Here There be Dragons: The TSensors Systems Technology Roadmap

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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
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 T Sensors. TSensor drivers comprise policy issues like hunger. T Sensors 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).

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

<table>
<thead>
<tr>
<th>Consortium</th>
<th>Protocol</th>
<th>Founder(s)</th>
<th>Other players</th>
<th>Differentiating Factor(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3MF Consortium</td>
<td>3MF</td>
<td>Dassault Systèmes S.A.; FIT AG/netfabb GmbH; Microsoft Corporation; HP; Shapeways, Inc.; SLM Solutions Group AG; and Autodesk Inc.</td>
<td>TBS</td>
<td>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.</td>
</tr>
</tbody>
</table>

**TABLE 1B. ENERGY HARVESTING CONSORTIUM.**

<table>
<thead>
<tr>
<th>Consortium in Japan</th>
<th>Protocol</th>
<th>Founder(s)</th>
<th>Other players</th>
<th>Differentiating Factor(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Harvesting</td>
<td>N/A</td>
<td>12 companies</td>
<td>Now 32 companies.</td>
<td>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.</td>
</tr>
</tbody>
</table>
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).
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 2. 3D Printing for Manufacturing Sensors and Sensor Components.

<table>
<thead>
<tr>
<th>Source</th>
<th>Technology Description</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>[56]</td>
<td>Direct printing of PDMS (polydimethylsiloxane) on glass lab-on-a-chip (LOC) devices implemented by micro stereo lithography.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[57], [58]</td>
<td>The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is printing electronic components and sensors.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[59]</td>
<td>GE Global Research is developing Direct Write to print 3D sensors that can withstand 2,000 degrees Fahrenheit and handle high mechanical forces.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[60]</td>
<td>IBM Research in Zurich developed a microscopic 3D printer capable of writing nanometer resolution patterns into a soft polymer.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[61]</td>
<td>Experimentally investigate the 3D printing of nanoscale objects by depositing electrospun polymer nanofibers.</td>
<td>TRL 1</td>
</tr>
<tr>
<td>[62]</td>
<td>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.</td>
<td>TRL 3</td>
</tr>
<tr>
<td>[63]</td>
<td>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.</td>
<td>TRL 4</td>
</tr>
</tbody>
</table>

### Table 3. Energy Harvesting for Operating Sensors.

<table>
<thead>
<tr>
<th>Source</th>
<th>Technology Description</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>[69]</td>
<td>Piezoelectric device comprising a MEMS cantilever mechanical resonator for scavenging energy from ambient vibrations.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[70]</td>
<td>Three different MEMS cantilever structures for power density and bandwidth.</td>
<td>TRL 9</td>
</tr>
<tr>
<td>[67]</td>
<td>A triangular cantilever beam harvests more energy than rectangular comb-shaped cantilever beam.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[73]</td>
<td>Highly-efficient, flexible piezoelectric PZT thin film nanogenerator that generates power from regular bending motions.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[68]</td>
<td>Cymbal-shaped transducers for piezoelectric rectangular beam.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>[71]</td>
<td>Multilayer piezoelectric stack.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>[74]</td>
<td>Piezoelectric ceramic nanowires in strain-driven nanogenerators (NGs), polymers for stress-driven NGs.</td>
<td>TRL 7</td>
</tr>
<tr>
<td>[75]</td>
<td>Piezo-electrochemical effect in Li intercalated carbon fibers.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>Cypress</td>
<td>Chips that can harvest their own energy from the sun, vibration or heat.</td>
<td>TRL 9</td>
</tr>
<tr>
<td>EnOcean GmbH</td>
<td>Energy converters that can harvest their own energy using motion, heat and solar energy.</td>
<td>TRL 9</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Source</th>
<th>Technology Description</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>[79]</td>
<td>Formation from beach sand of an interconnected 3D network of nano-silicon with a thickness of 8-10 nm.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[78]</td>
<td>Wirelessly charge micro-scale (2 mm) devices implanted inside the body.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[76]</td>
<td>Flexible electronic devices and storage using nanowires.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>[77]</td>
<td>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.</td>
<td>TRL 4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Technology Description</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>[80]</td>
<td>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.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>[83]</td>
<td>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.</td>
<td>TRL 6-7</td>
</tr>
<tr>
<td>[81], [82]</td>
<td>Flexible passive organic and MEMS RFID tags.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>EM Microelectronic</td>
<td>Bluetooth low energy based circuits and modules; Ultra-Low power, 2.45GHz transceivers and circuits for custom protocol applications; COIN Bluetooth beacon.</td>
<td>TRL 9</td>
</tr>
</tbody>
</table>
### TABLE 6. NETWORK INNOVATIONS.

