# Here there be dragons, a pre-roadmap construct for IoT service infrastructure

**Abstract**

The major challenges facing the 21st century world demands disruptive technology based solutions. One of the most promising exponential technology set to address world challenges is the Internet of Things (IoT) based Trillion Sensor System (TSS). The IoT supports many revolutionary commercial and societal solutions including wearable or unobtrusive medical sensors, Industry 4.0, power and water grids, smart cities, food production, education, transportation and roadway infrastructure needs. However, to support these solutions the current IoT infrastructure needs improved spectrum and the use of between one to ten Trillion Sensors (TS). The development of a robust IoT based TSS infrastructure would create an addition to world GDP equal to that of the U.S. GDP to double the worlds GDP. This new IoT based TSS would create a high paying job base that will form a new vibrant world middle class and an abundant economy. Yet while much is written about the ability of the IoT to transform society little effort is focused on its infrastructure. If this is true there is cause for concern. We add to the literature by developing a precursor road mapping construct which focuses on the service sector and supports 3rd generation road mapping techniques. We utilize the emerging IoT TSS technology base as our case study. We utilize the best thoughts of hundreds of experts from three organizations focused on accelerating IoT TSS road mapping efforts.

**Keywords:** Abundance; Technology Entrepreneurship; Global Finance; Service based Technology road-mapping; Trillion sensor systems; Additive Manufacturing

## 1. Introduction

The most commonly identified 21st world grand challenges include: water, education, health, energy, the environment, and food for the future nine billion people that will inhabit the planet (Chan, 2011). A functional Internet of Things (IoT) comprised of sufficient spectrum and powered by one to ten Trillion Sensors (TS) is a partial response to these challenges. The resultant Trillion Sensor System (TSS) is comprised of multiple technologies which require a third-generation roadmap activity like a Heterogeneous Integration Technology Roadmap (HITR) or Technology Landscaping (TL) (Wang et.al., 2013; Moutanabbir et al., 2010; Wolf et al., 2008). The current Electronics industry based HITR focuses on a Systems in a Package (SiP) approach. The TSS effort focuses on the broader system perspective that includes both sensors and spectrum portions of IoT infrastructure. The Micro, Nano and Emerging Technology Education Foundation (MANCEF), TSensor and TSensor Systems groups seek to accelerate the development of the IoT based TSS. The authors provide as a first step toward a technology road map (TRM) by adding to the literature, creating a pre-roadmap construct that identifies and evaluates all elements of an IoT based TSS. A similar exercise can be applied to other complex technology bases. Finally, this is one of the first constructs focused on the service sector.

The IoT based TSS provides us the case of a potential "Sensorized" world that embraces many of 21st century challenges through emerging exponentially improving technologies. When and if the IoT based TSS is successful it will create exceptionally large well paid new job bases throughout the world creating a burgeoning middle class directly in line with the "Abundance" economic philosophy (Diamandis, et al., 2012). Further a functional IoT based TSS is a harbinger for the "Bottom Billion" or base of the pyramid population becoming a viable economic force (Prahalad, 2006). Yet a functionalized IoT based TSS is not the currently available.

Our literature review is a discussion of the IoT, road-mapping and the use of readiness levels. One technique that has assisted companies, industries and regions to overcome technical, customer acceptance and cost hurdles for a given technology base are the three generations of Technology road-mapping(TRM). We have identified tremendous technical hurdles that are acting as a roadblock to TSS and IoT technology acceptance. They include spectrum deficiency (Reed, 2014), privacy and security concerns (Tully, 2015), fraud (Hakim, et al., 2015), and the development of low cost sensing (Bryzek, 2016). Exceptionally complex systems technologies requiring 3rd generation road-mapping techniques are not as well developed as the others.

One of the first to forecast the use of ubiquitous sensing based IoT was Hewlett Packard (HP) in 2010 (TSensors Summit, 2015). Their concept was a need for one to ten trillion sensors that would become the Central Nervous System of the Earth (CeNSE). A bold prediction since in 2010 there were less than 20 billion connected devices worldwide (TSensors Summit, 2015). HP also depicted a large technical hurdle stating that a trillion-sensor world would require the equivalent of a thousand times the spectrum or the number of internets that we had in 2010 to support it (Fredrich, 2012). Further, the TS group projected that Micro and Nano "Small tech" sensor prices of $1 per sensor would be a precursor for a trillion or more-sensor world (TSensors Summit, 2015). The TSS group postulated that the trillion sensor systemization costs would be conservatively $15 per sensor (TSensors Summit, 2015). Despite these cost figures the projected world use of sensors by 2020 continued to rise. Some now projected up to a 100 trillion sensor world (TSensors Summit, 2015).

