The Potential of IoT for Instrumentation and Measurement

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It is rare for someone in the engineering or science fields not to have heard of the Internet of Things (IoT). IoT has been disrupting many industries by providing an unprecedented approach for a (potentially large) number of distributed components connected over a network to collect data, collaborate, and perform tasks with almost no human intervention. Spending in IoT is forecasted to reach US $1 trillion by 2022 [1] and is considered to be one of the core enabling technologies behind the fourth industrial revolution. But what is IoT really? The deep understanding of IoT and therefore its definition are still evolving. Meanwhile, IEEE defines an IoT system as "a system of entities (including cyber-physical devices, information resources, and people) that exchange information and interact with the physical world by sensing, processing information, and actuating" [2]. Furthermore, the "Thing" in IoT can be defined as "an IoT component or IoT system that has functions, properties and ways of information exchange" [2]. The exact interpretation of the "Thing," and not the "Internet" part which has existed for many years, is causing IoT's definition to still evolve [3]. In essence, the components of an IoT system interact with each other to fulfill the goal for which the system has been designed. For example, in a smart home, an IoT system consisting of interconnected thermostats, switches, alarms, triggers, cameras, sensors, and actuators can autonomously control lighting, temperature, ambience, and security based on the inhabitants' observed behaviors, leading to more efficiency, comfort, and energy savings. Our transportation systems can benefit from an IoT consisting of connected vehicles, drivers, pedestrians, and traffic infrastructure (signs, lights, roads, etc.) for more efficient traffic routing, road assistance, emergency response, parking support, and toll collection. Or, in an industrial setting, IoT can enable the integration of manufacturing machines or robots equipped with instrumentation, sensing, processing, communication, and collaboration, leading to more efficiency and profitability in the management of equipment, assets, processes, and produced goods. This Industrial IoT, also known as IIoT, is of particular interest, since it is a core enabling technology behind Industry 4.0, estimated to generate a US $12 trillion market by 2030 [4].

While the concepts behind IoT were being discussed in the early 1990s, Cisco estimates that IoT was finally realized some time in 2008 or 2009, when the "things" to people ratio grew above 1.0 [5]. So, as IoT turns 10 years old, we take a look at how it impacts the field of Instrumentation and Measurement (I&M). In I&M, IoT provides an unprecedented approach for instruments to collect measurements, track, detect, monitor, characterize, identify, estimate or count physical phenomena, and perform analysis with almost no human intervention. In that view, we can say that IoT is in fact a natural extension of many measurement instruments. In this article, we first highlight the benefits of having IoT as part of measurement instruments, before discussing the caveats of incorporating IoT into measurement systems. We also cover how IoT is currently being used in I&M literature, and what voids need to be filled with further research. With that in mind, let us begin by looking at the benefits of IoT in I&M.

IoT Benefits for I&M

IoT can enhance measurement instruments to more efficiently perform continuous and thorough measurements, simultaneous wide area measurements, and real-time measurement analysis, as well as provide better integrity of measurement. Each of these is described next.

Continuous and Thorough Measurements

Before the advent of IoT, measurements were often taken manually, which meant that it was not cost effective to make continuous and thorough measurements. Without continuous measurements, it is very challenging if not impossible to capture measurand properties such as rate-of-change, autocorrelation, or causality. Without thorough measurements, we may even miss interesting events due to low sampling rates as required by the Nyquist-Shannon sampling theorem. IoT on the other hand, makes continuous thorough measurements possible through the implementation of low-power and wireless sensor nodes. There are many existing IoT measurement

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works that focus on getting continuous and thorough measurement and through such measurements obtain insights on the changes in the measurand.

Simultaneous Wide Area Measurements

IoT can enable cost effective simultaneous wide area measurement, by deploying many low-cost embedded devices with ubiquitous connectivity, which can simultaneously gather measurements over a large area more cost effectively compared to the conventional approaches such as coverage by a satellite. The changes of the measurand at the spatial domain can also be captured, for example, crowd size and movement of the crowd in public space over a specific duration can be captured and visualized with IoT.

Real-time Measurement Analysis

In a conventional measurement process, the measurement and the measurement analysis are two distinct stages, where measurements have to be collected and transferred to a computer for processing in batches. By incorporating IoT into the measurement process, the measurement collection and analysis are streamlined as one process. Such stream processing enables actions to be taken as soon as an event arises. The processing for analysis can be done in the smart instrument itself, or at a nearby edge node, or a combination of the two.

