized data storage and delivery platform.	2

7) Analytics. TRL 4.

In this section we address the technologies required to support the implementation of analytics of sensor data. These technologies will support data collection as well as analysis. Current solutions include proximity-sensing RFID tags [93] and platform strategies for consumer goods supply chains [94]. These capabilities are pushed as much as possible to the “edge of the swarm” [29], [95], i.e., closer to the sensors themselves.

This area has a TRL of 4 (Table 8).

V. DISCUSSION

A. Interpretation

The plurality of components in the TSensors Systems Technology Landscape (Figure 1) shows that, in order to achieve Abundance, several technologies must converge, miniaturize and fragment. For example, it has been asserted that the Sensor-Actuator-Internet framework will form a core technology for the IoT [4]; but that framework implies the convergence of the three technologies, each of which itself entails the ongoing convergence of technologies. These recursive convergences must occur within the context of the demands of multiple national legal systems and any potential international regulation whether bi-lateral or multi-lateral. Convergence is being facilitated in some areas by software. For example, network protocols are being developed for sensors having energy harvesting capabilities. As technologies continue to miniaturize, we expect to see technology convergence in energy harvesting and storage. One example is nanowires that act simultaneously as energy harvesters and capacitors. Sensors may also converge with the energy systems, as with nanowire detectors. The Internet of Things will be made possible only through distributed computing. By performing computations “at the edge” of the network (at the sensors rather than sending big data to central locations for processing), distributed architectures reduce the amount of bandwidth required by systems. We have reported several candidate Operating Systems and architectures for distributed computing.

Consortia are keys to the propagation of technological development and entrepreneurship. Entrepreneurship is nurtured by (open) standards [52], which themselves are nurtured by consortia. By consolidating the parties, consortia probably accelerate “Winner-take-all-or-most.” Our study shows that consortia are forming for IoT components. However, these consortia are directed towards specific components of the TSensors Systems, mainly network protocols. An all-encompassing IoT Consortium has yet to appear on the scene, and it may not appear for quite a while because the IoT crosses industrial sectors but consortia are formed only within single industrial sectors due to the presence of immediate economic benefits. As technologies converge and form a new industrial sector, consortia then form within the new industrial sector around the new hybrid technology. To accelerate technology development and entrepreneurship, consortia should be formed for the component technologies.

B. Recommendations

The preceding analysis suggests several measures. Consortia (or more inclusive consortia) are needed in energy harvesting, energy storage, operating systems, and analytics (Table 9). More detailed roadmaps are needed for each of the component technologies. The present roadmap is a system-level study. We have identified the component technologies and we have identified major hurdles for some of these component technologies (Table 10). Our focus however in this study has been on identifying the technology readiness levels rather than on the specific barriers to component development.

TABLE 9. CONSORTIA AROUND IOT COMPONENTS.

Component	Number of Consortia
Additive manufacturing (3D printing)	1
Energy harvesting	1
Energy storage	3
Ultralow power wireless	1
Network innovations	4
Operating Systems	0
Analytics	0

TABLE 10. MAIN HURDLES FOR TECHNOLOGY COMPONENTS.

Technology Component	Main Hurdle
Additive manufacturing (3D printing)	Printing at very small scales (nanoscale)
Energy harvesting	Harvested energy density; harvesting at the nano-scale
Energy storage	Storage at the nano-scale
Ultralow power wireless	Low transmit and circuit power at the device level
Network innovations	Low power, high security
Operating Systems	Optimize for innumerable, tiny low power sensors and high data rates
Analytics	Pushed to the edge of the swarm

Directed research is recommended in these areas:

- Additive manufacturing: 3D printing at nano-scale
- Energy harvesting and storage: harvested energy density; harvesting at the nano-scale
- Ultralow power wireless: low transmit/circuit power
- Network innovation: low power, high security
- Operating Systems: optimized for innumerable, tiny low power sensors and high data rates
- Analytics**:** pushed to the edge of the swarm

In addition, a universal sensor platform would facilitate both hardware and software development. It would integrate the independent components into a single technological unit, which could then be forecast.

To accelerate Abundance we need to know how to accelerate socio-technological change. A prerequisite to managing change of any type is having a theory of change. TSensors Systems is a socio-technological system. That is apparent from the components of the technology paradigm. The critical dimensions and the component technologies are technological, but the strict boundary conditions and the drivers are socio-technological. To accelerate TSensors Systems we first need a socio-technological theory of change. One candidate theory of change comes from the bioeconomics literature [96], [97], [98], [99]. It is referred to as a socio-ecological theory by its proponents, but it may just as well function as a socio-technical theory. This theory is based on evolution and natural selection. It assumes that selection acts not just on genes but also on many other levels including communities (e.g., institutions) and cultures [97]. At the community level, the genotype analogue is the (community) symbotype comprising cooperative rules, norms and institutions. At the level of culture we have cultural symbotypes comprising cultural variants, where a culture is "an interdependent set of world views, institutions, and technologies" [100: 2484]. Here technology is explicitly enumerated as a component of culture, which argues in favor of applying the socio-ecological theory to socio-technological issues. To design the future, we need to actually manifest our desired cultural variants so that selection can act on them. This raises the question of how desired cultural variants or symbotypes can be actually manifested.