We examined the 3rd generation road-mapping TL technique since it is designed to meet the challenges of a multi root technology, disruptive technology based (Linton, et al., 2008), policy constrained, technology system. We also found that the components required for the IoT based TSS lend themselves to pre HITR component identification constructs both TL and HITR providing a basis for discontinuous innovation analysis (Walsh, et al., 2000). Yet as advanced as these techniques were they both can be overwhelmed by complexity.

This effort is focused on providing insight into HITR and TL's operationalization process. Here we focus on pre-HITR and pre-TL road mapping activities by first, identifying all the relevant components. Then we evaluate their current state's ability to support a trillion-sensor world. Next, we provide the foresight on these critical components by providing expert opinions focused on each element's ability to underpin a trillion or more-sensor world. Finally, in our discussion section we provide the financial basis for abundant world with a vibrant middle class.

## 2. Literature Review

Our literature review is split into four different sections. The first is focused on a minimum trillion sensors based IoT. The second focuses on disruptive technologies and discontinuous innovations, its alignment with abundance and the subsequent potential rise of a worldwide middle class. Third, we discuss the use of TRM for complex multi-root technology disruptive technology systems and the resultant need for a pre-roadmap construct for effective 3rd generation TRM. Finally, we discuss the readiness level techniques focusing on those that we choose to use in our model of a pre- road mapping construct for 3rd generation TRM.

### *2.1 Trillion Sensor based IoT infrastructure*

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" (Gubbi, et al., 2013; Biro, 2009; The Economist, October 2015). The European Commission Information Society similarly defined the IoT as "Interconnected objects having an active role in what might be called the Future Internet" (Pang, et al., 2015). The value of an IoT based TSS resides in the data or information (Akhtar, 2017) which is derived from sensors with edge intelligence capabilities or streamed data forming the bases of many service products. The potentially disruptive IoT based TSS technology can enable products that have the potential to generate innovations that have global impact (Miranda, et al., 2012), and can form the backbone for Industry 4.0 (Bauer et al., 2015). If today's 20 billion sensor based IoT can be transformed to a 1 to 100 trillion based system it would itself without the products being developed from it initiate an abundant economy with knowledge based jobs laying the foundation of a new vibrant middle class worldwide.

Yet a vibrant IoT based TSS infrastructure to fuel this transformation does not yet exist. The current IoT bandwidth or spectrum is deficient even for today's use (Reed, 2010). Hewlett Packard, for example, stated that even a trillion-sensor world would require over 1000 of today's internets in order to be enabled (Fredrich, 2012). This is one of first service sector TRM's constructs and as such needs to reflect the nature of the technology environment. Sustainable product innovation in the service sector requires a robust infrastructure to be built before sustainable product innovation can thrive (Walsh, et al., 2000). In order to manage an effective IoT based TSS infrastructure or any complex systems based technology we need to first define its' components and their challenges. Then we need to measure them.

The IoT based TSS technology components comprise: radio frequency identification (RFID) tags, bandwidth, wireless sensor networks, edge intelligence, encryption, manufacturing sensor networks and their respective components; sensor and network energy harvesting and storage; edge intelligence; network protocols, standards, architectures, algorithms; operating systems; and analytics. The technology component challenges typically relate to: wireless sensor networks; low power and/or energy efficient sensors; energy harvesting; network security, privacy and innovation; and miniaturization (Miorandi, et al., 2012; Gubbi, et al., 2013). The HITR philosophy makes aware of another set of challenges relating to systems integration.

### *2.2 IoT as a disruptive technology base and springboard for discontinuous innovation*

A disruptive technology is one that creates new industries and redefines existing ones and can only be seen after it has accomplished this (Christensen, 2003; Kirchhoff, et al., 2013). IoT is currently a potential disruptive technology showing an ability to transform industries such as transportation infrastructure (Fredrich, 2012). Yet a new wave of products is poised to become important for the developed world and perhaps enabling the "bottom billion" people in the world to become an economic force (Prahalad, 2006). TSS based products are alternatively focused on "Killer Apps" globally (Kim, et al., 2016), developing smart cities (Bresciani, 2017). The "bottom billion" are redefining the barter system and education (Christensen, 2006). Abundance (Diamandis, et al., 2012) is the hypothesis that technological advances will resolve the world's most intractable problems by 2050. Abundance comprises the six pillars of abundant health care, abundant food, abundant water, abundant education, abundant energy and an abundant "green" environment (Diamandis, et al., 2012). The specific origins of Abundance are obscure but can be placed in the Twentieth Century attitude of optimism about science and then about technology (Forman, 2007).

