Internet of Things Examination

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Introduction

This paper is an examination of the emerging market of the Internet of Things (IoT) and serves as a guide to the two main areas of the technology, namely 1) commercial and consumer products and 2) industrial solutions, with an emphasis on the former, in particular solutions for building and home automation. Further this paper also examines the methodologies for connecting these devices for communication. This paper was written to capture the current state of the IoT market to provide a basis to propose novel research opportunities in the space.

IoT comprises the emerging networking of physical objects such as devices, vehicles, and building components that have been embedded with sensors, actuators, software, and the capability to communicate, allowing the collection and exchange of data [1, 2, 3, 4]. Different experts seldom offer identical definitions of IoT [5, 6, 7], but as it appears in the consumer or commercial space, it often also refers to objects that have not traditionally been connected (as opposed to mobile phones). As IoT technology solidifies, what has been typically connected naturally will change. IoT also promises to overtake traditional communications across the 3Vs (volume, velocity, and variety) [8, 9, 10], leaning on the promise of improved coverage, bandwidth, and latency to connect these devices to the network [11, 12].

IoT is often tied with the innovation of transparent Machine-to-Machine (M2M) communications [12, 13, 14], the exploitation of radio frequency identification (RFID) [15], and the concept of ubiquitous computing, which arose in the 1980s at Xerox Palo Alto Research Center [16, 17]. Ubiquitous computing distinguishes itself from both desktop computing and virtual reality by establishing a connected data-driven user experience with devices that occur in any different physical form, including everyday objects. So while these ideas have percolated for decades, they are only now seeing a strong emergence in the consumer market.

- Environmental monitoring
- Home and building automation
- Energy management
- Health monitoring
- Supply and manufacturing network control
- Infrastructure management

Figure 1: Common IoT applications

Because IoT generalizes to many different objects, it is suited to apply across varied use cases. Typical applications of IoT are listed in Figure 1; these often align with sensor network applications [18, 6]. IoT can be at the scale of tailored commercial solutions or targeted to individual consumers and purchasable as off-the-shelf products. Commercial IoT solutions cover topics such as smart cities and smart metering, retail and logistics, agriculture and animal husbandry, and industrial control systems. In contrast, consumer solutions are targeted at individual users or homes and small businesses, often as wearable devices or products for monitoring, automation, or energy saving in a domicile or office.

This market is also on the rise. For instance, while home security and monitoring solutions were a $6.5 billion market in 2015 in North America, it is projected to grow to $20.8 billion for that region by 2021. Similarly, for the same region over the same time scale, home energy conservation and management will grow from a $4.1 billion market to $15.6 billion [19]. As for IoT as a whole, Gartner predicts the number of devices will grow 30% in 2016 from the previous year and will, by 2020, comprise more than 20 billion devices [20], likely eclipsing other connected devices.

IoT for environmental monitoring and protection has been applied or suggested as applications of sensors [21] for monitoring water quality [22], air pollution [23, 24, 25], wildlife habitats [26], and early warning systems for natural disasters [27, 28]. These uses can cross over into the space of IoT applications for agriculture (e.g., monitoring soil, estimating rain fall, and aiding farmers in planning to improve their crop yields [28, 29]), supply and manufacturing networks (e.g., improving efficiency or facilitating the localization of transported goods [14, 30, 31]), or infrastructure (e.g., monitoring structural conditions and changes in power and transportation, such as roads and bridges, or other use-cases that often appear in a Smart Cities context [32, 33]). Beyond these environmental sensor use cases, IoT encompasses wearable devices typically for health care and monitoring applications [34, 35].

In addition to these domains, many IoT products are designed for home or office monitoring applications, whether for environmental sensing, energy or utility conservation, or security. The next section describes these in greater detail.

Building and Home Automation

While IoT spans many different categories of activities and use cases, here we describe those that typically fit under the umbrella of monitoring and controlling a building's internal systems in a home or small business. This context is a principal application of IoT targeted at consumers [36, 37]. In the home context, this is often referred to as home automation, smart homes, or domotics. It often manifests as controlling home elements and appliances remotely, such as through a mobile phone app [38, 39], or through a voice controller [40, 41]. While interest in domotics precedes the surge in IoT, the two are converging in the marketplace of consumer products.