The key to actually manifesting desired cultural variants, and through them triggering socio-technological change, is the prototype. These function as seeds. Making prototypes is like sowing a field with seeds. Inserting prototypes into the world intentionally alters what would naturally occur. It functions as pre-selection. Physical prototypes for the future can be made at all socio-cultural or socio-technological levels. We have seen this already in the deployment of smart grids, smart cities, smart homes, and in personal health and fitness devices. One can make virtual as well as physical prototypes, such as through scenario planning [97] and simulation modelling. As we saw above in the roadmap, these prototypes need to conform to any relevant strict boundary conditions. That leads us to the design process. We need a set of design principles (a "sociotecture" [97: 42]) to guide our prototype development. Many futures are possible. We naturally prefer the most efficient path to the desired future. This efficient path comprises targeted prototypes, designed for the desired future. Constructing design principles is complicated by the one-to-many relationship between ultimate and proximate causation [99]. In other words, a local solution may not be a global solution.

Our interference with natural selection doesn't have to stop with prototypes. We can also interfere with the mechanism of natural selection itself, by intentionally adopting our goals and worldviews. Selection at the social level is conceptualized as being driven by goals of our own creation and preference, which leaves us room to program natural selection to operate according to our preferences. We choose our goals based on our worldviews, so we first need to change our worldview [100: 2484] to accommodate the scope of these new goals. If the culture of Silicon Valley is a guide, we need a worldview with a high tolerance of risk. We are not urging faith in technology, like Pilar's parody in *The Church of the Nano-Bio-Info-Cogno* [101]; rather, the worldview we are advocating holds that precaution and skepticism are warranted by recent history. At some point we became a "risk society" [102], and for good reason. Opposition to technology is no longer merely based on the loss of jobs to automation [103]. It is now also based on the fear of the large-scale or long-time waste that contemporary technology can create [104]. Even leading scientists and technologists have expressed fears about Artificial Intelligence [105]. We think "there are contexts in which it is rational to use the Precautionary Principle as a policy tool" [106: 68]. But we are neither advocating a deep mistrust of the technology-driven society (as discussed in [104]), nor a "shift from maximizing growth of the market economy to maximizing sustainable human well-being..." [97: 42], [100]. We are saying that progress can be made only if all stakeholders are enfranchised, and that will require many parties to moderate their positions. Exactly what that moderation looks like will be context-dependent. Consumer concern about Genetically Modified Organisms [107] led a group of big food makers to recently announce plans to issue a smartphone application to enable consumers to get more detailed information about their food products [108]. Participatory and deliberative practices may have lessened the protest against nanotechnology [109]. Conceptually, moderation will require taking a position between Precautionary and Promethean worldviews [110].

VI. CONCLUSION

Technology roadmaps only implicitly address engineering design constraints. These constraints are implicit in the multiple critical (technological) dimensions. Roadmaps explicitly address socio-legal boundary conditions but they do not explicitly address technological boundary conditions.

That is probably because roadmaps are meant to show the way to overcome existing technological boundary conditions with emerging technologies. Yet there is one class of engineering design constraints that, as far as we know now, cannot be overcome with emerging technologies. They are laws of physics, laws of nature. There is another class of engineering design constraints that are hybrid engineering-finance. Both classes are relevant to the present analysis, and we discuss them now in turn.

One engineering design constraint of the TSensors Systems is stated by the Shannon-Hartley theorem, which tells the maximum rate that information can be transmitted over a channel of a specific bandwidth in the presence of noise [111]. We have

$$C = B \log_2(1 + S/N), \text{ where}$$

C is the channel capacity in bits per second;
B is the bandwidth of the channel in hertz;
S is the average received signal power over the bandwidth in watts; and
N is the average noise or interference power over the bandwidth, in watts.

At any given bandwidth, the way to increase the amount of information transmitted is to increase signal power. Yet the Internet of Things requires inexpensive, ultralow power wireless sensors. Higher power sensors are go-to solutions for communications engineers, but they are not solutions for TSensors Systems. This predicament drives the first of the aforementioned multiple critical dimensions (section 4.2), namely the amount of data that can be streamed in wireless networks; but because the sensors are at the core of IoT, this predicament also drives the design and evolution of TSensors Systems.

Another engineering design constraint to the Internet of Things is the price of sensors and their related infrastructure. Assuming that sensors and their related infrastructure on the average will cost $10 each, the trillion sensor world will cost $10 trillion. The world GDP in 2015 was estimated at $74.551 trillion [112]. That means a trillion sensors amounts to (10/74.551)*100 = 13.41% of the current world GDP. The world GDP Global growth is projected at 3.4 percent in 2016 and 3.6 percent in 2017 [113], and global GDP was expected to add another $10 trillion by mid-2017. Depending on how you calculate it, a trillion sensors amounts to 2-4 years of world GDP growth. Even at a modest $10 per sensor (including infrastructure), the cost of a trillion sensors appears to position them out of our reach.

