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Use of the IQRF Technology in Internet-of-Things-Based Smart Cities

MOHAMMED BOUZIDI[1], YASER DALVEREN[1,2], FAOUZI ALAYA CHEIKH[3], (Senior Member, IEEE), AND MOHAMMAD DERAWI[1]

[1] Department of Electronic Systems, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology, 2815 Gjøvik, Norway
[2] Department of Avionics, Atilim University, 06830 Ankara, Turkey
[3] Department of Computer Science, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology, 2815 Gjøvik, Norway

Corresponding author: Yaser Dalveren (yaser.dalveren@ntnu.no)

ABSTRACT In recent years, there has been a growing interest in building smart cities based on the Internet of Things (IoT) technology. However, selecting a low-cost IoT wireless technology that enables low-power connectivity remains one of the key challenges in integrating IoT to smart cities. In this context, the IQRF technology offers promising opportunities to provide cost-effective solutions. Yet, in the literature, there are limited studies on utilizing IQRF technology for smart city applications. Therefore, this study is aimed at increasing the awareness about the use of IQRF technology in IoT-based smart city development. For this purpose, a review of smart city architectures along with challenges/requirements in adopting IoT for smart cities is provided. Then, some of the common cost-effective IoT wireless technologies that enable low-power consumption are briefly presented. Next, the benefits of IQRF technology over other technologies are discussed by making theoretical comparisons based on technical documentations and reports. Moreover, the research efforts currently being undertaken by the authors as a part of ongoing project on the development of IoT-based smart city system in Gjøvik Municipality, Norway, are conceptually introduced. Finally, the future research directions are addressed.

INDEX TERMS Internet of Things, IQRF, low-cost, smart city, wireless communication.

I. INTRODUCTION

In the last two centuries, there was an unprecedented human migration from the rural areas toward the cities. The statistics of the United Nations (UN) population division show that the half of the world population currently lives in cities. According to the UN, this number is estimated to be 67% of the total world population in 2050. Obviously, this considerable population growth requires major urban infrastructure development. In this context, the International Electrotechnical Commission (IEC) estimates that the number of the infrastructures will rise exponentially in the coming years. Therefore, it is expected that cities might be exposed to many environmental and socio-economic problems due to several factors such as traffic, pollution, and the non-adequate management of the social and economic resources. Thus, the use of smart, digital, and intelligent systems is especially required to overcome these issues in building the cities of tomorrow. This hence leads to emerge the concept of Internet of Things (IoT)-based smart cities.

Basically, IoT is a communication paradigm that can be attributed to a network of interconnected electronic devices equipped with tiny sensors, processors, and storage units. It aims to make Internet more immersive by enabling communication between the devices along with the users. It should be noted that 27 billion devices including smartphones, tablets, connected home applications, cars, health applications etc. are expected to be connected to the Internet by 2022 as Cisco reported.[1] In this way, several applications for different purposes or domains including industry, healthcare, automotive, and many others might be developed. Yet, due to the variety of these applications, development of IoT becomes a challeng-

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[1] https://www.cisco.com

ing topic from a system perspective, and for this reason, it is still under discussion [1]. Moreover, developing of smart IoT system models are required to promote serious investments. This is indeed another concern for adopting and applying IoT paradigm in a broad manner. However, with growing of Information and Communication Technologies (ICT) in many societies, people become able to utilize the services provided by ICT in all aspects of daily life. Therefore, people are more interested to utilize these services in order to facilitate their lives. As a result, this inevitably paves the way for application of IoT paradigm to smart city concept [2]–[4].

In the literature, several surveys on IoT-based smart city concept have been conducted [5]–[12]. In these studies, the applicable technologies, architectures, and protocols have been comprehensively presented. Additionally, practical implementations of the concept around the world have been described, and research challenges have been discussed. As mentioned in these studies, common requirements for IoT devices in a typical smart city application are associated with wide coverage, low power consumption, and low cost. Although wireless communication technologies such as 6LoWPAN [13], Wi-Fi [14], [15], Bluetooth Low Energy (BLE) [16], and ZigBee [17], [18] have been widely used for IoT solutions in smart cities, limited coverage that they provide could be considered as a main concern [19]. Accordingly, Low-Power Wide Area Networks (LPWANs) radio technologies including SigFox, Ingenu, and LoRa, have been designed to improve transmission efficiency. Thus, these technologies have been begun to use in the development of IoT-based smart cities [9], [20]. Among these technologies, LoRa technology has been mostly preferred to utilize in recent systems due to the fact that it offers important advantages particularly in communication range [21]. However, it has some drawbacks that should be taken into account. One of them is related to energy consumption during transmitting data while the other one is pertaining to latency of end-to-end connection. Thus, selecting a low-cost wireless technology that provide low-power consumption becomes a challenging issue in smart cities.

On the other hand, IQRF is a promising technology that could be an alternative to current wireless technologies in the field of IoT [22]. It is worth noting that it is energy efficient, but still, it is not able to reach long communication range when comparing with LoRa technology. This disadvantage, however, is compensated by the usage of Mesh topology which increases the possibility of communication between the sensors. Therefore, in recent years, studies in the literature have been started to emerge on the use of IQRF technology to integrate IoT with smart environments or monitoring systems [23]–[28]. However, only few studies on smart city implementations using the IQRF technology have been introduced [29], [30]. And still, to the best of authors' knowledge, a comprehensive study on its usage in IoT-based smart city concept has not been provided.

The study presented in this article constitutes a part of ongoing project on the development of IoT-based smart city system in Gjøvik Municipality, Norway. The main purpose is to provide a review on the usage of IQRF for the design of smart city based on the IoT concept. To this end, firstly, an overview of the smart city architecture and challenges/requirements in adopting IoT to smart city are provided by referring to the conducted surveys. Then, common low-cost IoT wireless technologies using unlicensed ISM (Industrial, Scientific, and Medical) bands for smart cities are discussed. Next, the IQRF technology is introduced, and its actual and potential usage in smart city applications is examined. Besides, by making theoretical comparisons based on the technical documentations, its potential benefits in terms of low-cost communication over relevant technologies are reviewed. Further, use of IQRF in streetlight controlling use-case is presented in detail, and some of the current research efforts made by the authors in the context of Gjøvik smart city project are introduced. Finally, conclusion and future works are addressed. Therefore, it is believed that this study may increase the awareness of researchers about the use of IQRF technology in IoT-based smart city development.

II. OVERVIEW OF SMART CITIES BASED ON IoT CONCEPT

In a smart city, various type of digital devices such as sensors, cameras, smartphones and tablets are used for several urban applications (services). With the help of growing technologies, it is inevitable to have a significant increase in the number of such devices. It is already known that these devices are able to communicate with each other on the Internet. Indeed, IoT allows the interaction between person to machine (P2M), or machine to machine (M2M). To this respect, the usage of IoT is expected to be more widespread in smart cities as people's life become connected to the Internet. Therefore, IoT could be an efficient way to improve the residents' life by facilitating the operations in urban services like security, health, entertainment, education, and transportation. Besides, IoT has a significant potential that could assist to economic and environmental sustainability in different aspects such as pollution control, economic progress, and energy saving initiatives.