Yet as more people embrace the "IOT" bandwidth is becoming precious (FCC), data security seems nonexistent (Ransom WannaCry attack, 2017) and corporate fraud abounds. Even as many see the value in IoT seemingly insurmountable hurdles face its use. There are potential solutions both political like reallocation of bandwidth to the IoT from other areas and technical like the development of a 50 Gig global 5G network (Kushnick, 2017) but even those advances do not promise to totally enable a 1 to 100 trillion sensor world. We need a technological road mapping process to assist our organically developed IoT infrastructure to mature into a useful IoT infrastructure for a trillion-sensor world.

*2.3 Road mapping and pre-road mapping activities and readiness levels*

Technological road mapping (Walsh, 2004; Tierney, et al., 2013; Yasunaga, et al., 2009) is a useful tool for navigating the path to abundance by speeding up the technology commercialization process. There are varieties of technology roadmaps (Walsh, 2004; Tierney, et al., 2013; Yasunaga, et al., 2009) and most at their core address the state of maturity of the technology. Any road mapping technique starts with an understanding or characterization of the system under study.

The TSS IoT is comprised of an extremely complex and organically enabled infrastructure and can best be described as a "systems of systems." HITR and TL (Forman, 2007) are the two third generation road mapping techniques have been proposed to deal with multi root technology (Tierney, et al., 2013; Pang, et al., 2015; Federal Communication Commission, 2014a; Federal Communication Commission, 2014b, Adomavicius, et al., 2008) or system of systems emergent enabling technologies. HITR is a top-down system view of road mapping (Semiconductor Industry Association, 2015; Wang, et al., 2013; Moutanabbir, et al., 2010; Edenfeld, et al., 2004; Lapisa, et al., 2011) that emphasizes a systems approach. Most HITR efforts are motivated by perceived technology development limits (Semiconductor Industry Association, 2015) in devices. TL and HITR are driven by market developments and boundaries. In the best case, both TL and HITR techniques require pre-road mapping constructs in order to identify the technologies stage of maturity so that professionals using these techniques can be most effective. The pre-road mapping efforts that HITR and TL require are an understanding of the current components ability to meet in our case a Trillion or more sensor world. Here we use Technology Readiness Level (TRL) (Tierney, et al., 2013) and Innovative Manufacturing Readiness levels (IMRL) (Islam, 2010a; Islam, 2010b) to assess the state of maturity of the technology, component or product within the TSS.

We will provide a first effort at the ensemble of artifacts precursor road mapping construct. The task for TSS pre-roadmap construct includes not only the Systems in a Package (SiP) but also the software, transmission, big data analysis, policy, new business models, socio-technology issues like privacy, surety and security among others. The IoT is a critical component of a functioning TSS.

*2.4 The use of readiness levels in road-mapping*

The use of readiness level techniques is not new to road mapping, for example, TL utilizes TRL's to generate a multiple root technology sigmodal curve. We reviewed four readiness level techniques before settling on two. They included the nine stage TRL, Manufacturing readiness Levels' (MRL), and Innovation Readiness Levels (IRL), IMRL literature (Islam, 2010a; Islam, 2010b) and utilized TRL and IMRL for our study.

TRLs provide structure and a systematic metric to assess the maturity of a particular technology, a technology product paradigm or component. We functionalized the 9 stage TRL which provides structure and a systematic metric to assess the maturity of a particular technology.

Stage one being the most immature and stage nine being mission tested ready technology. We next reviewed the ten stage Manufacturing MRL technique developed by the DOD in 2015. This readiness level technique seemed more suited to established technologies ones that already had processes lean production practices and therefore we chose to the IMRL technique due to the emergent nature of the TSS IoT infrastructure. We then analyzed the Innovation Readiness Levels (IRL) for possible inclusion in our technique but found it too elemental for a road-mapping effort. We choose the IMRL technique for our pre-road mapping construct. This technique has five levels. The concept also had four key performance measures. The key performance measures were static for each of the five levels. The key measures included: Science and technology performance; Product and process performance; Market and business performance and Firm and industry performance. We found this a perfect complement to TRL in our semi-structured survey.

We add to the literature by providing evidence that the IoT based TSS infrastructure will have to change dramatically to embrace a trillion sensors (Gouvea, et al., 2012; Walsh, 2004; Walsh, et al., 2005). Second, by showing that the development of a TSS would create a more abundant economy based on a new and vibrant middle class. Finally, by creating a pre-road mapping construct that simplifies extremely complex service infrastructure by identifying candidate technologies and evaluate their Technology Readiness Levels (TRL) and Innovative Manufacturing Readiness Levels (IMRL) (Islam, 2010a; Islam, 2010b). We do this through our IoT based TSS study.