Enhance the Integrity of Measurements

Data captured by sensors can be blockchained to ensure the integrity of the measurements, for instance, a government agency's monitoring of emission of gases by factories. The data coming from the sensors at the factory can be recorded and blockchained to avoid being tampered with by any party. As such, the integrity of the measurements can be maintained without any centralized party.

The Caveats in Deploying IoT in I&M

Unfortunately, incorporating IoT into measurement systems and instruments is not without consequences. While there are many existing research works to push the limits of IoT technology, it is important for us to be aware that by incorporating IoT into I&M, the measuring process inherits additional uncertainties from the IoT system itself. These are discussed next.

Network and Operating System Latencies

IoT can provide continuous and thorough measurements where the sensor nodes are designed to perform measurement, continuously using a wireless, low power and embedded microcontroller. However, due to the transmission latency, the read intervals between successive measurements may not be consistent. A measurement from a sensor node will experience the latency of both the IoT-gateway and the cloud. Therefore, analysis that requires frequency domain transformation may not be able to represent the original measurement accurately. Fig. 1 illustrates the impact of measurement experiencing an average delay of 150 ms with a standard deviation of 70 ms.

In order to reduce the effect of network latency on the measurement, we might employ a store-and-forward approach where the local latency is lower between the sensor node and the IoT-gateway. The collected measurements are then transmitted to the cloud in batches. Fig. 2 shows the same measurement with an average latency of 15 ± 7 ms, which is achievable via WiFi and BLE.

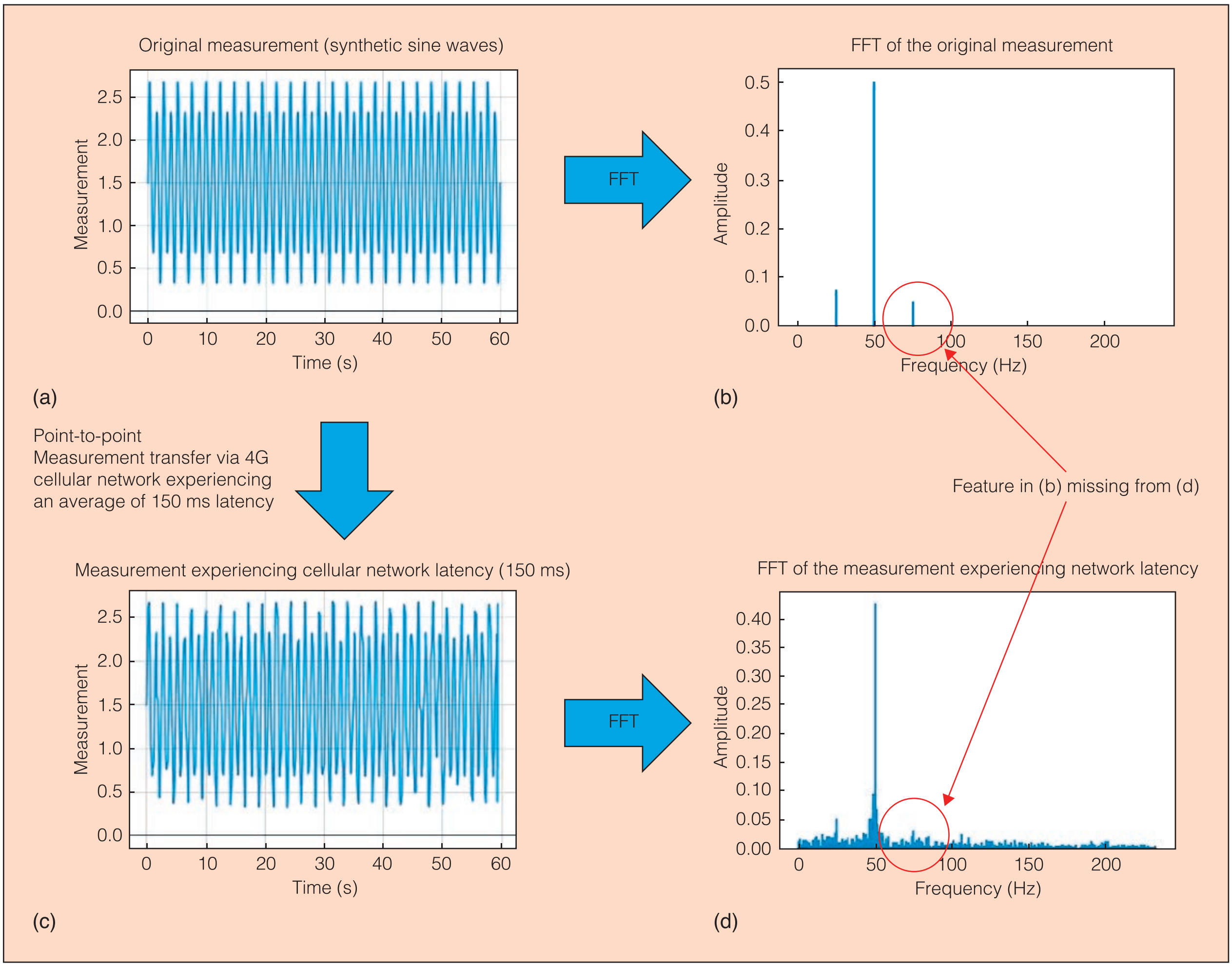
In order to further reduce the effect of network latency, it is possible to store the measurements locally in the sensor node with a timestamp and subsequently send the measurements to the cloud. However, such implementation will make it difficult to perform causality analysis from the measurements from two different sensor nodes due to the high likelihood that the clocks of the two sensors have some drift and are not completely synchronized.