In the current literature, several surveys have been conducted to provide a review on the IoT-based smart cities [5]–[12]. In [5], a comprehensive survey of the enabling technologies, protocols, and architecture for an urban IoT has been provided. The study also presents the technical details of a smart city project in the city of Padova, Italy. The article presented in [6] surveys the research efforts performed in the area of IoT-based smart environments. According to the conducted survey, it devises a taxonomy of IoT-based smart environments, and also discusses some of the case studies. The review studies of smart cities based on IoT concept [7], [8] introduces the possible IoT technologies, and discusses their capabilities to implement them in smart city environments. Moreover, the potential IoT applications for smart cities along with the practical experiences around the world are presented. In [9], another taxonomy is devised to overview of the IoT for smart city, ICT, network types, and

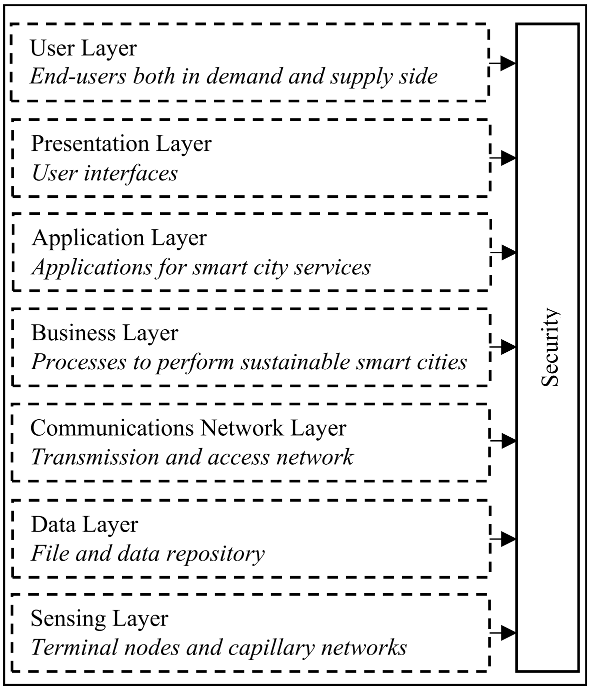

FIGURE 1. The architecture of a smart city in information flow perspective [31].

requirements. Similar to other surveys, it also provides the taken initiatives in worldwide to promote IoT in smart cities. In [10], IoT in the context of smart cities is overviewed, and then the weaknesses along with the risks pertaining to IoT integration into the smart city environment are described. Another study presented in [11] also provides an overview of on IoT-based smart cities. It discusses both current achievements and future trends. It also presents a simple case study on real time monitoring system for IoT-based smart cities. The other survey presented in [12] describes the characteristics to understand IoT-based smart city by presenting main areas, technologies, and practical cases around the world.

Therefore, it is evident that IoT-based smart city environment has been already thoroughly scrutinized in the literature in terms of IoT-related technologies, IoT open source platforms, and actual/potential applications. In this section, in the light of the studies discussed above, it is only intended to provide some significant issues regarding IoT-based smart city environments to motivate the readers to go through the rest of the content. In this context, architecture for a smart city is briefly described in the following subsection to comprehend main structure behind smart cities. Then, the common challenges and requirements in adopting IoT to smart cities are discussed in order to realize the importance of the usage of IoT technologies.

A. THE ARCHITECTURE OF SMART CITIES

As ICT point of view, a generic architecture for smart cities in information flow perspective has been depicted in Fig. 1 [31]. It includes certain layers to organize the sustainable smart cities. Within the presented architecture, the sensing layer is consisted of terminals and capillary network. Capillary network such as sensor networks, wireless personal area network (WPAN), supervisory control and data acquisition (SCADA), etc., is used for connecting the terminals to the network layer. Here, terminals including sensors, actuators, transducers, etc., are used for sensing of the smart environment. In fact, this forms to basis of monitoring and controlling of infrastructures in smart cities such as pipelines, buildings, roads, and so on.

Another layer is the data layer which includes the data retrieved from the terminals, information repositories, servers, and databases. In fact, this layer carries out several tasks in terms of storing, analyzing, managing, and manipulating of data. Hence, the efficiency of smart city services is strictly relied on this layer.

The other layer is the communications network layer that is comprised of transmission (3/4/5G, LPWAN) and access (Bluetooth, Wi-Fi, etc.) networks to ensure the realization of data flow on the smart city services. In order to implement this layer, creating a new network is not required. For a specific application, well-known networks in the current literature can be utilized. This layer, which can be considered as the spine of the architecture, also has an importance for maintaining an efficient smart city service.

Moreover, the business layer, as its name implies, is consisted of business processes to be performed for smart city services. Smart city enterprises should have a well-defined business plan which significantly impacts on the effectiveness or viability of smart city services. As a matter of fact, providing that an explicit purposes and processes to achieve the goals, more investments regarding smart city applications can be expected from the investors/stakeholders.

Furthermore, the application layer includes various software applications to execute the smart city services such as waste management, health, emergency, education, and so on. As a part of this, the presentation layer covers all user interfaces such as mobile applications, web pages, etc., to allow connection between the end-user and smart city services.

As a last layer, the user layer coordinates the requirements or concerns of end-users from both demand and supply sides as it directly affects the performance improvement of a smart system. In this regard, the needs of citizens and investors/stakeholders should be analyzed, and according to these needs, the systems should accurately operate to achieve the user satisfaction.

Although many studies have been concentrated on providing an architecture for a smart city development, the main purpose of the efforts remains the same. This is related to offer efficient smart services to citizens with low operational cost. Obviously, this purpose could be achieved by adopting IoT technologies bringing several benefits in the connection between the layers. Since these technologies with huge number of devices will be an integral part of large-scale networks, various challenges and requirements are expected to be demanded. Therefore, selecting a proper technology is key to fulfill these requirements such as low-power connectivity

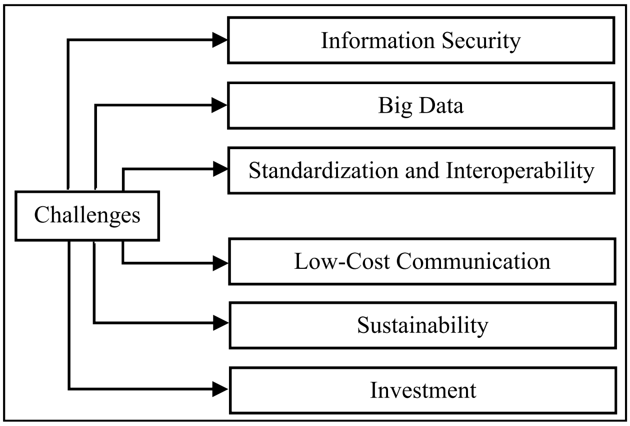

FIGURE 2. The common IoT challenges for smart cities.

between the devices. Before introducing candidate technologies to be considered, major challenges and requirements are discussed in the following subsection.

B. CHALLENGES AND REQUIREMENTS IN INTEGRATING IoT INTO SMART CITIES

Although several projects and case studies on smart city concept exist in the world [32], there are still certain challenges and requirements needed to discuss in integrating IoT to smart cities. Recently, these issues have been discussed in several studies existed in the current literature [6]–[11]. In the following, common IoT challenges and their requirements obtained from these studies are presented. As an illustration, these challenges are shown in Fig. 2.