Taken together, these two engineering design constraints suggest that ushering in an era of Abundance will require engineers to think outside of the box. Rather than relying on traditional, conventional designs and approaches, engineers will need to focus on highly efficient, economical solutions that offer only marginal improvements and limited functionality. The sum of these marginal improvements may eventually be enough to provide the desired functionality.

The present study has copious limitations, not the least of which is our total neglect of the insights of economic geography [114]. Economic geography hypothesizes that institutions within regions influence technology transition outcomes within those regions. This suggests that geographical choices are just as important technology choices when developing and commercializing a new technology. Future research should be directed to identifying candidate pairs of geographical regions and technology development and commercialization centers.

Abundance offers the opportunity to transcend historical socio-political dichotomies by synthesizing thesis and antithesis. Narratives around capitalism set up the goal of maximizing the growth of the market economy in opposition to the goal of maximizing sustainable human well-being, e.g., [97]. Abundance may provide the opportunity to achieve both goals simultaneously. We have not fully explored the fascinating possibilities of what potentially may be a new socio-techno-economic paradigm.

Our contemporary narrative about the world is full of talk of complexity, nonlinearity, bifurcations and catastrophes. It has been asserted that institutional change will not always be an evolutionary process [98]. Even stable systems are said to have evolved so that they are poised on the edge of chaos [115]. The history of the earth's biota is replete with mass extinctions. Entire civilizations have collapsed and disappeared [116]. Moreover, the specter of a social change project being infiltrated and hijacked by terrorists no longer sounds like science fiction. The perils and uncertainty of mankind taking hold of its own evolution should not be underestimated, but we must not be afraid. If we proceed with a spirit of curiosity and discovery, we cannot fail. Cartographers over the last several hundred years drew dragons and other beasts in uncharted places. The Hunt-Lenox globe from 1510 displays the phrase *Hic sunt dracones:* here, there be dragons [117]. Here, there is danger. Here, there is a place to be explored.

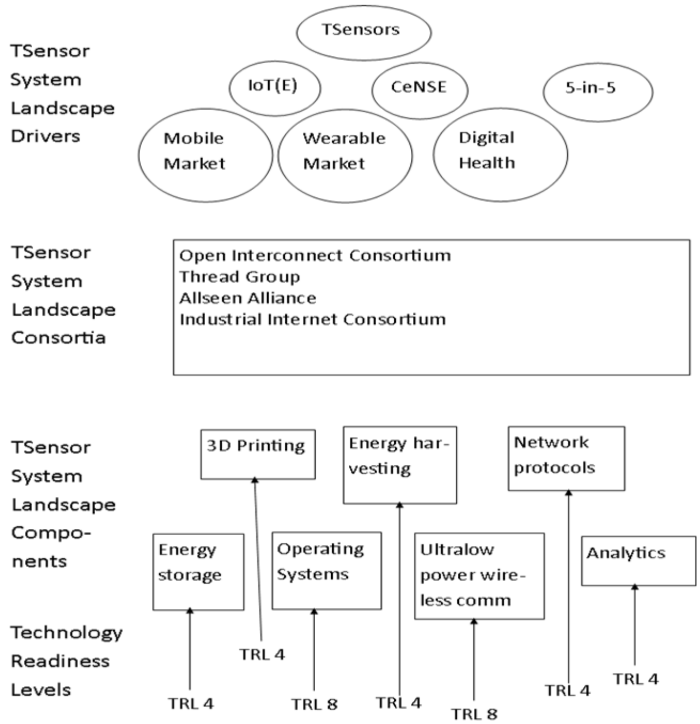

Figure 1. The TSensors Systems Technology Roadmap.

REFERENCES

[1] Diamandis, P. and Kotler, S., (2012), *Abundance: The Future Is Better Than You Think*, Free Press.

[2] TSensors Summit, (2015), website, Retrieved 10/15/2015 World Wide Web, http://www.tsensorssummit.org.

[3] Miorandi, Daniele, Sabrina Sicari, Francesco De Pellegrini, and Imrich Chlamtac, "Internet of things: Vision, applications and research challenges," *Ad Hoc Networks* 10, no. 7, pp. 1497-1516, 2012.

[4] Gubbi, Jayavardhana, Rajkumar Buyya, Slaven Marusic, and Marimuthu Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Generation Computer Systems* 29, no. 7, pp. 1645-1660, 2013.

[5] Adomavicius, Gediminas, Jesse C. Bockstedt, Alok Gupta, and Robert J. Kauffman, "Technology roles and paths of influence in an ecosystem model of technology evolution," *Information Technology and Management* 8, no. 2, pp. 185-202, 2007.

[6] Adomavicius, G., J. Bockstedt, A. Gupta, and R. J. Kauffman, "Making sense of technology trends in the IT landscape: A design science approach for developing constructs and methodologies in IT ecosystems analysis," *MIS Quarterly* 32, no. 4, pp. 779-809, 2008.

[7] Adomavicius, Gediminas, Jesse Bockstedt, Alok Gupta, and Robert J. Kauffman, "Understanding evolution in technology ecosystems," *Communications of the ACM* 51, no. 10, pp. 117-122, 2008.

[8] Liu, Jun, Robert J. Kauffman, and Dan Ma, "Competition, cooperation, and regulation: Understanding the evolution of the mobile payments technology ecosystem," *Electronic Commerce Research and Applications* 14, no. 5, pp. 372-391, 2005.