## 3. Methods

Our effort was derived from the over 250 experts that presented either at the MANCEF COMS (2013, 2014, and 2015) series of conferences and the T Sensor Summit conference series (TSensors Summit, 2015). These experts where represented by a variety of international experts from a variety of countries. These professionals came from many different backgrounds. They included: government policy makers, science, technology, and management based academics, sensor manufactures, large and small firm executives engaged in sensors manufacture and IoT infrastructure manufacturers, IoT service product manufacturers, and smart city executives Our methods focus on the development of a pre HITR, and pre-TL roadmap construct that included component identification and level requirements for a TSS components that is necessary to create an abundant world. We initiated the TS and TSS activity by stating that the systems requirement for a minimum trillion sensor world are; MEMS and Nano sensing devices whose costs cannot exceed $1 and systemization costs of $15 per sensor. We add to these HITR and TL requirements a vastly improved edge intelligence, local network systems, security and surety additions to the sensors that must not exceed power, bandwidth and cost budgets, that must be developed, and the IoT organically grown infrastructure must improve.

We began generating primary data with structured interviews of experts in the emerging technologies using questionnaire development techniques (Fowler, 2008). These emerging technologies are comprised of those used for retrieval of information from with the backbone of the IoT based TSS and the critical components of the manufacture and use of sensors. In these interviews, we identified the critical dimensions, boundary conditions, market drivers, and some of the components focused on by TSS. 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 TRL's and IMRL's which were derived from semi-structured interviews with our expert responder base (Fowler, 2008) validated by published secondary data sources.

We mined the 250 documents from our MANCEF and TS database and developed both a TRL questionnaire and an IMRL questionnaire. We utilized TRL structure previously used by Tierney, et al., 2013) for the TRL questions and emulated it for our IMRL questions. We chose traditional IMRL's developed for the micro and nano technology bases in 2010. This system has 5 IMRL levels. We defined and discussed each technology and each TRL and IMRL level to the respondents through the administration of a simplified semi-structured assessment questionnaire.

We define TRL level 9 as the necessary and sufficient condition for our Abundance based TSS. We define an IMRL level 5 as the necessary and sufficient condition for our Abundance based TSS. We define the technical components of the top down systems roadmap in our results below. Previous TL efforts provided fractioned TRL averages due to its need to develop a sigmoidal curve, however, we e do not that constraint and found it more useful to round off the results to the nearest whole number for a pre-roadmap construct.

## 4. Results

Our first result is the characterization of artifacts that comprise a TSS. Second, we provide the results of a small pilot study from respondents on two separate readiness level measurements of the TSS artifacts. We included privacy and security concerns as boundary condition for TSensors Systems due to the distributed computing model of the IoT (Roman, et al., 2013). Moreover, we provide the corroborating secondary data

*4.1 TSS components and their 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 (Tierney, et al., 2013). There the researchers used Technology Readiness levels. Here we looked at not only TRL but also IMRL (Islam, 2010a; Islam, 2010b).

In accordance with our definition of IoT based TSS, 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. We provide the

*4.1.1 Additive manufacturing (3D printing, Roll to Roll Plastic Processing and CNT for manufacturing IC's, sensors and sensor components. TRL 4, IMRL 2*

While the popular press focuses on high-value, low-volume usages such as printing houses and bridges (The Economist, September 2015), the TSS effort focuses on 3D printing of sensors. Additive Manufacturing, Roll to Roll plastic processing and or CNT will be needed to make low-cost IC's, sensors and sensor components. The main technological challenges for TSS arise from the need to print very small devices such as sensors at the nanoscale. This TSS component area has a TRL of 4 and an IMRL of 2 (Table 1).

Table 1. 3D printing, Roll to Roll plastic processing, and CNT for manufacturing IC's, sensors and sensor components.