1) INFORMATION SECURITY

In smart cities, the internet connectivity between the IoT devices provides users to communicate with the smart services. This introduces the system to various external threats. The critical IoT applications for smart services might be then confronted with undesired consequences due to the malicious data. Specifically, as all information gathered from the users is collected in the same platform, it is exposed to several attacks such as side channels and cross site scripting. In addition to this, data leakage is a potential threat because of the system's multi-tenancy. For these reasons, security issues in terms of privacy, trust and data confidentiality are some of the main concerns for the IoT users.

2) BIG DATA

It is expected that a large set of data including both user and environmental information collected from IoT devices could become a resource of big data. Hence, for an efficient IoT application, a robust data management service should be planned and installed. In this context, it is also necessary to adapt machine and/or deep learning algorithms to analyze massive amount of IoT data.

3) STANDARDIZATION AND INTEROPERABILITY

As is known, IoT-based smart cities are consisted of heterogeneous devices used for several smart applications. However, this diversity brings about a key challenge in smart city development which could be attributed to interoperability between the devices. Typically, the IoT data is collected from heterogenous devices with various communication technologies using different protocols. Thus, standardization of IoT devices is strictly required to process such data. Currently, owing to the lack of standardization, interoperability becomes the main difficulty for the successful implementation of IoT systems. Therefore, standardization of IoT devices is still necessary to eliminate non-standard data formats, to improve the integration between protocols, and to progress the overall integration of devices.

4) LOW-COST COMMUNICATION

Evidently, it is necessary to supply continuous energy to operate tiny IoT devices which are equipped with sensors. However, this may be costly when battery life being still one of the biggest challenges for IoT. In some cases, the cost of replacing batteries might be higher than the cost of the device itself. Thus, the low-cost devices consuming less power are strictly required for energy efficient IoT based smart city applications. Further, various cost aspects such as spectrum, device, and deployment cost are needed to be taken into account. Moreover, low-power communication protocols and networks also necessary for reducing the amount of energy while transmitting data. On the other hand, attaining of wide coverage area and dense sensor deployments with low-cost are also required in IoT solutions.

5) SUSTAINABILITY

Since the network of smart cities based on IoT system may include billions of devices, it is highly possible to encounter with several types of failures stemming from network failures/latencies and natural disasters. Apparently, this could adversely affect the functionality of the IoT system. Therefore, precision and reliability of IoT environments should be assured through a sustainable failure management. However, installing and implementing of such mechanism is too costly for large-scale applications.

6) INVESTMENT

In each of the aforementioned challenges, it is clear that the design, implementation, and maintenance of a smart city require high cost to achieve higher efficiency. This indeed increases the burden on municipal budgets. In order to ease this load, massive investment should be provided by the private sector companies. However, this can be accomplished only if the innovative solutions are developed within the boundaries of existing software and hardware architectures.

III. LOW-COST IoT WIRELESS TECHNOLOGIES FOR SMART CITIES

A smart city based on IoT concept is expected to include several numbers of devices in the network. Particularly, the heterogenous network environment and huge data access result in some important issues like spectrum resource, bandwidth efficiency, and security concerns which have been addressed in [33], [34] that provide promising solutions for handling these issues. On the other hand, to improve the performance of IoT networks, an aggregated traffic modeling approach [9] could be adopted in order to ensure the interconnection between these devices or applications. This approach enables huge number of IoT devices to share the data with the help of a gateway that can be operated by any of wireless technologies for short-range and wide-range data transmission. However, it is necessary to concern some certain requirements to achieve low-cost communication as described in Section II.B4. Based on these requirements, in this section, only some of the common IoT wireless technologies operating in ISM bands are briefly introduced.

A. BLUETOOTH LOW ENERGY

Bluetooth Low Energy (BLE) is short-range wireless technology operating at 2.4 GHz frequency band. It enables low-power communication between the devices due to its shorter wavelength radio signals. Originally, Bluetooth was designed for Star network which limits the coverage range. Thus, it is appropriate to use for point-to-point, single-link applications. Recently, the latest versions of BLE (BLE 5.0-5.1) have adapted the Mesh network topology with its solutions [35], [36].

B. ZigBee

ZigBee is another short-range wireless communication technology based on 802.15.4 standard that operates at 2.4 GHz. To extend its coverage, it is generally deployed in Mesh network. However, the Mesh configuration adversely affects its power-efficiency. Still, when comparing with BLE, it can achieve higher data rates. It is generally used in various smart city applications such as monitoring of wireless networks, logistics, traffic management, and smart lightening [17], [18].

C. SigFox

SigFox provides a LPWAN technology that uses ultra-narrow band (UNB) spectrum channel for data transmission. In this technology, IoT devices transmit the data to the SigFox gateways. Its network has a Star topology where these gateways are able to communicate with SigFox cloud. Since the data transmission is low, this technology enables IoT devices to reduce the energy consumption. Besides, the coverage can achieve a more extended range. In rural environments its coverage is 30 to 50 km whereas in urban environments the coverage is extended from 3 to 10 km. With recent developments, it supports both unidirectional and bidirectional communication. Currently, this technology can offer several benefits for many IoT solutions in smart cities. For this reason, SigFox-based networks have been built in several cities, and currently operating in many countries in the world [10], [12].

D. LoRa

LoRa is a well-known LPWAN radio technology in today's competitive IoT market. It provides several advantages like reducing device cost, enhancing network capacity, and increasing devices' battery life. Its physical layer modulates the signal in sub-GHz band using chirp-spread-spectrum (CSS) modulation. This yields to extend the coverage range, in order of 5 Km and 15 Km in urban and rural environments, and to endure the environmental obstacles/interferences. At MAC layer, it uses LoRaWAN protocol to enable networking. LoRaWAN uses Star topology where the central node is considered as a gateway. This increases the devices' battery lifetime especially when long-range connectivity is desired. As the network architecture is designed to service large number of end devices (nodes), its deployment is simple and cost-effective. Nowadays, it has employed in many IoT implementations for smart cities [13], [14].

IV. AN ALTERNATIVE LOW-COST IoT WIRELESS TECHNOLOGY: IQRF

In addition to technologies mentioned in the previous section, IQRF technology, which has recently developed for wireless connectivity, offers low-cost wireless solutions for smart cities. In this section, an overview of IQRF technology and its actual and potential usage in smart city applications is presented. Its potential benefits over relevant technologies in low-cost communication aspect are also discussed by making theoretical comparisons.

A. A BRIEF INTRODUCTION TO IQRF TECHNOLOGY

IQRF is a technology/platform which includes transceivers, gateways, development tools, protocols, and supporting services. It provides reliable, low-power, low-speed, and low-data wireless connectivity in sub-GHz ISM bands (433MHz, 868MHz, and 916MHz). The coverage range extends from tens to hundreds of meters. However, the range could be extended up to several kilometers in certain conditions. Thus, it can be easily used for different application domains where a wireless transfer from any electronic equipment to a wireless network is required. It is based on packet-oriented communication. Using IQRF technology is extremely simple, and it is ideal to implement IoT.

Initially, IQRF technology was used for providing simple building automation system [22]. However, over the past ten years, the technology has been noticeably developed to become an alternative to other technologies in the challenging market. Accordingly, preliminary studies have been started to take place in the literature for telemetry [23], automated meter reading/smart meters [24]–[26], wireless sensor networks [27], and smart homes [28]. On the other hand, although there are plenty of commercial solutions available in the market, case studies utilizing IQRF technology in the

TABLE 1. List of existing experimental studies with IQRF.