Causality Analysis

As mentioned before, IoT has the ability to provide simultaneous measurements from a large area, and it is interesting to draw the correlation from the measurements of different sensors nodes, for instance, to identify heat sources in a server room by interpolating the temperature data collected via multiple sensors with known locations distributed in the server room. The challenge of such a feat is to ensure that the clock of all the sensor nodes are synchronized for every measurement taken. Such synchronization is not trivial, and unless we use additional solutions, such as those based on IEEE standard 1588 which allows clock synchronization with a sub-microsecond accuracy [6], it is very challenging to ensure all of the clocks of the sensors are synchronized. Drifted clocks of these sensor nodes will affect the causality analysis among the sensors. Fig. 3 illustrates measurements taken from two sensor nodes in sequential order at their respective clocks. Unfortunately, due to drifted clock and network latency, the measurements may arrive at the cloud in different orders. Therefore, causality analysis of the measurements might not necessarily represent the causality of the actual scenario without knowing the consistency model of the measurement instruments. For example, it is possible for the scenario shown in Fig. 4 to happen if the underlying protocol used for transmitting the measurements is not TCP but UDP, in which datagrams might arrive at the destination out of order.

Aging and Faulty Sensors

As is well known in the I&M community, conventional uncertainty evaluation focuses on type A and type B, where type A estimates uncertainty using repetitive readings and statistic approaches, and type B estimates uncertainty based on information such as manufacturer's specification [7]. Typically, for type A uncertainties, we calculate the arithmetic mean, standard deviation, standard uncertainty and degrees of freedom. Unfortunately, these evaluations may not be able to reveal aging or intermittent failing of the sensors. In IoT, sensors are often deployed to run for a long period. As the sensors age, they might produce inaccurate readings. IoT measurement instruments must take such uncertainties into consideration.



Original measurement (synthetic sine waves)