| **Source** | **Technology or Component Description** | **Technology Readiness Level (TRL)** | **Innovative Manufacturing Readiness Level (IMRL)** |
|---|---|---|---|
| Comina, et al., 2014 | Direct printing of PDMS (polydimethylsiloxane) on glass lab-on-a-chip (LOC) devices implemented by micro stereo lithography. | 4 | 2 |
| Fraunhofer-Gesellschaft, 2014; Kutter, 2014 | The Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM is printing electronic components and sensors. | 4 | 2 |
| GE Reports, 2014 | GE Global Research is developing Direct Write to print 3D sensors that can withstand 2,000 degrees Fahrenheit and handle high mechanical forces. | 4 | 2 |
| Johnson, 2014 | IBM Research in Zurich developed a microscopic 3D printer capable of writing nanometer resolution patterns into a soft polymer. | 4 | 2 |
| Lee, et al., 2014 | Experimentally investigate the 3D printing of nanoscale objects by depositing electro-spun polymer nanofibers. | 1 | 1 |
| Martino, et al., 2014 | 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. | 3 | 2 |
| Muth, et al., 2014 | Embedded 3D printing of a carbon-based resistive ink within an elastomeric matrix, | 4 | 2 |

| | | | |
|---|---|---|---|
| | for creating soft functional devices for wearable electronics, human/machine interfaces, soft robotics, etc. | | |
| Forrest, 2004 | Roll to Roll Plastic IC's. The path to ubiquitous and low-cost organic electronic appliances on plastic | 6 | 2 |
| Franklin, et al., 2012 | Carbon Nanotube sub ten nanometer IC development | 6 | 3 |

*4.1.2 Energy harvesting for operating sensors. TRL 4, IMRL 2*

Energy harvesting technologies scavenge energy from the ambient environment. They convert heat, strain, vibration, sun and sound into electricity. The central challenge is to miniaturize 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 (Kausar, et al., 2014), and we used this as a benchmark to measure progress. Some of these power densities and strength-weakness assessments will change as the technologies are further developed. TSS requires an emphasis 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 (Khan, 2015) sources. With piezoelectric energy, the main technological challenge is harvested energy density (Caliò, et al., 2014). The main design issue, however, is beam shape (Muthalif, et al., 2015). Much of the recent research relates to cantilever beams (and their transducers, e.g., (Tufekcioglu, et al., 2014)), such as optimal piezoelectric shape and configuration (Iannacci, et al., 2014; Jackson, et al., 2014). 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 (Muthalif, et al., 2015). Some researchers are investigating stacked configurations (Zhao, et al, 2014), shells, spirals and zigzags (Muthalif, et al., 2015). For greater energy requirements, multiple sources of piezoelectric energy harvesting may be required, and three harvesting interface circuits have been proposed to enable the use of multiple sources (Xia, et al., 2014). In terms of TSensor System needs this component area has an overall TRL of 4 and IMRL of 2 (Table 2).

Table 2. Energy harvesting for operating sensors

| **Source** | **Technology or Component Description** | **Technology Readiness Level (TRL)** | **Innovative Manufacturing Readiness Level (IMRL)** |
|---|---|---|---|
| Iannacci, et al., 2014 | Piezoelectric device comprising a MEMS | 4 | 2 |

| | | | |
|---|---|---|---|
| | cantilever mechanical resonator for scavenging energy from ambient vibrations. | | |
| Jackson, et al., 2014 | Three different MEMS cantilever structures for power density and bandwidth. | 9 | 5 |
| Muthalif, et al., 2015 | A triangular cantilever beam harvests more energy than rectangular comb-shaped cantilever beam. | 4 | 1 |
| Park, et al., 2014 | Highly-efficient, flexible piezoelectric PZT thin film nanogenerator that generates power from regular bending motions. | 4 | 2 |
| Tufekcioglu, et al., 2014 | Cymbal-shaped transducers for piezoelectric rectangular beam. | 2 | 1 |
| Zhao, et al, 2014 | Multilayer piezoelectric stack. | 2 | 1 |
| Crossley, et al., 2015 | Piezoelectric ceramic nanowires in strain-driven nanogenerators (NGs), polymers for stress-driven NGs. | 7 | 4 |
| Jacques, et al., 2015 | Piezo-electrochemical effect in Li intercalated carbon fibers. | 2 | 1 |
| Cypress | Chips that can harvest their own energy from the sun, vibration or heat. | 9 | 5 |
| EnOcean GmbH | Energy converters that can harvest their own energy using motion, heat and solar energy. | 9 | 5 |

*4.1.3 Energy storage for operating sensors. TRL 4, IMRL 3*

Energy storage technologies are being developed at spatial scales that are appropriate for the emerging nanoscale energy harvesting technologies. These include nanowires (Liu, et al., 2015), nanotubes (Yu, et al., 2014), and nanoscale 3D electrodes. In addition, technology has been developed to wirelessly power micro-scale devices implanted in deep tissue, a micro-implant (2 mm, 70 mg) capable of closed-chest wireless control of the heart (Ho, et al., 2014). These individual components and technologies generally have a TRL of 4 and an IMRL of 3 (see Table 3 below).