	[22]	[28]
Functionality	*NA*	Temperature measurement
Application Area	Smart Grid, Smart City, Smart Home	Smart Home
# Nodes	5	20
Measurement Environment	a) Indoor (10 m × 6 m sized room). b) Outdoor - open space (Max. communication range is 1120 m). c) Outdoor - urban area (Max. communication range is 115 m).	A building environment
Operating Frequency	868 MHz	868 MHz

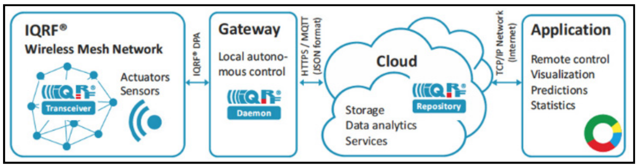

FIGURE 3. A typical design of IoT application with IQRF network.[2]

field of IoT for smart city solutions are still considerably limited [29], [30]. Moreover, among the studies mentioned above, only few experimental studies consider the appropriate measurements to assess the implementation of IQRF technology [22], [28]. In [22], simulations and real experimental measurements have been conducted in the selected indoor and outdoor scenarios (open space & urban area). In the simulations, the received signal strength has been predicted for each scenario and then compared with the experimental measurements to discuss the advantages and limitations of the IQRF technology. In [28], a simple implementation of temperature measurement in smart homes is presented. With basic IQRF components, a simple network has been built-up, and experimentally tested. Measurements have been also compared with simulation results to evaluate the received signal strength in certain scenarios. As a summary, the experimental setups used in these studies are presented in Table 1.

The main reason of limited studies could be linked with the fact that researchers are not aware about the use of IQRF technology in smart city development. To increase the awareness, the following sub-sections is devoted to present the technical details of IQRF technology. This may provide to review its potential usage in IoT-based smart cities in a better way.

B. DESIGNING OF IoT APPLICATION WITH IQRF

To provide an effective IoT solution, a typical design of IQRF is shown in Fig. 3 which is consisted of the IQRF network, gateway, cloud, and mobile application. These components are summarized in the following.

1) IQRF NETWORK

IQRF technology uses its own Mesh network topology (IQMESH). In the network, data packets are delivered through routing mechanism which may provide to overcome some drawbacks of Star topology in terms of reliability, robustness, and the range. The key element of the network is the IQRF transceiver (IQRF-TR) module which is a tiny board including an eight-bit microcontroller unit (MCU) to execute a built-in operating system (OS) for organizing the transceiver operations.

The specific functionality is implemented to the IQRF transceiver in two different application approaches. The first approach is based on a user application layer under OS which uses predefined OS functions. Functionality of this approach can be programmed in C language. However, this approach is not supported by IQMESH networks. The second approach based on the three-layer IQRF architecture where there is a hardware profile (HWP) which is a ready to use software application plug-in. All device resources and services can become accessible through the HWP. In fact, HWP implements device peripheral access (DPA) above the OS which is a simple byte-oriented protocol. Thus, programming is not required, and functionality is achieved by a simple control through a data flow. Yet, programming is possible and optional by means of custom DPA handler in C language. This can be accomplished by extending HWP through a programming. It should be noted that this is a unique approach for RF transceivers in world-wide. It is also worth noting that all IQRF-TRs support both OS and DPA approaches.

Therefore, two different RF communication modes can be implemented by IQRF: (a) non-networking, (b) networking. In non-networking mode, networking features are not supported. It is suitable for two or more peer-to-peer devices. Within a maximum achievable range, the data packets are accessible for all devices in this case. In networking mode, there is a one coordinator node which manages the Mesh network containing up to 239 nodes for a single network. In such a network, the data packets are accessible for the nodes that are addressed. Every node in the network can be served as a coordinator or a common node. Thus, up to 65000 devices can work in a single network. Besides, every node is able to route on the background. As a consequence, up to 240 hops per packet is supported. Packets routes can be found and created automatically as virtual routing structure with the help of the discovery option. With the help of discovery option, routing paths can be found automatically through the redundant paths in the Mesh network.

2) GATEWAY

IQRF nodes can be directly controlled by a cloud server. To do this, a gateway is required to use. It provides an interface between the IQRF network and other networks by enabling connectivity to the internet. Wi-Fi, GSM, and ethernet

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[2] https://www.iqrfalliance.org/technology

gateways are the types of gateways that have been developed by the IQRF alliance so far. These gateways include a sensor node which is programmable by the user. Indeed, the sensor node inside of a gateway acts as a coordinator of the other nodes in the network. It then allows for data collection, accessing, and device controlling in the network.

It is also possible to create an IQRF gateway by utilizing an open source package, IQRF gateway daemon. The IQRF gateway can be then implemented from a Linux-based machines like Raspberry Pi [38]. Besides, IQRF software development kit (SDK) is also provided to support machines without any operating system such as single-board computers (Arduino, chipKIT, etc.), standalone MCUs, and any device with MCU.

3) CLOUD AND APPLICATION

The IQRF cloud is a server that provides Plug and Play service between the users and the IQRF network. There is a client-server type of communication. Once the data is logged in the gateway, it is directly uploaded to the server. The data on the cloud can be reached through web and application program interface (API). By means of API, users can have access to the cloud for complex monitoring by utilizing high-level tools including PHP, database, and JavaScript. For configuration or simple monitoring, web interface can be used.

C. COMPARISON WITH OTHER TECHNOLOGIES

In this sub-section, it is intended to review potential benefits of IQRF over relevant technologies introduced in Section III. To do this, comparisons are made by considering the requirements to achieve low-cost communication mentioned in Section II.B2. In fact, IQRF technology has been theoretically compared with LWPAN technologies in the literature [39], [40]. However, it is already known that IQRF technology also belongs to short/medium range networks such as Wireless Personal Area Network (WPAN) and Wireless Local Area Network (WLAN). For this reason, as discussed in [22], it is also needed to compare IQRF with the other technologies belonging to these networks. Therefore, in this study, the comparisons were made according to short/medium and long communication range wireless technologies as listed in Table 2 and Table 3, respectively. The parameters used in the comparisons were selected from technical documentations of the technologies and various sources given in [6], [9], [21], [22], [39]–[41]. In the following, IQRF technology is compared with both short/medium and long communication range wireless technologies in terms of these parameters.

TABLE 2. Comparison between IQRF and short/medium range IoT wireless technologies.

	BLE	ZigBee	IQRF
Operating Frequency	2.4 GHz	2.4 GHz	433, 868, 916 MHz
Data Rate (kb/s)	2000	250	20
Max. Payload (byte)	251	128	64
Max. Range (free-space)	400 m	300 m	1 km
Modulation	GFSK	BPSK, OQPSK	GFSK
Topology	Mesh	Star, Mesh, Tree	Mesh
Latency (ms)	6	16	400
Power Consumption (max.)	15 mA	30 mA	15 μA
Max. Transmission Power (dBm)	20	20	11
Nodes per Gateway	65×10^3	65×10^3	65×10^3 (OS), 240 (DPA)
Battery Lifetime (years)	1 – 2	2	5 – 10

TABLE 3. Comparison between IQRF and long range IoT wireless technologies.