FFT of the original measurement

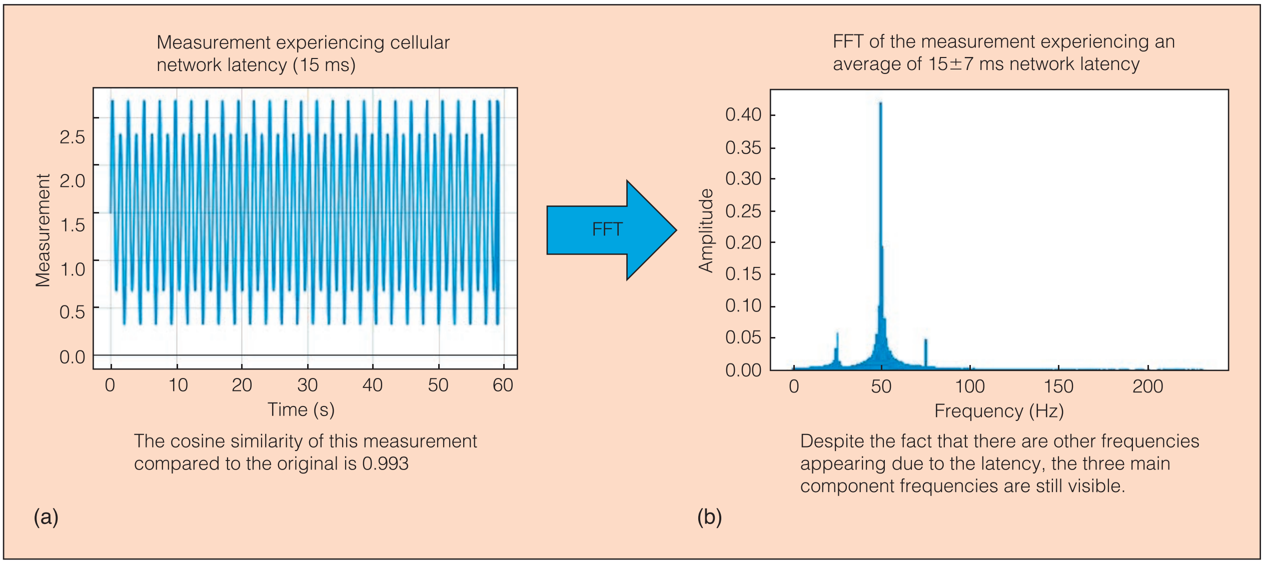
Point-to-point Measurement transfer via 4G cellular network experiencing an average of 150 ms latency

Feature in (b) missing from (d)

Measurement experiencing cellular network latency (150 ms)

FFT of the measurement experiencing network latency

Fig. 1. The effect of network latency on measurement data. (a) Shows the original measurement; (b) shows the FFT of the original measurement, giving 3 harmonic frequencies; (c) shows the measurement experiencing a delay of 150±70 ms; and (d) is the FFT of (c), showing that a feature detected in (b) has become too insignificant to detect.



Measurement experiencing cellular network latency (15 ms)

FFT of the measurement experiencing an average of 15±7 ms network latency

The cosine similarity of this measurement compared to the original is 0.993

Despite the fact that there are other frequencies appearing due to the latency, the three main component frequencies are still visible.

Fig. 2. Same measurement as in Fig. 1, but with an average latency of 15±7 ms.

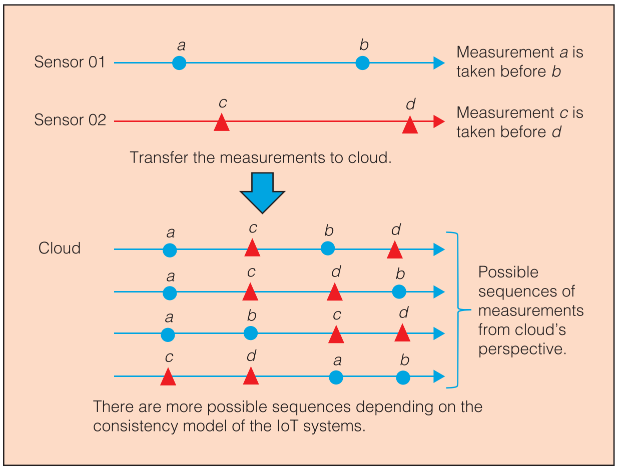


Fig. 3. Although the measurements taken from each sensor are in sequence, without a global clock and end-to-end real-time computing, the cloud is not able to capture the actual sequence of the measurement from different sensor nodes.

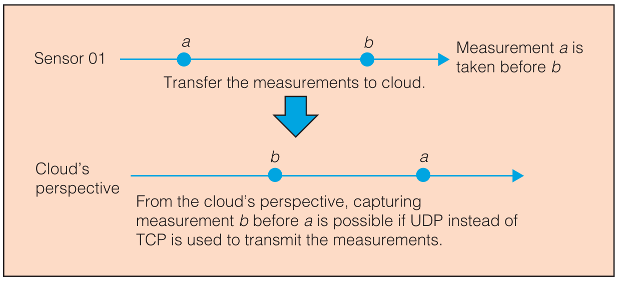


Fig. 4. The underlying protocol for transmitting the measurements (e.g., UDP instead of TCP) affects the cloud's perspective and subsequently affects the possibility of using that data to do causality analytics.