<table>
<thead>
<tr>
<th>Source</th>
<th>Technology Description</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>[18]</td>
<td>IoT architecture comprising spectrum and energy management engines for maximizing the spectral and energy efficiencies.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>Alljoyn (Open Source)</td>
<td>Protocol that allows devices to communicate with other devices around them.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>Apple</td>
<td>HomeKit protocol</td>
<td>TRL 8-9</td>
</tr>
<tr>
<td>EnOcean GmbH [88]</td>
<td>Wireless standard “for sustainable buildings” (optimized for solutions with ultra-low power consumption and energy harvesting; ISO/IEC 14543-3-10).</td>
<td>TRL 9</td>
</tr>
<tr>
<td>[90]</td>
<td>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.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>Google</td>
<td>Weave protocol</td>
<td>TRL 8-9</td>
</tr>
<tr>
<td>[86]</td>
<td>Post-IP network architecture</td>
<td>TRL 2</td>
</tr>
<tr>
<td>IEEE</td>
<td>802.11af and ah standards provides extended range Wi-Fi networks and lower energy consumption.</td>
<td>TRL 7</td>
</tr>
<tr>
<td>IETF 6TSCH Working Group; [91]</td>
<td>IETF standardization group “6TSCH” aims to significantly improve IoT data flows over IEEE802.15.4e TSCH and IETF 6LoWPAN/ROLL enabled technologies.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>[87]</td>
<td>An integrated network management framework comprising sensor localization, routing, data scheduling, and data aggregation for a large-scale WSN.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>[92]</td>
<td>Modified IEEE 802.11 PSM for the M2M communications network deployed with numerous energy-harvesting devices.</td>
<td>TRL 2</td>
</tr>
<tr>
<td>Linear Technology</td>
<td>Dust Networks’ WirelessHART (IEC 62591) standard.</td>
<td>TRL 9</td>
</tr>
<tr>
<td>Thread Group</td>
<td>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.</td>
<td>TRL 4</td>
</tr>
</tbody>
</table>


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 Tessellation 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.

<table>
<thead>
<tr>
<th>Source</th>
<th>Technology Description</th>
<th>Technology Readiness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contiki (Open Source)</td>
<td>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.</td>
<td>TRL 9</td>
</tr>
<tr>
<td>RIOT (Open Source); originally developed by FU Berlin, INRIA and the HAW Hamburg</td>
<td>RIOT OS; based on a microkernel architecture, originally developed for sensors.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>Swarm Lab, UC Berkeley (<a href="http://swarmlab.eecs.berkeley.edu/research/distributed-swarm-infrastructure">http://swarmlab.eecs.berkeley.edu/research/distributed-swarm-infrastructure</a>)</td>
<td>Swarm-OS, Tessellation 2.0: OS’s that can simultaneously support real-time, responsive, and high-throughput parallel applications.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>TINY OS Alliance (Open Source); originally UC Berkeley, Intel Research and Crossbow Technology</td>
<td>TINY OS targeting wireless sensor networks.</td>
<td>TRL 4</td>
</tr>
<tr>
<td>Apple</td>
<td>HomeKit home automation platform</td>
<td>TRL 8-9</td>
</tr>
<tr>
<td>Google</td>
<td>Devices that use Brillo OS (stripped down Android) can communicate through the Weave protocol.</td>
<td>TRL 8-9</td>
</tr>
</tbody>
</table>
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.
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

\[
C = B \log_2(1 + S/N),
\]

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.
REFERENCES