[9] Walsh, Steven T.; "Roadmapping a disruptive technology: A case study: The emerging microsystems and top-down nanosystems industry," *Technological Forecasting and Social Change* 71, no. 1, pp. 161-185, 2004.

[10] Tierney, Robert, Wahid Hermina, and Steven T. Walsh, "The pharmaceutical technology landscape: A new form of technology roadmapping," *Technological Forecasting and Social Change* 80, no. 2 pp. 194-211, 2013.

[11] Forman, Paul; "The primacy of science in modernity, of technology in postmodernity, and of ideology in the history of technology," *History and technology* 23, no. 1-2, pp. 1-152, 2007.

[12] Carlopio, Jim; "A history of social psychological reactions to new technology," *Journal of Occupational Psychology* 61, no. 1, pp. 67-77, 1988.

[13] McQuire, S; "'Technology', Theory, Culture and Society," Special issue, New Encyclopaedia Project 'problematizing global knowledge,' vol. 25, no. 2/3, pp. 253–65, 2006.

[14] Paredis, Erik; "Sustainability transitions and the nature of technology," *Foundations of Science* 16, no. 2-3, pp. 195-225, 2011.

[15] Borck, Cornelius; "Sound work and visionary prosthetics: artistic experiments in Raoul Hausmann," *Papers of Surrealism* Issue 4, pp. 1-25, 2005.

[16] Biro, Matthew; *The Dada cyborg: visions of the new human in Weimar Berlin*, U of Minnesota Press, 2009.

[17] Ogden, T.; "Techno-Optimists Beware," *Stanford Social Innovation Review,* Summer 2012, Retrieved 10/25/2015 World Wide Web, http://ssir.org/book_reviews/entry/techno_optimists_beware.

[18] Afzal, Asma, Syed Ali Raza Zaidi, Muhammad Zeeshan Shakir, Muhammad Ali Imran, Mounir Ghogho, Athanasios V. Vasilakos, Desmond C. McLernon, and Khalid Qaraqe, "The cognitive Internet of Things: a unified perspective," *Mobile Networks and Applications* 20, no. 1, pp. 72-85, 2015.

[19] Pang, Zhibo, Qiang Chen, Weili Han, and Lirong Zheng, "Value-centric design of the internet-of-things solution for food supply chain: value creation, sensor portfolio and information fusion," *Information Systems Frontiers* 17, no. 2, pp. 289-319, 2015.

[20] Yasunaga, Yuko, Masayoshi Watanabe, and Motoki Korenaga, "Application of technology roadmaps to governmental innovation policy for promoting technology convergence," *Technological Forecasting and Social Change* 76, no. 1, pp. 61-79, 2009.

[21] McDowall, Will; "Technology roadmaps for transition management: The case of hydrogen energy," *Technological Forecasting and Social Change* 79, no. 3, pp. 530-542, 2012.

[22] Riccaboni, Massimo, and Rocco Moliterni, "Managing technological transitions through R&D alliances," *R&d Management* 39, no. 2, pp. 124-135, 2009.

[23] Lee, Jung Hoon, Robert Phaal, and Chihoon Lee, "An empirical analysis of the determinants of technology roadmap utilization," *R&D Management* 41, no. 5, pp. 485-508, 2011.

[24] Zhang, Xian, Jing-Li Fan, and Yi-Ming Wei, "Technology roadmap study on carbon capture, utilization and storage in China," *Energy Policy* 59, pp. 536-550, 2013.

[25] Branscomb, Lewis M; *Empowering technology: Implementing a US strategy*, MIT Press, 1993.

[26] Dosi, Giovanni, and Richard R. Nelson, "The evolution of technologies: an assessment of the state-of-the-art," *Eurasian Business Review* 3, no. 1, pp. 3-46, 2013.

[27] Han, Jin K., Seh Woong Chung, and Yong Seok Sohn, "Technology convergence: when do consumers prefer converged products to dedicated products?," *Journal of Marketing* 73, no. 4, pp. 97-108, 2007.

[28] Kim, Keun-Hwan, We Shim, Young-Ho Moon, Oh-Jin Kwon, Kang-hoe Kim, and Jong-ku Son, "The structure of bio-information-nano technology convergence from firms' perspective," *foresight* 16, no. 3, pp. 270-288, 2014.

[29] Zhang, Ben, Nitesh Mor, John Kolb, Douglas S. Chan, Nikhil Goyal, Ken Lutz, Eric Allman, John Wawrzynek, Edward Lee, and John Kubiatowicz, "The cloud is not enough: saving iot from the cloud," In *Proceedings of the 7th USENIX Conference on Hot Topics in Cloud Computing*, pp. 21-21. USENIX Association, 2015.

[30] Pautrat, Jean-Louis; "Nanosciences: Evolution or revolution?," *Comptes Rendus Physique* 12, no. 7, pp. 605-613, 2011.

[31] Teece, David J., Gary Pisano, and Amy Shuen, "Dynamic capabilities and strategic management," *Strategic management journal* 18, no. 7, pp. 509-533, 1997.