	SigFox	LoRa	IQRF
Operating Frequency	868 MHz, 902 MHz	433, 868, 780, 915 MHz	433, 868, 916 MHz
Data Rate (kb/s)	0.1	0.3 – 37.5	20
Max. Payload (byte)	12	243	64
Max. Range (free-space)	50 km	15 km	1 km
Modulation	DBPSK, GFSK	CSS	GFSK
Topology	Star	Star	Mesh
Latency (ms)	> 1000	> 1000	400
Power Consumption (max.)	1 mA	1 mA	15 μA
Max. Transmission Power (dBm)	27	14	11
Nodes per Gateway	10^6	10^4	65×10^3 (OS), 240 (DPA)
Battery Lifetime (years)	5 – 10	5 – 10	5 – 10

1) NETWORK DESIGN AND COVERAGE

For short/medium range IoT wireless technologies, Mesh network topology is the common topology of BLE, ZigBee, and IQRF as stated in Table 2. Hence, both technologies enable to deploy a great number of nodes which are usually employed for control and monitoring applications such as home and industrial automation. Among these technologies, as mentioned in Section III, BLE and ZigBee use 2.4 GHz ISM band. However, the number of technologies operating at this band are increasing day by day. In this regard, the 2.4 GHz band becomes overcrowded which results in interference and coexistence problems. In this case, higher packet loss rates are expected to be occurred. This may then adversely affect the system performance. The efficiency of a system based on the technologies operating at 2.4 GHz band is also sensitive to obstacles like human bodies, walls, trees in the environment because of shorter wavelengths [42]. Therefore, the maximum achievable communication range is limited. Due to these drawbacks, the sub-GHz band is ideal for IoT applications as it provides especially long-range communication. In this context, the frequencies used by IQRF technology (433, 868, and 916 MHz) are more suitable for mixing indoor/outdoor applications because IQRF signals can penetrate obstacles such as walls and furniture, or cover large outdoor areas easier than BLE or ZigBee. Thus, IQRF offers greater coverage when compared to BLE and ZigBee technologies.

Based on Table 3, when compared to long range IoT wireless technologies like SigFox and LoRa organized in a Star topology, IQRF is the one that only uses Mesh topology. Using Mesh topology brings some advantages over Star topology. First of all, the failure of a link does not directly affect the whole system. This is due to the fact that devices can exchange the data between each other in Mesh topology, and in case of a link failure, the device tries to make connection with its any of neighbors. As devices can only communicate with the gateway or base station in Star topology, losing the connection between the device and the gateway could cause the inoperability of the entire system. When it comes to natural disasters which may destroy some part of the link, the rest of the network in Mesh topology could be still worked same as long as one of the network components is connected to the Internet. On the other hand, the main disadvantage of Mesh topology is the limited transmission range. For this reason, as can be seen in Table 3, IQRF is not completely suitable for long range IoT applications. However, longer communication ranges (hundreds of meters range per hop in the outdoors) can be achievable with the precise antenna arrangement. Thus, wide coverage could be reached at certain conditions. Although LoRa and SigFox offer important advantages particularly in communication range, very long radio links between the nodes and the gateway could be a disadvantage. Indeed, these technologies could be vulnerable to obstacles in the propagation path between the node and the gateway, which reduces signal levels. Yet, the problems of Star topology associated with RF range such as RF noise or interferences could be fixed, as data packets are conveyed in IQRF Mesh network through routing mechanism.

2) ENERGY EFFICIENCY

In addition to better propagation characteristics at sub-GHz frequencies that provides extended ranges, lower current consumptions can also be obtained when compared to 2.4 GHz band technologies. This is shown in Table 2 from where it is clear that IQRF offers better energy consumption than BLE and ZigBee. Moreover, due to their operating frequency, BLE and ZigBee technologies suffer from the effective transmit power limitations. Thus, energy demands adversely affect the battery lifetime of these technologies. As provided in Table 2, device battery lifetime of IQRF is higher than devices based on other technologies. It should be also noted that low-power consumption is essential for several systems where tracking and monitoring assets are needed. This may make IQRF more suitable for use in short-range smart tracking and monitoring applications from the logistics and construction sectors.

As for long-range IoT wireless technologies (Table 3), one of the important factors that affects the energy efficiency is the network topology. The primary advantage of Mesh topology used in IQRF is the lower energy consumed while relaying a packet. The reason is that the nodes can only connect to closest node with shorter radio links in a Mesh network. As described previously, the nodes can only communicate with the gateway in Star topology. Then, in some cases, especially when the radio link between the node and the gateway is very long, more transmission power is required to cover the node or the gateway. However, nodes in Star topology can be in idle or sleep mode during the data transmissions. This, in fact, helps to conserve the total amount of energy which is consumed by each node in the network. Therefore, the nearly identical life expectancy of the batteries for both technologies could be achieved.

3) LATENCY

It is necessary to know latency expectations of an IoT application when selecting an appropriate IoT technology. To do this, the relationship between the latency and energy consumption should be concerned, as there is a trade-off between these IoT factors. Hence, when short/medium range IoT technologies are compared in terms of latency as provided in Table 2, BLE and ZigBee have the advantage of low latency due to the higher energy demands. For this reason, IQRF could only be used in short/medium range IoT applications which are insensitive to the latency.

On the other hand, as can be seen in Table 3, IQRF provides lower latency when compared to SigFox and LoRa due to its low energy consumption. For this case, contrary to comparison in short/medium range IoT wireless technologies, choosing IQRF could be a good option for long range IoT applications that require low latency.

4) PAYLOAD AND DATA RATE

As it is already known, the IoT wireless technologies are developed for achieving low power consumption. This results in limitations for the data rate. However, as presented in Table 2, short range IoT technologies, BLE and ZigBee, provide medium/high data rates. This can be associated with the higher energy consumption which also adversely affects battery lifetime as discussed before. Furthermore, it is also necessary to review payload size being crucial for maximizing spectral efficiency. From Table 2, it is obvious that BLE enables more higher transmission of data than the other short/medium range technologies. Note that the payload size is directly related to the latency. Specifically, the payload size could be minimized, if the latency is reduced. Hence, although IQRF has drawbacks in terms of data rate and payload when compared to BLE and ZigBee, it could still be an optimum technology for short-range IoT applications where the large amount of data to be sent is not required and battery lifetime is a critical factor.

TABLE 4. Cost comparison between IQRF and short/medium range IoT wireless technologies.

	BLE	ZigBee	IQRF
Deployment Cost (min.)	100$ (a gateway)	50$ (a gateway)	80$ (a gateway)
Module Cost (max.)	5$	5$	8$

TABLE 5. Cost comparison between IQRF and short/medium range IoT wireless technologies.

	SigFox	LoRa	IQRF
Deployment Cost (min.)	400$ (a base station)	100$ (a gateway)	80$ (a gateway)
Module Cost (max.)	5$	5$	8$

When long range IoT technologies are compared in terms of data rate and payload, it is clear that Sigfox offers the lowest payload size and data rate (Table 3). Even though LoRa offers maximum data rate and payload size, IQRF also allows high transmission of data and provides high/moderate data rates. This makes IQRF proper and alternative technology to be used in long range IoT applications demanding high data transmission rates.