Therefore, the incorporation of IoT into measurement instruments should also check for possibility of aging and faulty sensors. For instance, we can automate the process to check the normality of residuals to detect bias and systematic errors.

Privacy

An IoT system by definition is a networked system, with the measurement data traveling across a network. Hence, privacy becomes a major concern, not just for I&M but for any other application of IoT as well. We mentioned earlier that the integrity of the measurement data in an IoT system can be protected by blockchaining. If the measured data needs to be kept private, for example data coming from a patient's wearable medical sensor which should only be seen by the person's doctor, then the blockchain must be configured to control when and how a third party intercepting or receiving the data can actually access it. Security and privacy must therefore be built into the design of the measurement system. Adding security and privacy later as an after-thought will make intrusion into the system easier.

IoT in Today's I&M

Our literature review, which was restricted to IoT literature published in only *IEEE Transactions on Instrumentation and Measurement* and *IEEE Instrumentation & Measurement Magazine*, showed that currently IoT is being applied to I&M in the following topics:

Monitoring and Sensing

The nature of IoT helps to automate the measurement process. Therefore, there are a number of works that use IoT for monitoring and sensing. For instance, Mois *et al.* [8] developed a complete IoT solution that monitors ambient conditions of indoor spaces at remote locations. They showed their proposed solution is capable of capturing and visualizing wide area measurements simultaneously from various devices by simply using IEEE 802.11 b/g standards [8]. Structural health monitoring (SHM) is one of the applications that makes full use of the continuous and wide area measurements features provided by IoT. IoT enabled SHM improves safety for humans while reducing the costs of continuous structural monitoring [9]. Besides wide area measurements, IoT is also capable of providing continuous and thorough measurements. Fisher *et al.* used IoT approach to perform nonintrusive and high-speed measurement of jet-engine exhaust, and in the process, they developed a method to mitigate the impact of lost packets during the measuring process [10]. Yang *et al.* highlighted the potential of using IoT in developing smart and automated seaports, and they developed crane health structure monitoring with built-in features such as localization to improve safety and monitoring efficiency [11].

Identification and Indoor Positioning

The positions of sensors are crucial information especially when IoT is used to provide simultaneous wide area measurement. The origin of the measurement must be correctly identified. Thus, to prevent data labeling error caused by hard-coding the position into the sensor, it is best for sensor nodes to be able to locate their own position. The importance and usefulness of using RFID for product identification and position of the product in a manufacturing line is highlighted by Murofushi *et al.* in [12]. From their study, despite the maturity of RFID technology for product identification, using RFID for indoor positioning is yet to be a solved research problem [12]. Bellagente *et al.* in [13] compared BLE Beacon and ultra-wide-band (UWB) based positioning techniques in a real environment. Despite the fact that UWB based positioning techniques can provide higher positioning accuracy, the BLE beacon has lower deployment cost and the BLE technology is readily available in many commercial smartphones [13].

IoT Architecture

One of the important objectives of having a proper IoT architecture is to ensure the success of future expansion of an IoT system. Cai *et al.* [14] studied IoT-architecture for sensing and local data processing specifically for ambience intelligence in environments such as smart homes, intelligent vehicles and healthcare. They emphasized the benefits of local computing for IoT, especially dealing with privacy-sensitive and time-critical operations. Network latencies among devices in smart systems are crucial for many IoT applications. Silva *et al*. investigated network latencies of different technologies and proposed a middleware for IoT solutions which is fully compatible with existing networking technologies such as WiFi [15]. Ooi *et al*. showed that measurements from different sensors of a same measurand may be correlated and such correlation may be used for detecting faulty and abnormal sensors [16].