[32] Arthur, W.B.; "Competing technologies, increasing returns, and lock-in by historical events," T*he Economic Journal* 99, pp. 116-131, 1989.

[33] Katz, Michael L.,and Carl Shapiro, "Network externalities, competition, and compatibility," *The American economic review* 75, no. 3, pp. 424-440, 1985.

[34] Choi, Hanool, Sang-Hoon Kim, and Jeho Lee, "Role of network structure and network effects in diffusion of innovations," *Industrial Marketing Management* 39, no. 1, pp. 170-177, 2010.

[35] Shapiro, Carl, and Hal R. Varian, *Information rules: a strategic guide to the network economy*, Harvard Business Press, 2013.

[36] Cusumano, Michael A; "Platform wars come to social media," *Communications of the ACM* 54, no. 4, pp. 31-33, 2011.

[37] Fuentelsaz, Lucio, Juan Pablo Maicas, and Yolanda Polo, "Switching costs, network effects, and competition in the European mobile telecommunications industry," *Information Systems Research* 23, no. 1, pp. 93-108, 2012.

[38] van de Kaa, Geerten, Henk Jan de Vries, and Jafar Rezaei, "Platform selection for complex systems: Building automation systems," *Journal of Systems Science and Systems Engineering* 23, no. 4, pp. 415-438, 2014.

[39] Chabridon, Sophie, Romain Laborde, Thierry Desprats, Arnaud Oglaza, Pierrick Marie, and Samer Machara Marquez, "A survey on addressing privacy together with quality of context for context management in the internet of things," *annals of telecommunications-annales des télécommunications* 69, no. 1-2, pp. 47-62, 2014.

[40] De Hert, Paul, and Vagelis Papakonstantinou, "The proposed data protection Regulation replacing Directive 95/46/EC: A sound system for the protection of individuals," *Computer Law & Security Review* 28, no. 2, pp. 130-142, 2012.

[41] Castro-Edwards, J.; "The proposed European data protection regulation," *Journal of Internet Law*, 17, no. 3, pg. 3, 2013.

[42] Victor, Jacob M.; "The EU General Data Protection Regulation: Toward a Property Regime for Protecting Data Privacy," *Yale LJ* 123, pp. 513-528, 2013.

[43] Kerr, O.S.; "The Next Generation Communications Privacy Act," *University of Pennsylvania Law Review* 162, pp. 373-419, 2013.

[44] Chik, W.B.; "The Singapore Personal Data Protection Act and an assessment of future trends in data privacy reform," *Computer Law & Security Review* 29, no. 5, pp. 554–575, 2013.

[45] The Economist; "The Balkanised web: New EU privacy rules could widen the policy gap with America," *The Economist*, Retrieved 10/27/2015 World Wide Web, http://www.economist.com/news/international/21671081-court-ruling-october-6th-could-alter-way-data-flow-around-internet-new-european-privacy.

[46] The Economist; "Data and privacy (1): Get off of my cloud," *The Economist*, Retrieved 10/27/2015 World Wide Web, http://www.economist.com/news/international/21671982-european-court-ruling-presages-transatlantic-battle-over-data-protection-and.

[47] The Economist; "Data and privacy (2): Under my thumb," *The Economist*, Retrieved 10/27/2015 World Wide Web, http://www.economist.com/news/international/21672204-governments-grapple-law-enforcement-virtual-world-under-my-thumb.

[48] Roman, Rodrigo, Jianying Zhou, and Javier Lopez, "On the features and challenges of security and privacy in distributed internet of things," *Computer Networks* 57, no. 10, pp. 2266-2279, 2013.

[49] Greenberg, A.; "Hackers remotely kill a Jeep on the highway—with me in it," *Wired Magazine*, Retrieved 10/27/2015 World Wide Web, http://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway.

[50] Greenberg, A.; "Senate bill seeks standards for cars' defenses from hackers," *Wired Magazine*, Retrieved 10/27/2015 World Wide Web, http://www.wired.com/2015/07/senate-bill-seeks-standards-cars-defenses-hackers.

[51] Fried, I.; "Google, Freescale Backing Yet Another Internet-of-Things Standard Effort," *re/code*, July 14, 2014, Retrieved 10/19/2015 World Wide Web, http://recode.net/2014/07/15/google-freescale-backing-yet-another-internet-of-things-standard-effort.

[52] Funk, Jeffrey L. and Jianxi Luo, "Open standards, vertical disintegration and entrepreneurial opportunities: How vertically-specialized firms entered the US semiconductor industry," *Technovation* 45, pp. 52-62, 2015.

[53] Chandhok, R.; "About AllJoyn," *Qualcomm Developer Network* (2014), Retrieved 10/19/2015 World Wide Web, https://developer.qualcomm.com/blog/about-alljoyn.

[54] Hardy, Q.; "Intel, Qualcomm and Others Compete for 'Internet of Things' Standard," New York Times Bits Blog, July 8, 2014, Retrieved 10/19/2015 World Wide Web, http://bits.blogs.nytimes.com/2014/07/08/standard-behavior-in-an-internet-goldrush.

[55] The Economist; "3D printing: a bridge to the future," *The Economist*, September 5, 2015, Retrieved 10/27/2015 World Wide Web, http://www.economist.com/news/technology-quarterly/21662647-civil-engineering-3d-printing-technologies-are-being-adapted-use.