Many home automation products can connect to a central hub that unify the control of many facets of a smart home, such as off-the-shelf products like those in Figure 2. Users often exercise control through mobile phone apps, but can also do this via voice controllers such as are included in the Amazon Echo or Echo Dot [42, 43]. While a product like the Echo can provide access to

- Samsung SmartThings hub [64]
- Iris Smart Hub [66]
- VeraEdge [67]
- Wink [85]
- Insteon hub [55]

Figure 2: Example IoT central hubs

- Lutron's Caseta Wireless [84]
- GE Link bulbs [54]
- OSRAM LIGHTIFY lights [78]
- Philips Hue [79]
- Belkin WeMo bulbs and switches [65]

Figure 3: Example IoT lighting products

- Nest Thermostat [71]
- Ecobee [72]
- Honeywell Smart Thermostats [73, 74]

Figure 4: Example IoT thermostat products

- Budderfly power outlets [83]
- iHome SmartPlug [75]
- Smart Switch 6 [82]
- Insteon Plug-In Devices [76]

Figure 5: Example smart plug products

- Skybell [68]
- Ring [69]
- Nest Cam [70]
- MUL-T-LOCK GotU [77]

Figure 6: Example video doorbell products

- Kwikset Kevo [57]
- Schlage deadbolts [80]
- Yale deadbolts [81]

Figure 7: Example smart lock products

various services such as news, music, and audiobooks, what is of greatest interest here is how these integrate into the home and building's infrastructure.

When it comes to consumer products for automating the home, the most prevalent products are those that deal with lighting (see Figure 3), thermostats (see Figure 4), smart plugs (see Figure 5), and whole building solutions (e.g., Daintree ControlScope [44]). Most of these are intended to assist in the energy management of the home, but some solutions are often tied to monitoring, as in for instance the Curb energy management solution [45], which makes a point about the ability to detect aberrant energy usages in the home.

Monitoring is a key part of the home and building automation context of IoT, whether for energy management (as described above), safety, or security. Environmental monitoring solutions include smoke and gas detectors (e.g., RLE GD200 [46]) and temperature and humidity sensors (e.g., Eve Room [47]). Security solutions cover items ranging from motion sensors (e.g., Insteon Wireless Motion Sensor [48], Synapse SNAP LightSense [49]) or video doorbells (see Figure 6). Furthermore, there are security solutions in IoT that extend past monitoring, such as smart locks (see Figure 7). There are also other monitoring solutions for more particular home use cases, such as tags for items to ensure they can be found when lost (e.g., Wireless Sensor Tags [50]).

Device Connection Methodologies

While the earlier sections have described the history and landscape of IoT applications, they are not sufficient to explain the underlying technology and how different devices typically work. The applied network technology and communication used in IoT will be explored in this section.

There is some diversity in how IoT devices and applications interact. A standard network configuration for consumer devices (as depicted in Figure 8) is for the different IoT sensors to connect to an IoT hub, which in turn connects to a local area network (LAN) router that links to either the internet or a user-interface device (for instance, a smart phone). Alternately, some IoT devices and sensors can connect directly to the LAN, bypassing the need for connecting by way of a hub.

The network configuration can sometimes be determined by the product and sometimes customized by the end-users for their circumstances, but it is often driven by the underlying technologies and protocols used for wireless communication from the IoT devices. As shown in Figure 8, while the range of different wireless communication can span from proximity (0 – 10 cm) to wireless wide area networks, WWANs, (up to 100 km), typically the wireless connections most relevant to IoT network maps are wireless personal area networks, WPANs, (10 – 100 m) for IoT hubs and wireless local area networks, WLANs, (100 – 1000 m) for LAN routers. Some significant examples of WPANs are ZigBee [51] and Z-Wave [52].