5) COST

Evidently, while comparing IoT technologies, another important IoT factor is the total cost that needs to be considered. Basically, the total cost is comprised of spectrum cost, deployment cost, and module (device) cost. In this study, as it is only intended to compare IoT wireless technologies using unlicensed bands, cost comparison between the technologies are made in terms of deployment and module cost as listed in Table 4 and Table 5. To do that, various popular e-commerce websites and some sources given in [43], [44] have been utilized.

In Table 4, the costs of IQRF and short/medium range IoT technologies (BLE, ZigBee) are presented. According to the given table, ZigBee offers relatively cost-effective option. This indicates that the cost of IQRF could be a slight drawback when compared to ZigBee. When the cost of IQRF is compared with long range IoT technologies (SigFox, LoRa) as in Table 5, IQRF and LoRa are the technologies that could provide cost-effective solutions for long range IoT applications. Again, in addition to its several benefits, it has also advantage in terms of cost that makes it alternative to other LPWAN technologies.

D. DISCUSSION

Based on the comparison results, IQRF could be a proper technology when some of the basic IoT factors like coverage, low energy consumption, and even cost are concerned in short range IoT applications such as smart home or smart health typically provided indoors. It could be also a reasonable alternative when low energy consumption, low latency, high data transmission, and cost factors are concerned in long range IoT applications such as smart controlling, monitoring, and surveillance systems provided outdoors. Although IQRF technology offers several advantages, we believe that selecting the convenient technology in the field of IoT for smart city solutions still depends on the application requirements. For this reason, the technologies compared in this study should be quite complementary to each other in the concept of IoT-based smart city. However, especially when LWPAN technologies are concerned in IoT environment, the technology coexistence becomes a significant issue that should be addressed. As mentioned in [39], it severely degrades the performance of IQRF, Sigfox, and LoRa technologies particularly operating at 868 MHz. Therefore, it is necessary to provide novel approaches for enabling different technologies to coexist on the same channel. Moreover, security and mobility are other important factors that should be taken into account in IoT applications. As the main purpose is to review potential benefits of IQRF technology over relevant technologies in terms of low-cost communication requirements (Section II.B4), security and mobility issues have not been addressed in this study. Yet, it is still necessary to review IQRF technology in terms of security and mobility aspects to provide additional arguments about the technology. Moreover, it is also necessary to support and improve the findings of this study by experimental studies.

V. STREETLIGHT CONTROLLING USING IQRF TECHNOLOGY AT GJØVIK MUNICIPALITY: USE-CASE

The municipality of Gjøvik in Norway has decided to be at the forefront of using smart/technological solutions, and thus has prioritized the smart-city project. The municipality and Norwegian University of Science and Technology (NTNU) at Gjøvik are today working together on an initiative that will benefit both the inhabitants and the environment. The goal is to offer a concrete commitment for becoming ''The University City of Gjøvik - a leader in sustainable growth and development''. To achieve this goal, research efforts by the authors, who are the members of Smart Wireless Systems team at the Department of Electronic Systems (IES) in NTNU, are currently underway in the context of Gjøvik smart city project. In the project, it is aimed to utilize IQRF technology for IoT-based smart city applications. In this section, the use of the IQRF technology in streetlight controlling supported by Gjøvik Municipality is presented.

For smart cities, one of the most demanded technologies is smart streetlighting system which offers several benefits in many aspects. It enables to achieve low-cost public lighting and to reduce the energy consumption. Additionally, it improves safety for both drivers and pedestrians. It also allows remote management system to control streetlights. Thus, it is aimed to build an intelligent streetlight control system using IQRF technology as it offers simple implementation. For a better view of the system, the fol-

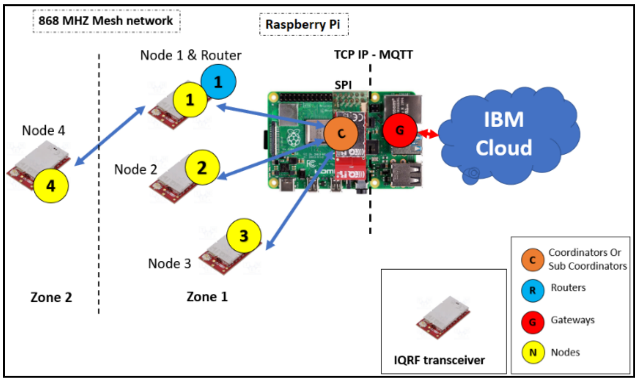

FIGURE 4. The network architecture.

lowing subsections are devoted to describing the system from both a network and a real implementation point of view.

1) NETWORK ARCHITECTURE

The network architecture is illustrated in Fig. 4. It is composed of four levels: a) end nodes, b) coordinator, c) gateway, and d) cloud service.

The first level includes the end nodes which are IQRF-TR modules that acquire field information such as the light intensity, ambient temperature and relative humidity. Each node has an embedded RF SPIRIT1 which is a very low-power Sub-1 GHz RF transceiver. Note that, the end nodes can also send data to the other end nodes which are out of the coordinator range (Zone 2).

In the second level, a privileged IQRF-TR module is deployed as the coordinator node. The coordinator node holds the IQRF sensor network (IQMESH) configuration and routing information. Moreover, it interrogates the end nodes and controls the communication.

The third level corresponds to IQRF gateway created by IQRF gateway daemon. IQRF gateway is implemented from a Linux-based machine, Raspberry Pi. Here, the coordinator node is mounted on a Raspberry Pi by using an adapter KON-RASP-01 which is an IQRF product used for connecting IQRF-TR to Raspberry Pi.

In the last level, IBM Watson IoT platform, as one of IBM cloud services, is used to control and monitor the connected nodes in the network. The gateway sends data to the cloud by using Message Queuing Telemetry Transport (MQTT) messaging protocol. Then, it is possible to manage the connected nodes in the network with an online dashboard or an API from IBM.

At each level, the architecture involves different types of communication technologies. Specifically, the end nodes are connected to the coordinator by means of IQRF technology. The coordinator node is connected to the Raspberry Pi by Serial Peripheral Interface (SPI). Besides, the connection between the Raspberry Pi and the cloud is ensured by TCP/IP protocol.

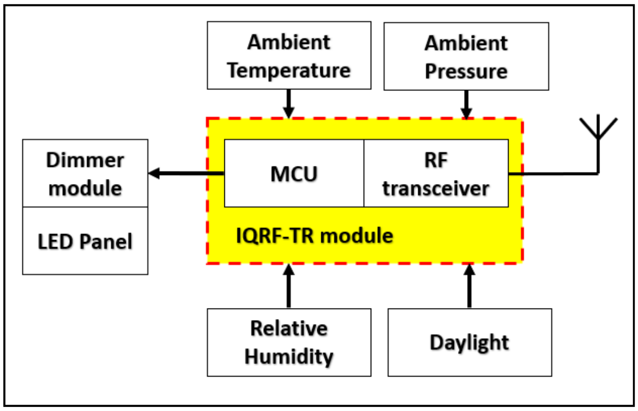

FIGURE 5. The block diagram of a light controller.

FIGURE 6. The attached IQRF-TR on the streetlight.