[56] Comina, Germán, Anke Suska, and Daniel Filippini, "Low cost lab-on-a-chip prototyping with a consumer grade 3D printer," *Lab on a Chip* 14, no. 16, pp. 2978-2982, 2014.

[57] Fraunhofer-Gesellschaft; "Circuits and sensors direct from the printer," *Phys.org* (2014), April 30, 2014, Retrieved 08/06/2014 World Wide Web, http://phys.org/news/2014-04-circuits-sensors-printer.html.

[58] Kutter, C.; "Flexible printed electronics as enabler for Trillion Sensor applications," *Trillion Sensors Summit* (2014), Tokyo 2014, December 8 & 9, 2014. No page numbers.

[59] GE Reports; "Brilliant machines will have industrial internet written all over themselves." *Product Design and Development*, June 3, 2014, Retrieved 08/06/2014 World Wide Web, http://www.pddnet.com/news/2014/06/brilliant-machines-will-have-industrial-internet-written-all-over-themselves.

[60] Johnson, R.C.; "IBM's 3D Printer to Revolutionize Chip Prototyping Translates brightness to force at third of cost," *EE Times*, April 25, 2014., Retrieved 08/06/2014 World Wide Web, http://www.eetimes.com/document.asp?doc_id=1322091.

[61] Lee, Minhee and Ho-Young Kim, "Toward nanoscale three-dimensional printing: nanowalls built of electrospun nanofibers," *Langmuir* 30, no. 5, pp. 1210-1214, 2014.

[62] Martino, Chiara, Simon Berger, and Robert CR Wootton, "A 3D-printed microcapillary assembly for facile double emulsion generation," *Lab on a Chip* 14, no. 21, pp. 4178-4182, 2014.

[63] Muth, J.T., Vogt, D.M., Truby, R.L., Menguc, Y., Kolesky, D.B., Wood, R.J. and Lewis, J.A., “Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers,” *Advanced Materials* 26, pp. 6307–6312, 2014.

[64] Kausar, ASM Zahid, Ahmed Wasif Reza, Mashad Uddin Saleh, and Harikrishnan Ramiah, “Energizing wireless sensor networks by energy harvesting systems: Scopes, challenges and approaches,” *Renewable and Sustainable Energy Reviews* 38, 973-989, 2014.

[65] Khan, Farid Ullah; “State of the art in acoustic energy harvesting,” *Journal of Micromechanics and Microengineering* 25, no. 2, 023001, 2015.

[66] Caliò, Renato, Udaya Bhaskar Rongala, Domenico Camboni, Mario Milazzo, Cesare Stefanini, Gianluca de Petris, and Calogero Maria Oddo, “Piezoelectric energy harvesting solutions,” *Sensors* 14, no. 3, 4755-4790, 2014.

[67] Muthalif, Asan GA and NH Diyana Nordin, “Optimal piezoelectric beam shape for single and broadband vibration energy harvesting: Modeling, simulation and experimental results,” *Mechanical Systems and Signal Processing* 54, pp. 417-426, 2015.

[68] Tufekcioglu, Emre and Aydin Dogan, "A flextensional piezo-composite structure for energy harvesting applications," *Sensors and Actuators A: Physical* 216, pp. 355-363, 2014.

[69] Iannacci, J., E. Serra, R. Di Criscienzo, G. Sordo, M. Gottardi, A. Borrielli, M. Bonaldi et al., “Multi-modal vibration based MEMS energy harvesters for ultra-low power wireless functional nodes,” *Microsystem technologies* 20, no. 4-5, pp. 627-640, 2014.

[70] Jackson, Nathan, Rosemary O’Keeffe, Finbarr Waldron, Mike O’Neill, and Alan Mathewson, "Evaluation of low-acceleration MEMS piezoelectric energy harvesting devices," *Microsystem technologies* 20, no. 4-5, pp. 671-680, 2014.

[71] Zhao, S. and A. Erturk, “Deterministic and band-limited stochastic energy harvesting from uniaxial excitation of a multilayer piezoelectric stack,” *Sensors and Actuators A: Physical* 214, pp. 58-65, 2014.

[72] Xia, Huakang and Renwen Chen, “Design and analysis of a scalable harvesting interface for multi-source piezoelectric energy harvesting,” *Sensors and Actuators A: Physical* 218, pp. 3-40, 2014.

[73] Park, K.I., Son, J.H., Hwang, G.T., Jeong, C.K., Ryu, J., Koo, M., Choi, I., Lee, S.H., Byun, M., Wang, Z.L. and Lee, K.J., “Highly-efficient, flexible piezoelectric PZT thin film nanogenerator on plastic substrates,” *Adv Mater* 26, no. 16, 2514-20, 2014.

[74] Crossley, Sam and Sohini Kar-Narayan, “Energy harvesting performance of piezoelectric ceramic and polymer nanowires,” *Nanotechnology* 26, no. 34, 344001, 2015.