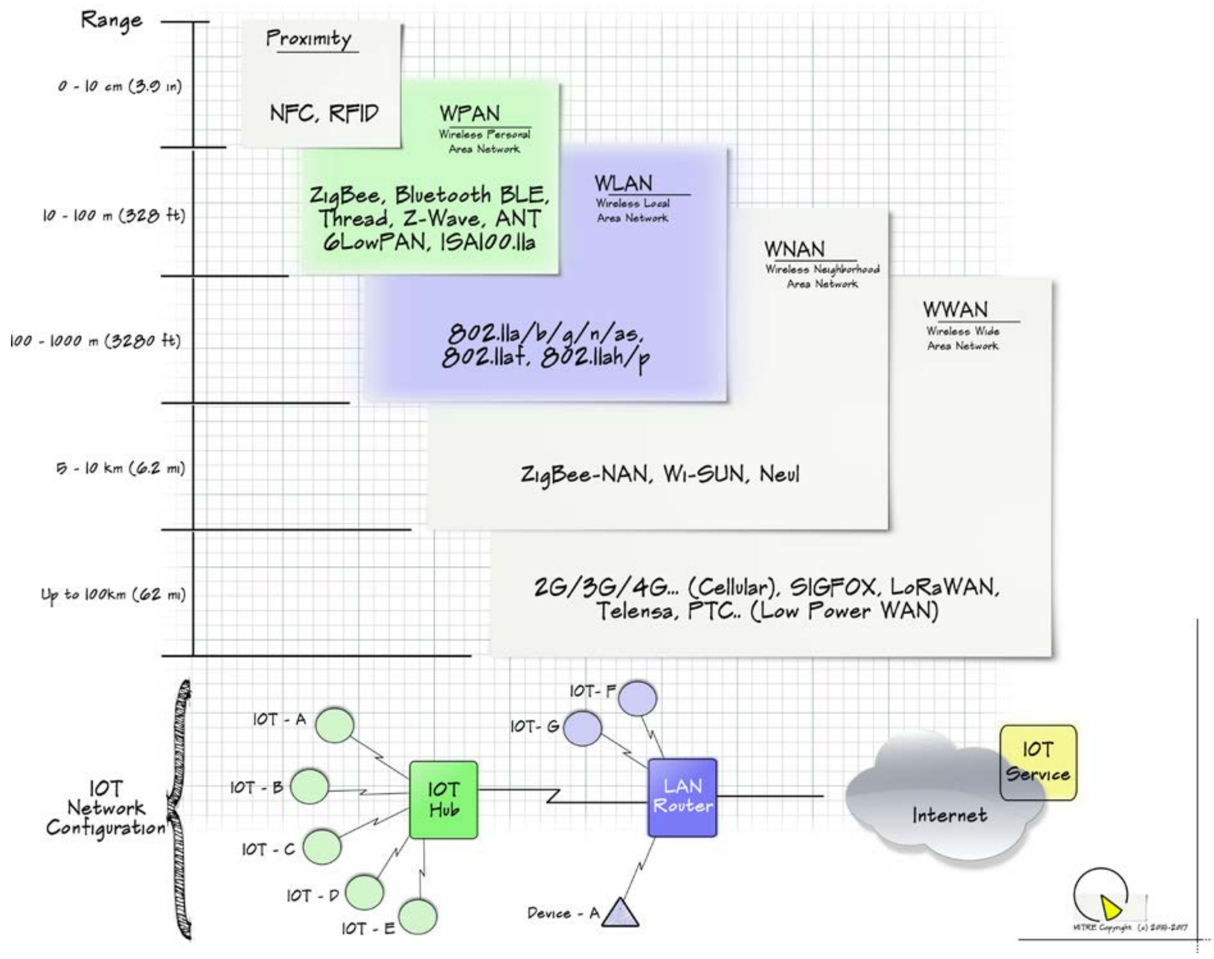

Figure 8: IoT Network Technology and Configuration

This basic map of connectivity lends itself to several different network traffic configurations. In Figure 9, three different example configurations are depicted. In configuration A, an IoT sensor connects and sends sensor information to its hub. An end-user device, for monitoring the sensor, connects to the LAN, which contacts the IoT hub to retrieve data to send back to the end-user device. Of course, this first configuration assumes only a connectivity relationship within the scope of the user's local area network, but other configurations can or may require internet connectivity. For example, configuration B follows a path of activity where the information collected by the hub is relayed by the LAN to some external internet repository and it is this repository that the end-user device accesses (by way of the wireless LAN router). This is often the case when the raw results of a device need to be enriched by a back-end internet analytic service before being rendered to the end-user. Configuration C bears a strong resemblance to the configuration B, but it covers cases where there is no need for an IoT hub and the IoT sensor connects directly to the LAN router to reach the internet service. Different products may be able to conform to multiple configurations. For example there are products that require a hub (e.g., CAO Gadget Sensor Tags [53], GE Link Bulbs [54], Insteon Wireless Motion Sensor [55]) and products that do not (e.g., Elgato Eve Room Indoor Sensor [47], August Smart Lock [56], Kwikset Kevo [57]), but typically products that do