2) SYSTEM ARCHITECTURE

The smart component of the system is a light controller integrated into a LED streetlight. As shown in Fig. 5, it is composed of an IQRF-TR module, a dimming module, a photosensor, an ambient temperature sensor, a relative humidity sensor, and a LED panel. Here, photosensor measures the daylight intensity, and is used as a feedback element to control the light. Moreover, ambient temperature and relative humidity sensors are used in the system to measure the environmental parameters. Before the implementation, IQRF-TR modules have been attached on the streetlights as shown in Fig. 6.

As described in the previous subsection, the streetlights are connected to each other in a Mesh network. To provide connection between the streetlights and IBM Watson IoT platform, the IQRF gateway daemon software is used. It is installed on a Raspberry Pi board running on the Raspbian operating system. Then, the system dashboard is created IBM Watson IoT platform to measure the light dimming percentage, the light intensity, and the other environmental parameters. In order to program the entire system, a flow-based development tool for visual programming (Node-RED) that enables the accessing of information from the Internet is used. Fig. 7 shows the system architecture for controlling three streetlights used in the system implementation.

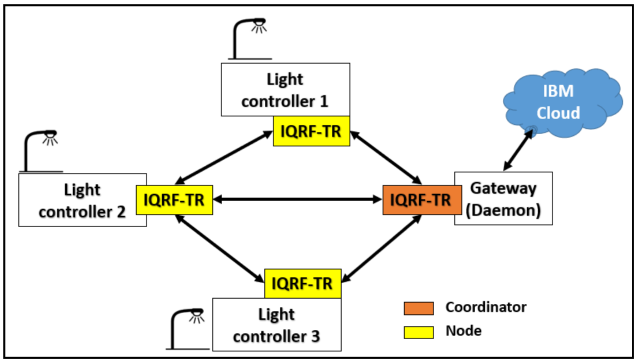

FIGURE 7. A system architecture for controlling the streetlights.

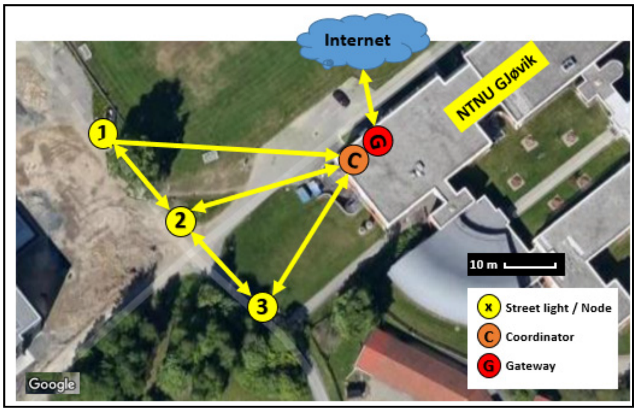

FIGURE 8. NTNU Gjøvik campus - deployment of the nodes and the gateway (top-view).

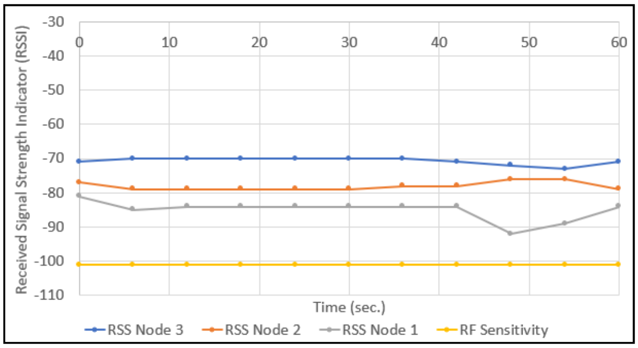

FIGURE 9. Comparison of RSSI values and IQRF-TR sensitivity.

TABLE 6. RSSI measurements of the streetlight network.

Time (min)	RSSI Node 1 (dBm)	RSSI Node 2 (dBm)	RSSI Node 3 (dBm)
0	-71	-77	-81
6	-70	-79	-85
12	-70	-79	-84
18	-70	-79	-84
24	-70	-79	-84
30	-70	-79	-84
36	-70	-78	-84
42	-71	-78	-84
48	-72	-76	-92
54	-73	-76	-89
60	-71	-79	-84
avg RSSI (dBm)	**-70.7**	**-78.1**	**-85.0**

3) SYSTEM IMPLEMENTATION

Before the implementation, three streetlights (nodes), a coordinator node, and a gateway were deployed at the NTNU Gjøvik campus as shown in Fig. 8. The distance between node 1, 2, 3, and the coordinator node was 60 m, 38 m and 28 m, respectively. Moreover, IQRF-TRs (TR-72DA[3]) attached to the top of the street pole were 10 m above the ground to establish Line-of-Sight (LOS) communication links.

In the implementation, it has aimed to analyze the stability of the network. To this end, all nodes have been deployed within the coordinator range like in Zone 1 shown in Fig. 4. Here, the coordinator node and the gateway were deployed at the nearest building to the network. In order to ensure that the system is fulfilling its aim, Received Signal Strength Indicator (RSSI) which is one of the parameters of radio transmission has been checked at regular time intervals.

The value of the RSSI has been measured at every 6 minutes in an hour and by each one of the three nodes. The measured RSSI values are listed in Table 6. The values are also compared with the RF sensitivity of the used IQRF-TR as shown in Fig. 9. Theoretically, the RF sensitivity can be considered as a reference indicating that the minimum magnitude of the RSSI of each node must be greater than the specified sensitivity value. According to the results, it is clear that the values are sensitive to the measurement range as expected. It has also observed that the lowest RSSI values are obtained for Node 1 as around -85 dBm. Still, all recorded values are below the RF sensitivity which proves the consistency of the implemented system.

In is worth noting that the effects of the obstacles/interferences near the propagation link have not been taken into account in the implementation. As a future work, propagation effects on the system performance will be evaluated by considering various environmental conditions. Additionally, RSSI measurements will be expanded with additional measurements in greater distances with more nodes for competing existing technologies.

VI. ONGOING RESEARCH BASED ON IQRF TECHNOLOGY FOR THE DEVELOPMENT OF GJØVIK SMART CITY PROJECT

In this section, current research efforts in the context of Gjøvik smart city project are discussed. It should be noted that these studies are still in the developing phase and expected to be completed in the near future.

A. SMART WASTE MANAGEMENT

Smart waste management systems have several advantages to make the environment healthier. By means of these systems,

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[3] https://iqrf.org/weben/downloads.php?id=337

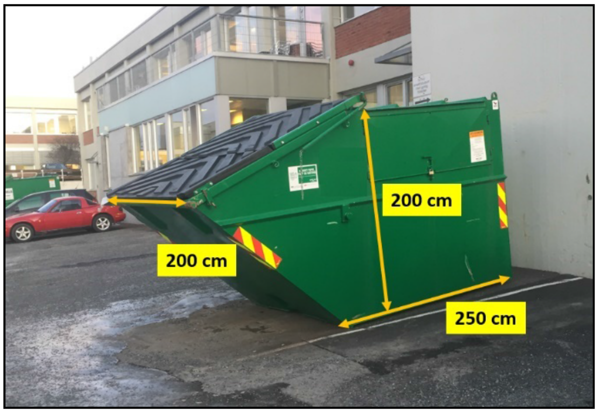

FIGURE 10. A garbage container in Gjøvik.