Wireless Connectivity Evaluation

In terms of energy consumption and coverage, many existing wireless connectivity technologies are yet to be suitable for many IoT applications. IoT applications often need to provide continuous and thorough as well as simultaneous wide area measurements. Although narrow-band-IoT can provide long range and low-cost communication for IoT solutions, their performance and availability are rather limited compared to communication technologies such as cellular networks, which on the other hand are more power hungry. Rizzi *et al*. evaluated the performance of LoRaWAN for wide area distributed measurement applications and highlighted the challenges of timestamp uncertainty of events due to network latencies and large area unsynchronized clocks [17]. Lee *et al*. designed and evaluated the performance of LoRa mesh network system for large-area monitoring to overcome the need to have dense deployment of LoRa gateways to ensure indoor coverage, especially in urban areas [18]. On wide area connectivity, Palisetty *et al*. developed a multicarrier scheme to provide real-time implementation for narrow-band-IoT [19]. At the application layer, Ferrari *et al*. estimated the delay of industrial IoT applications based on messaging protocols, specifically on MQTT over intercontinental links in their evaluation process [20]. Mois *et al*. in [21] analyzed and evaluated three different IoT-based wireless sensor implementations for environmental and ambient monitoring. They included wireless sensor nodes that use UDP-based WiFi communication, HTTP on TCP-based WiFi communication and also Bluetooth Smart communication. They concluded that although WiFi consumes more energy, it is more cost effective to develop IoT solutions due to its popularity and existing infrastructure.

Healthcare

Healthcare applications are high-value applications. Monitoring patient health continuously is crucial as it involves human life. Unfortunately, without IoT the monitoring process is laborious and not cost effective. There are times that certain measurement instruments are expensive. Russell *et al*. in [22] used sensory substitution and IoT to replace pressure sensors with sound and temperature sensors for recognizing a patient's chair posture. Bassoli *et al*. explored the potential of using WiFi to develop active and assisted living solutions to improve conditions of life for the older adults [23]. They concluded that although WiFi consumes more energy compared to technologies such as ZigBee, because of the high adoption of WiFi technology, it greatly simplifies system development and the deployment process in terms of cost, scalability and user acceptance [23].

Energy Management

The aim of energy management is to reduce CO_2 emission and the objective of energy management is to ensure productivity is not affected by the energy consumption reduction process. Thus, it is important to monitor the load of appliances for more effective, safe, and efficient electric distribution. For instance, Yu *et al*. in [24] developed nonintrusive, real-time electrical appliance load monitoring for smart homes to allow users to better understand energy usage as well as detect abnormal operations of electrical appliances for safety purposes. Besides that, IoT sensors themselves consume power too, and having batteries in sensor nodes means that these sensor nodes require maintenance. Interestingly, there is work done by Porto *et al.*, which proposed incorporating wireless power transfer capabilities into measurement instrumentation [25]. Despite the fact that it works in labs, the distance and efficiency of wireless power transfer is still far from practical [25].

Discussion and Opportunities for Future Work

In this article, we highlighted the benefits of having IoT as part of measurement instruments and also the caveats of incorporating IoT into measurement systems. From our I&M literature study, we found that:

- Monitoring and sensing is the most widely used application of IoT in I&M, comprising 30% of the papers we read.
- The majority of the works focus on extending conventional measurement systems with IoT to achieve continuous and wide-area monitoring. However, other than sensing, IoT also encompasses actuators. In the I&M domain, almost none of the papers we read mention post-measurement analysis or suggest improvements that may be made to IoT systems.
- There are a number of papers focusing on measuring the latencies of IoT networks. The objective of these works is to identify the limitation of the IoT in terms of data transmission rate and coverage. Unfortunately, many of them assume that IoT is limited to homogenous networks which is not completely true. One of the roles of an IoT-gateway is to bridge devices that use different network technologies and are designed for future protocol expansions in mind.
- To our surprise, none of the papers highlighted security concerns. End-to-end communication among IoT devices can be encrypted, but due to the nature of wireless communication, IoT is also prone to side-channel attacks. Attackers may listen to the presence of wireless packets to infer the state of an IoT system despite not being able to see the content of the packet. More work is needed in this area, and it is crucial for security to be built into the core design of the system, and not added later as an after-thought.

IoT indeed promises many attractive advantages for measurement instrumentation. Besides automating the measurement process, it improves the measurement process in terms of providing continuous and thorough measurements, simultaneous wide area measurement, and real-time measurement analysis, along with enhancing the integrity of measurements. However, it is important for us to be cautious with the issues inherited from IoT in the measurement process especially due to the network latencies, unsynchronized clocks, and undetected faulty sensors. 5G, the fifth-generation cellular network technology, may be a good solution, but for now we need to be aware that there are caveats when IoT is part of a measurement system.

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