[75] Jacques, Eric, Göran Lindbergh, Dan Zenkert, Simon Leijonmarck, and Maria Hellqvist Kjell, “Piezo-Electrochemical Energy Harvesting with Lithium-Intercalating Carbon Fibers,” *ACS applied materials & interfaces* 7, no. 25, pp. 13898-13904, 2015.

[76] Liu, Zhe, Jing Xu, Di Chen, and Guozhen Shen, “Flexible electronics based on inorganic nanowires,” *Chemical Society Reviews* 44, no. 1, pp. 161-192, 2015.

[77] Yu, D., Goh, K., Wang, H., Wei, L., Jiang, W., Zhang, Q., Dai, L. and Chen, Y., “Scalable synthesis of hierarchically structured carbon nanotube–graphene fibres for capacitive energy storage,” *Nature Nanotechnology* 9, no. 7, pp. 555-562, 2014.

[78] Ho, J.S., Yeh, A.J., Neofytou, E., Kim, S., Tanabe, Y., Patlolla, B., Beygui, R.E. and Poon, A.S.Y., “Wireless power transfer to deep-tissue microimplants,” *PNAS* 111, no. 22, pp. 7974-7979, 2014.

[79] Favors, Z., Wang, W., Hosseini Bay, H., Mutlu, Z., Ahmed, K., Liu, C., Ozkan, M. and Ozkan, C.S., “Scalable Synthesis of Nano-Silicon from Beach Sand for Long Cycle Life Li-ion Batteries,” *Scientific Reports* 4, no. 5623, pp. 1-7, 2014.

[80] Ghosh, Amitava, Achintya Halder, and Anindya S. Dhar, “A Variable RF Carrier Modulation Scheme for Ultralow Power Wireless Body-Area Network,” *Systems Journal, IEEE* 6, no. 2, pp. 305-316, 2012.

[81] Altenberend, U., Molina-Lopez, F., Oprea, A., Briand, D., Barsan, N., De Rooij, N.F. and Weimar, U., “Towards fully printed capacitive gas sensors on flexible PET substrates based on Ag interdigitated transducers with increased stability,” *Sens. Act. B: Chem.*, 187, pp. 280-287, 2013.

[82] Zhan, Y., Mei., Y. and Zheng, L., “Materials capability and device performance in flexible electronics for the Internet of Things,” *J. Mater. Chem.* C, no. 2, pp. 220–1232, 2014.

[83] Shimizu, M.; “IoT will start with the logistics-enhancing smart pallet,” *Trillion Sensors Summit* (2014), Tokyo 2014, December 8 & 9, 2014. No page numbers.

[84] Biagioni, Edoardo, Robert Harper, and Lee, P., “A network protocol stack in Standard ML” *Higher-Order and Symbolic Computation* 14, no. 4, pp. 309-356, 2001.

[85] Day, J.D. and Zimmerman, H., “The OSI reference model,” In *Proceedings of the IEEE*, 71, no. 12, pp. 1334–1340, 1983.

[86] Ichikawa, H., Shimizu, M., Akabane, K., Ishida, O. and Teramoto, M., “A Ubiquitous wireless network architecture and its impact on optical networks,” *Computer Networks* 52, pp. 1864–1872, 2008.

[87] Karim, Lutful, Qusay H. Mahmoud, Nidal Nasser, and Nargis Khan, "An integrated framework for wireless sensor network management," *Wireless Communications and Mobile Computing* 14, no. 12, pp. 1143-1159, 2014.

[88] Rawat, Priyanka, Kamal Deep Singh, Hakima Chaouchi, and Jean Marie Bonnin, “Wireless sensor networks: a survey on recent developments and potential synergies,” *The Journal of Supercomputing* 68, no. 1, pp. 1-48, 2014.

[89] Nguyen, Kim Thuat, Maryline Laurent, and Nouha Oualha, “Survey on secure communication protocols for the Internet of Things,” *Ad Hoc Networks* 32, pp. 17-31, 2012.

[90] Esteves, Volker, Angelos Antonopoulos, Elli Kartsakli, Manel Puig-Vidal, Pere Miribel-Català, and Christos Verikoukis,“Cooperative Energy Harvesting-Adaptive MAC Protocol for WBANs,” *Sensors* 15, no. 6, pp.12635-12650, 2015.

[91] Ishaq, Isam, David Carels, Girum K. Teklemariam, Jeroen Hoebeke, Floris Van den Abeele, Eli De Poorter, Ingrid Moerman, and Piet Demeester, "IETF standardization in the field of the internet of things (IoT): a survey," *Journal of Sensor and Actuator Networks* 2, no. 2, pp. 235-287, 2013.

[92] Lin, Hsiang-Ho, Hung-Yu Wei, and Rath Vannithamby, “DeepSleep: IEEE 802.11 enhancement for energy-harvesting machine-to-machine communications,” In *Global Communications Conference (GLOBECOM), 2012 IEEE* (2012), pp. 5231-5236. IEEE, 2012.

[93] Bolic, Miodrag, Majed Rostamian, and Petar M. Djuric, "Proximity Detection with RFID: A Step Toward the Internet of Things," *IEEE Pervasive Computing* 2, pp. 70-76, 2015.