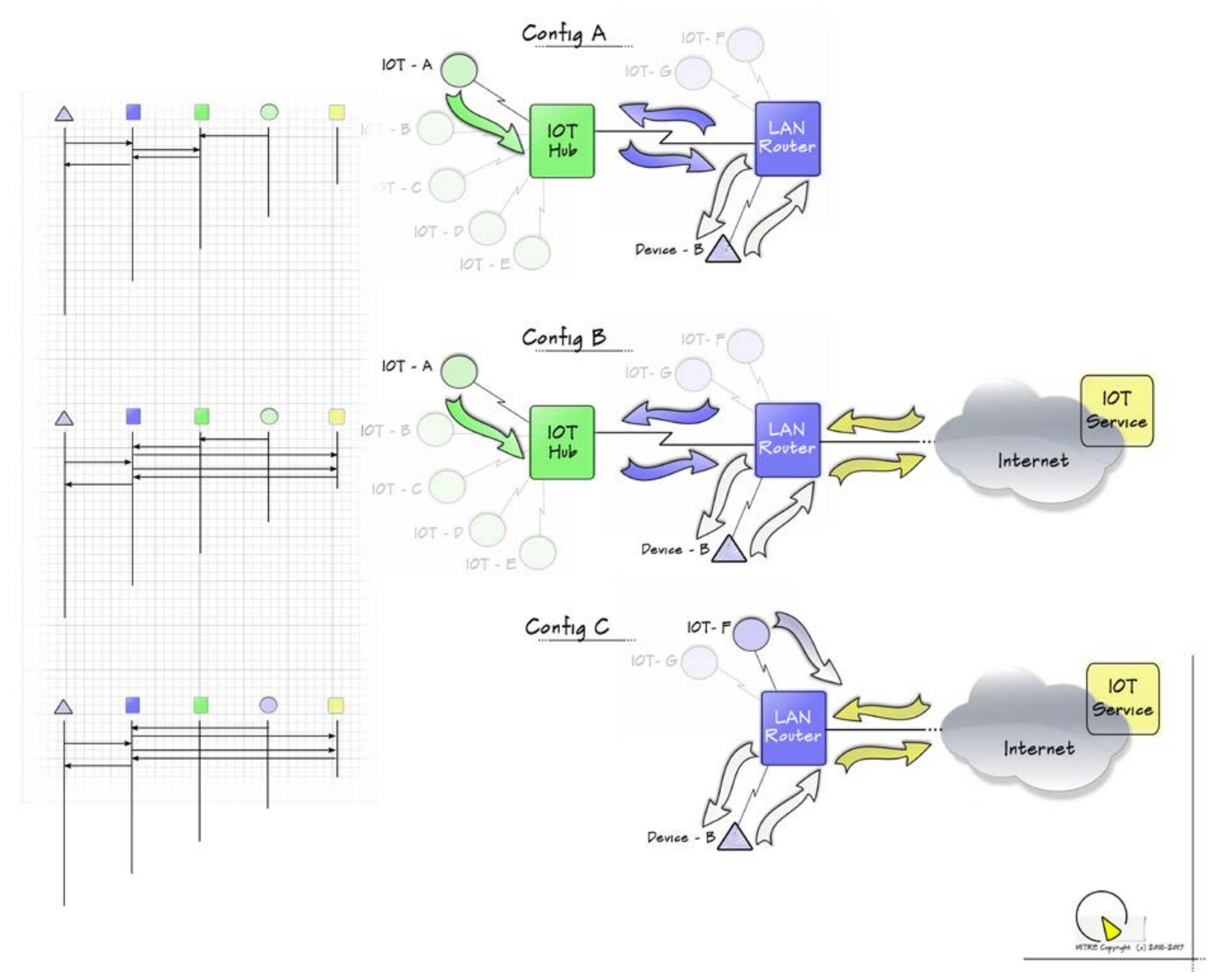

Figure 9: Different IoT Network Configurations

not can still use a hub if they are configured to do so. Similarly, some products do not use a remote backend service at all (e.g., Elgato Eve Room Indoor Sensor [47]) while others can use such a service but do not require it (e.g., August Smart Lock [56]). Particularly perilous to consumers are products that require connectivity to a remote service, as the product may become unusable if and when the company no longer supports it.