Table 3 Energy storage for operating sensors

| Source | Technology or component Description | Technology Readiness Level (TRL) | Innovative Manufacturing Readiness Level (IMRL) |
|---|---|---|---|
| Favors, et al., 2014 | Formation from beach sand of an interconnected 3D network of nano-silicon with a thickness of 8-10 nm. | 4 | 2 |
| Ho, et al., 2014 | Wirelessly charge micro-scale (2 mm) devices implanted inside the body. | 4 | 3 |
| Liu, et al., 2015 | Flexible electronic devices and storage using nanowires. | 4 | 3 |
| Yu, et al., 2014 | 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. | 4 | 2 |

*4.1.4Ultralow power wireless. TRL 4, IMRL3*

Wireless sensor networks (WSNs) are relevant to TSS 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 (Ghosh, et al., 2012) and/or low circuit power (Altenberend, et al., 2013; Zhan, et al., 2014). In this section, we discuss device-level innovations. This TSS Component area has a TRL of 4 and an IMRL of 3 (see Table 4 below).

Table 4. Ultralow power wireless

| Source | Technology or component Description | Technology Readiness Level (TRL) | Innovative Manufacturing Readiness Level (IMRL) |
|---|---|---|---|
| Ghosh, et al., 2012 | 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. | 2 | 2 |

| | | | |
|---|---|---|---|
| Shimizu, 2014 | 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. | 6 | 3 |
| Altenberend, et al., 2013; Zhan, et al., 2014 | Flexible passive organic & MEMS RFID tags. | 4 | 3 |
| Linear Technology | Dust Networks has more than 30,000 networks installed in 120 countries. | 9 | 5 |
| EM Microelectronic | Bluetooth low energy based circuits and modules; Ultra-Low power, 2.45GHz transceivers and circuits for custom protocol applications; COiN Bluetooth beacon. | 9 | 5 |

*4.1.5 Network innovations. TRL 4, IMRL 3*

Networking protocols are rules and conventions for how networked electronic devices identify each other, make connections with each other, and send and receive data (Biagioni, et al., 2001). 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) (Day, et al., 1983). These layers comprise the network architecture. Emerging architectures have been designed for ubiquitous wireless applications (Ichikawa, et al., 2008), for wireless network management and control (Karim, et al., 2014), and for spectrally efficient with power consumption awareness (Afzal, et al., 2015).

Though several wireless network protocols are currently in use (Rawat, et al., 2014), 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 (Ichikawa, et al., 2008). 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 (Ichikawa, et al., 2008; Rawat, et al., 2014) and to provide heightened network-level security (Nguyen, et al., 2012). 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 (Afzal, et al., 2015). Commercial protocols have also been issued by Apple and Google as part of their IoT Operating Systems. This TSS HITR component area has a TRL of 4 and an IMRL of 3 (Table 5).

Table 5. Network innovations

| **Source** | **Technology or Component Description** | **Technology Readiness Level (TRL)** | **Innovative Manufacturing Readiness Level (IMRL)** |
|---|---|---|---|
| Afzal, et al., 2015 | IoT architecture comprising spectrum and energy management engines for maximizing the spectral and energy efficiencies. | 2 | 1 |
| Alljoyn | Open source protocol that allows devices to communicate with other devices around them. | 4 | 2 |
| Apple | HomeKit protocol | 9 | 4 |
| EnOcean GmbH; Rawat, et al., 2014 | Wireless standard "for sustainable buildings" (optimized for solutions with ultra-low power consumption and energy harvesting; ISO/IEC 14543-3-10). | 9 | 4 |
| Esteves, et al., 2015 | 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. | 2 | 1 |
| Google | Weave protocol | 8 | 4 |
| Ichikawa, et al., 2008 | Post-IP network architecture. | 2 | 1 |
| IEEE | 802.11af and ah standards provides extended range Wi-Fi networks and lower energy consumption. | 7 | 3 |
| IETF 6TSCH Working Group; Ishaq, et al., 2013 | IETF standardization group "6TSCH" aims to significantly improve IoT data flows over IEEE802.15.4e TSCH and IETF 6LoWPAN/ROLL enabled technologies. | 2 | 1 |

| | | | |
|---|---|---|---|
| Karim, et al., 2014 | An integrated network management framework comprising sensor localization, routing, data scheduling, and data aggregation for a large-scale WSN. | 2 | 1 |
| Lin, et al., 2012 | Modified IEEE 802.11 PSM for the M2M communications network deployed with numerous energy-harvesting devices. | 2 | 1 |
| Linear Technology | Dust Networks' WirelessHART (IEC 62591) standard. | 9 | 5 |
| 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. | 4 | 2 |

*4.1.6 Operating Systems. TRL 4, IMRL 3*

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 (Roman, et al., 2013). This TSS component area has a TRL of 4 and an IMRL of 3 (see Table 6 below).