[94] Ng, Irene, Kimberley Scharf, Ganna Pogrebna, and Roger Maull, "Contextual variety, Internet-of-Things and the choice of tailoring over platform: Mass customisation strategy in supply chain management," *International Journal of Production Economics* 159, pp. 76-87, 2015.

[95] Satyanarayanan, Mahadev, Pieter Simoens, Yu Xiao, Padmanabhan Pillai, Zhuo Chen, Kiryong Ha, Wenlu Hu, and Brandon Amos, "Edge Analytics in the Internet of Things," *IEEE Pervasive Computing* 2, pp. 24-31, 2015.

[96] Ostrom, Elinor; "Do institutions for collective action evolve?," *Journal of Bioeconomics* 16, no. 1, pp. 3-30, 2014.

[97] Costanza, R.; "A theory of socio-ecological system change," *Journal of Bioeconomics* 16, no. 1, pp. 39-44, 2014.

[98] Poteete, Amy R.; "How far does evolution take us? Comment on Elinor Ostrom’s: do institutions for collective action evolve?," *Journal of Bioeconomics* 16, no. 1, pp. 91-98, 2014.

[99] Wilson, David Sloan; "Cultural species and their ecosystems," *Journal of Bioeconomics* 16, no. 1, pp. 31-38, 2014.

[100] Beddoe, Rachael, Robert Costanza, Joshua Farley, Eric Garza, Jennifer Kent, Ida Kubiszewski, Luz Martinez et al., "Overcoming systemic roadblocks to sustainability: The evolutionary redesign of worldviews, institutions, and technologies," *Proceedings of the National Academy of Sciences* 106, no. 8, pp. 2483-2489, 2009.

[101] Tornero, Paz; "Technoheroines: Transhuman resistances to technoscientific control," *Technoetic Arts* 11, no. 1, pp. 85-93, 2013.

[102] Beck, Ulrich; *Risk society: Towards a new modernity*. Vol. 17. Sage, 1992.

[103] Carlopio, Jim; "A history of social psychological reactions to new technology," *Journal of Occupational Psychology* 61, no. 1, pp. 67-77, 1988.

[104] Hanekamp, J. C., G. Vera-Navas, and S. W. Verstegen, "The historical roots of precautionary thinking: the cultural ecological critique and 'The Limits to Growth'," *Journal of Risk Research* 8, no. 4, pp. 295-310, 2005.

[105] The Economist; "The dawn of artificial intelligence; Powerful computers will reshape humanity's future. How to ensure the promise outweighs the perils," *The Economist*, May 9, 2015, Retrieved 12/05/2015 World Wide Web, http://www.economist.com/news/leaders/21650543-powerful-computers-will-reshape-humanitys-future-how-ensure-promise-outweighs.

[106] Dana, David; "The Contextual Rationality of the Precautionary Principle," *Queen's LJ* 35, pp. 67-96, 2009.

[107] Ramani, Shyama V., and Ajay Thutupalli, "Emergence of controversy in technology transitions: Green Revolution and Bt cotton in India," *Technological Forecasting and Social Change* 100, pp. 198-212, 2015.

[108] Gasparro, A.,;"Food Makers Try Higher-Tech Labels Amid Calls for Transparency," Wall Street Journal, Dec. 2, 2015, Retrieved 12/05/2015 World Wide Web, http://www.wsj.com/articles/food-makers-to-address-desire-for-ingredients-transparency-1449085886.

[109] Seifert, Franz, and Alexandra Plows, "From anti-biotech to nano-watch: early risers and spin-off campaigners in Germany, the UK and internationally," *NanoEthics* 8, no. 1, pp. 73-89, 2014.

[110] Dryzek, John Stanley, Robert Edward Goodin, Aviezer Tucker, and Bernard Reber, "Promethean elites encounter precautionary publics: The case of GM foods," *Science, Technology & Human Values,* 2008.

[111] Price, Eric, and David P. Woodruff, "Applications of the Shannon-Hartley theorem to data streams and sparse recovery," In *Information Theory Proceedings (ISIT), 2012 IEEE International Symposium on*, pp. 2446-2450. IEEE, 2012.

[112] IMF; World Economic Outlook Database, April 2015, Retrieved 2/25/2016 World Wide Web, http://www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx

[113] IMF; World Economic Outlook Update, January 19, 2016, Retrieved 2/25/2016 World Wide Web, http://www.imf.org/external/pubs/ft/weo/2016/update/01/pdf/0116.pdf.

[114] Gilbert, Brett Anitra, and Joanna Tochman Campbell, "The geographic origins of radical technological paradigms: A configurational study," *Research Policy* 44, no. 2, pp. 311-327, 2015.

[115] de Oliveira, Paulo Murilo Castro; "Why do evolutionary systems stick to the edge of chaos," *Theory in Biosciences* 120, no. 1, pp. 1-19, 2001.

[116] Diamond, Jared; *Collapse: How societies choose to fail or succeed*, Penguin, 2005.

[117] Meyer, R., "No Old Maps Actually Say 'Here Be Dragons' But an ancient globe does," The Atlantic, December 12, 2013, Retrieved 12/11/2015 World Wide Web, http://www.theatlantic.com/technology/archive/2013/12/no-old-maps-actually-say-here-be-dragons/282267.