As indicated in Figure 8, there are many different WPAN protocols, and while these serve the same function in the network map, they can span different layers of the ISO OSI model [58], as shown in Figure 10. The ISPO, Thread, and ZigBee protocols extend throughout all layers of the abbreviated ISO OSI model, from physical hardware to the application layer [59, 60]. Currently, there is some consolidation between these threads, as ISPO shares commonalities with Thread at the lower levels, while the ZigBee Alliance and the Thread Group are aligning their application layers for ZigBee 3.0 [61]. Above these layers, there are no longer constraints on the protocols used, unlike another example, Z-Wave, which stretches from the physical layer up through the applications and the commands they issue during communication [62, 63]. As for BlueTooth, it is

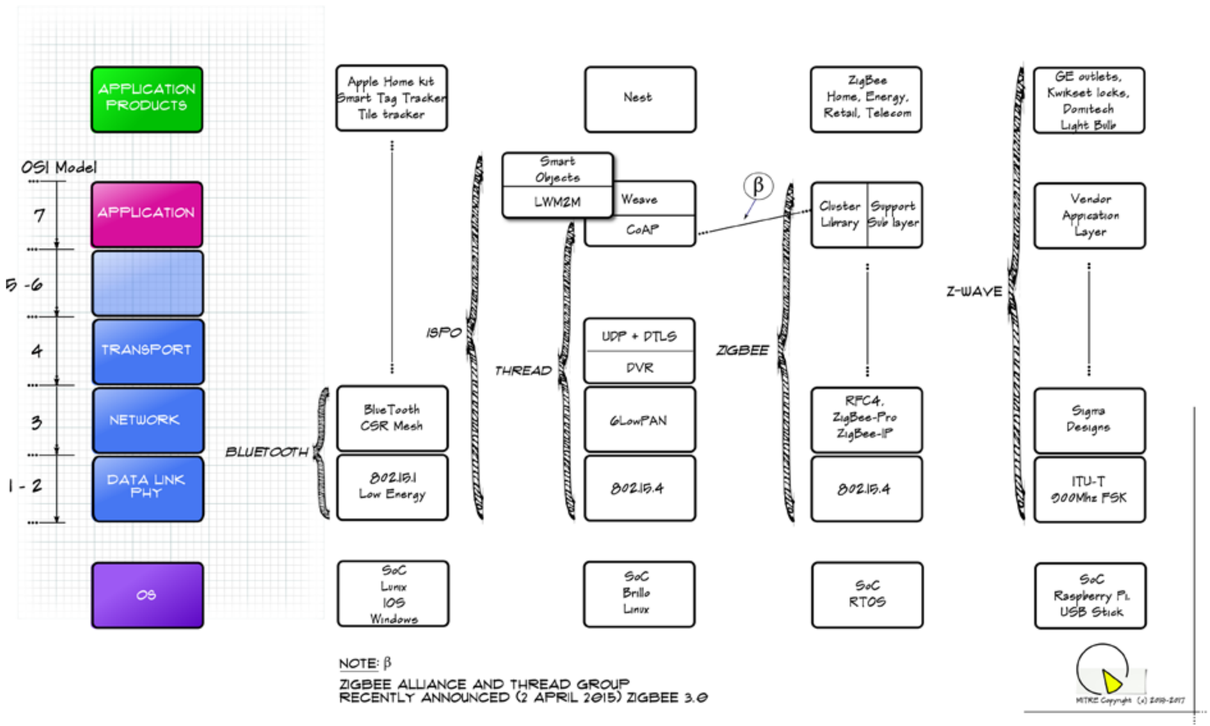

Figure 10: Example IoT Protocol Stacks

another well-established communication capability that is used in the IoT space. Figure 10 also indicates example products that rely on these capabilities.

Given the map of network connectivity, the different network configurations and communications observed across IoT devices and applications, and the varied protocol stacks, a diverse picture of IoT takes shape. These patterns of activity reveal how communication occurs and what elements can be or must be involved, which can serve as a template for evaluating further IoT devices and their behaviors.

Conclusion

IoT is poised to become the largest contributor to network traffic in the next five years, and given its growing consumer market of products that can be purchased off-the-shelf, it deserves further examination to understand the texture of the activity and capabilities of the manifold devices that fall within IoT's varied use cases, especially with respect to building and home automation.

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