Table 6. Operating systems

| **Source** | **Technology or Component Description** | **Technology Readiness Level (TRL)** | **Innovative Manufacturing Readiness Level (IMRL)** |
|---|---|---|---|
| Contiki | Contiki is an open source which product that 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. | 9 | 5 |
| RIOT | RIOT is open source (OS) based on a microkernel architecture, originally developed for sensors. | 4 | 2 |

| | | | |
|---|---|---|---|
| | This was originally developed by FU Berlin, INRIA and the HAW Hamburg | | |
| 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. | 4 | 2 |
| TINY OS Alliance (Open Source); originally UC Berkeley, Intel Research and Crossbow Technology | TINY OS targeting wireless sensor networks. | 4 | 2 |
| Apple | HomeKit home automation platform | 9 | 5 |
| Google | Devices that use Brillo OS (stripped down Android) can communicate through the Weave protocol. | 9 | 5 |

*4.1.7 Analytics. TRL 4, IMRL 3*

Here, 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 (Bolic, et al., 2015) and platform strategies for consumer goods supply chains (Ng, et al., 2015). These capabilities are pushed as much as possible to the "edge of the swarm" (Zhang, et al., 2015; Satyanarayanan, et al., 2015), i.e., closer to the sensors themselves. This TSS Component area has a TRL of 4 and a IMRL of 3 (see Table 7 below).

Table 7. Analytics

| **Source** | **Technology or Component Description** | **Technology Readiness Level (TRL)** | **Innovative Manufacturing Readiness Level (IMRL)** |
|---|---|---|---|
| Bolic, et al., 2015 | Proximity sensing RFID tags. | 4 | 3 |

| | | | |
|---|---|---|---|
| Ng, et al., 2015 | Model suggests platform strategies will win in the IoT world. | 2 | 3 |
| Satyanarayanan, et al., 2015 | Architecture comprising a federated system of VM-based cloudlets that perform video analytics at the edge of the Internet or Edge Intelligence | 2 | 2 |
| Fuentelsaz, et al., 2012 | Architecture for a decentralized data storage and delivery platform. | 2 | 2 |

## 5. Discussion

The authors present the pre-road mapping construct as a method to identify and rank the differing technology bases associated in a complex service infrastructure system in this case IoT based TSS. The construct assists any firm or region interested in IoT TSS service product value statements or any complex service infrastructure to generate a basis for any road mapping or strategic exercise. The use of the construct readily assists the user to identify hurdles in the complex infrastructure systems required by service based products. In the case of the IoT based TSS the construct readily shows that the IoT is not the infinite resource that many producing and using IoT service based products infer.

This inference has its roots in technology advances associated with the IoT. IoT internet addresses protocols started with IPv4's of approximately 4.3 billion addresses. When those were exhausted, the internet protocol progressed to IPv6. This move allowed approximately $3.4 \times 10^{38}$ new addresses to be generated. This is an amount that many believe will never be exceeded (TSensors Summit, 2015). This instilled confidence in the user community that IoT will adapt to the capacity demands of users. Yet increasing the number of addresses is akin to making more holes in a hose rather than increasing any water carrying power (TSensors Summit, 2015). Over the last three years the IoT spectra has been deficient in the United States (Federal Communication Commission, 2014b; BroadBand.gov, 2016). This deficiency is the result of the use of billions of connected devices (Federal Communication Commission 2014a) rather than the trillions of connected devices that TSS forecasts. Further, we found that the IoT infrastructure was developed organically without benefit of structure and was initially focused on video streaming. Finally, that the IoT infrastructure that has developed thus far was never optimized for data transference.

### *5.1 Importance for Abundance and a rising middle class*

A future were these several components and technologies converge, miniaturize and provide a stable infrastructure (Gubbi, et al., 2013) that meets the demands of multiple national legal systems will create Abundance. It can help generate an economic force of the bottom billion and revitalize the world middle class. How will this middle class arise?

When the world moves from a few billion sensors to 1 to 100 trillion sensors that have a demand price of $1 dollar and a systemization price of $15 per sensor the resultant revenue is 16 trillion to 1,600 trillion dollars or the GDP of the United States to 20 times the GDP of the world.

We averaged the revenue per person generation for 8 most related industries. They include computer hardware, computer networks, computer processing and cloud services, electric wiring and equipment, electronic instruments and controls, internet services & social media, semiconductors, and software & programming. We analyzed the data from 1st quarter 2017 trailing twelve months (TTM) (Csimarket.com, 2017). The average TTM per employee for this group of industries was $656,485. If you add in a high-tech job multiplier of 3. The number of new high paying jobs becomes 97,488,881 jobs to 9.7 billion jobs derived from TSS infrastructure development alone. This last number might be difficult to reach since the World Bank (2017) states that there were only 3.422 billion workers in the global labor force in 2016.

*5.2 Where is the infrastructure today compared to what will soon be required?*

We provide in Table 8 each infrastructure parameter we calculate versus TRL 9 which is a fully technology readiness level robust system. This show that the TSS IoT service infrastructure is not quite robust. The problems with privacy, and spectrum are indicative of this lack of IoT system utility.

Table 8: Current state of IoT infrastructure parameters versus desired

| Parameter | TRL current | TRL desired |
|---|---|---|
| 3D printing, Roll to Roll plastic processing, and CNT for manufacturing IC's, sensors and sensor components. | 4 | 9 |
| Energy harvesting for operating sensors. | 4 | 9 |
| Energy storage for operating sensors | 4 | 9 |
| *4Ultralow power wireless* | 4 | 9 |
| *Network innovations* | 4 | 9 |
| *Operating Systems* | 4 | 9 |
| Analytics. | 4 | 9 |

## 6. Future Research

The IoT based TSS will be made possible only through distributed computing. By performing computations "at the edge" of the network (at the sensors rather than sending all data to central locations for processing), and thus this distributed architectures reduces the amount of bandwidth required by systems. We have reported several candidates operating systems and architectures for distributed computing. More research needs to be developed on Public Private Partnerships, Consortia and Entrepreneurial action.

Consortia are starting to become keys to this process through the propagation of component, standards, technological development and entrepreneurship. Entrepreneurship is nurtured by (open) standards (Funk, et al., 2015), which themselves are nurtured by consortia. By consolidating the parties, consortia will probably accelerate "Winner-take-all-or-most"

(Cusumano, 2011). These are further areas for research. If we proceed with a spirit of curiosity and discovery, we cannot fail to provide value. 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 (Meyer, 2013). Here, there is danger. Here, there is a place to be explored.

## 7. Conclusion and Limitations of the study

Knowledge based service products are critical to the economies of all developed countries. Yet no pre-road mapping or road mapping technique has ever been developed for services specifically. Many of the firms and regions involved have taken the complex service infrastructure of the IoT based TSS as a given and perform road mapping activities on product rather than infrastructure development leaving big gaps in their service product performance in areas like security, privacy and spectrum deficiencies. We have identified the elements for one case of a complex service infrastructure and provide some insight into market, engineering design, political and legal constraints.

Yet there are class of engineering design constraints that, as far as we know now, cannot be overcome with emerging technologies. They are laws of physics and 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 TSS 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 (Price, et al., 2011). It states that at any given bandwidth, the way to increase the amount of information transmitted is to increase signal power. Yet the IoT based TSS requires inexpensive, ultralow power wireless sensors. Higher power sensors are go-to solutions for communications engineers, but they are not solutions for TSS. This predicament drives the first of the aforementioned multiple critical dimensions (section 4), namely the amount of data that can be streamed in wireless networks; but because the sensors are at the core of the IoT, this predicament also drives the design and evolution of TSS.

Another engineering design constraint to Abundance through TSS is the price of sensors and their related infrastructure. Assuming that sensors and their related infrastructure on the average will cost $16 each, the TSS will cost $16 trillion or just short of the United States GDP in 2015. The world GDP in 2015 was estimated at $74.551 trillion (IMF, April 2015). That means a TSS amounts to (16/74.551) *100 = 21.47% of the current world GDP. The world GDP Global growth is projected at 3.4 percent in 2016 and 3.6 percent in 2017 (IMF, January 2016), and global GDP was expected to add another $10 trillion by mid-2017. Depending on how you calculate it, a trillion sensors amount to 2-4 years of world GDP growth. Even at a modest $16 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. The present study has copious limitations. They include: the possibility of new technologies not yet known, the use of other readiness level measures, the potential of governmental financial intervention and many others.

We wish to state that need creates innovative opportunity and from a technological determinism point of view there is probably new technology available that have novel ways to improve system security like the uses of continuous use of random number to improve encryption or a manner improve data compaction and then "zip" or expand data at the end of data transmission

Abundance offers the opportunity to transcend historical socio-political dichotomies. 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., (IMF, April 2015). 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.

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