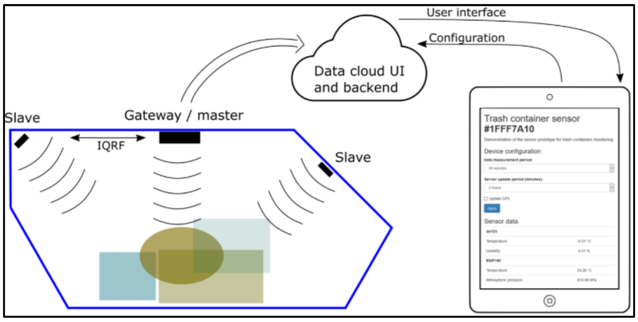

FIGURE 11. Smart waste management system diagram.

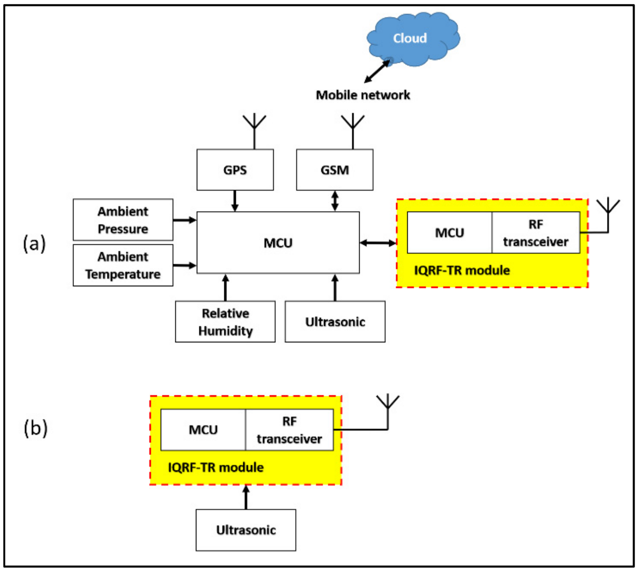

FIGURE 12. Sensor architecture: (a) Master, (b) Slave.

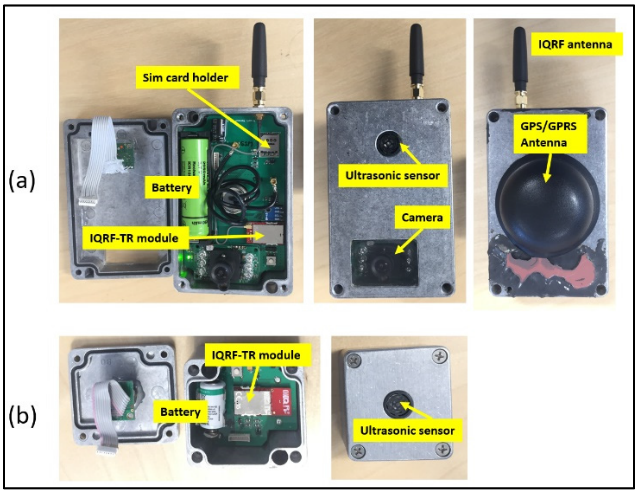

FIGURE 13. Prototypes for the sensors: a) Master, b) Slave.

the routes followed by the waste collection vehicles belonging to municipalities could be optimized. This may reduce not only urban traffic but also fuel consumption of the waste collection vehicles. As an example, in Gjøvik, big and stationary garbage containers shown in Fig. 10 are placed in public places. A waste collection vehicle tracks container's location even if the container is not fully filled. The missing information about the fill-level of garbage container makes this operation costly and time consuming. Thus, our main motivation is to develop a novel smart waste management system by making use of IQRF technology.

The system is typically comprised of one master and two slave sensors to measure the fill-level of the container as shown in Fig. 11. Both master and slave sensors are placed in the same container to provide reliable information regarding the fill-level of the containers. The architectures for both master and slave sensors are shown in Fig. 12.

As shown in Fig. 12 (a), the master sensor contains pressure, temperature, and humidity sensors to measure the typical environmental parameters inside the container. It also contains a Global Positioning System (GPS) module sending information about the location of each container for the sake of easy tracking of containers by the control service. Moreover, to detect the fill-level of the garbage, there is a camera used in the master sensor. In addition to these, it contains Global System for Mobile (GSM) module for connecting the system to the mobile network, and then to the cloud. In this case, the master sensor acts as a gateway transferring all gathered information to the cloud.

On the other hand, both sensors contain a high-performance ultrasonic ranging module which uses sound beam to detect distant objects from 1 cm to 4 m away. Indeed, this range is enough to detect the fill-level of the garbage when the size of a regular garbage is considered: 200 cm (width) × 200 (height) × 250 cm (base). Further, both sensors use a battery for their power source. Most of the components consuming power are activated and deactivated when needed by the software.

Fig. 13 shows the first prototypes built for the sensors. It again should be noted that the designing of these sensors is still in the development and testing phase. Currently, our team is mainly focused on enhancing the ability of these sensors to remove the disadvantages or challenges encountered in a typical smart waste management system. In this context, one

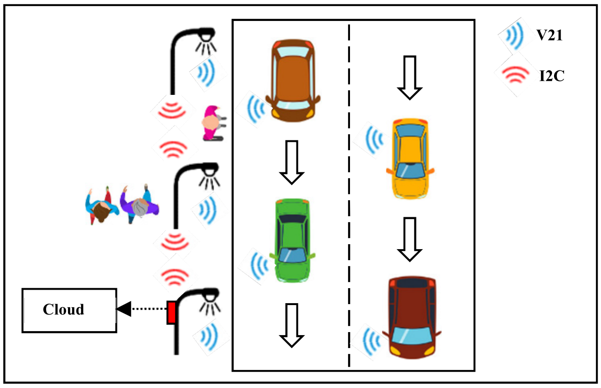

FIGURE 14. Networking via IoT technology for V2I and I2C.

of the important tasks is to provide new case for the sensors to overcome humidity challenges for Infrared Camera (IR) camera. Another is to measure the trash level continuously as the current version only allows for measuring the level in certain intervals. Hence, the future version of the sensor is expected to enable real-time monitoring of containers. Besides, the other task is to integrate odor sensor/smell detector as an electronic nose into the sensors. The system will also be designed to be fully functional within the temperature range from −40 °C to +85 °C, since the temperature in Norway drops dramatically and can reach −25 °C in some cases.

B. SAFE SMART TRAFFIC

Driving conditions in the dark winter days in Norway are rather challenging and may cause several fatalities along with the accidents in each year. However, it is expected that these undesired events could be avoidable if IoT-based vehicle to infrastructure (V2I) communication solution is implemented as a part of smart city. With the advantages of the recent IoT wireless technologies, it is possible to allow roads, cars, and city infrastructure to communicate and share information that could make roads safer. Therefore, our focus is to develop a prototype IoT solution that improves traffic safety using V2I communication based on COMLIGHT AS,[4] IQRF technology and Telenor[5] for mobile network and cloud. The main concept is illustrated in Fig. 14.

IQRF technology offers lightweight seamless networking capabilities to vehicles and infrastructure enabling the integration of a multitude of sensors into a single system. In this context, authors are currently investigating the safety benefits brought by communication between onboard sensors embarked on vehicles and road infrastructure such as light poles, traffic lights, and parking places implemented through the IQRF technology. Currently, authors are also working on the limitations of the system. In the near future, it is planned to scrutinize the most important safety information to communicate between vehicles and infrastructure at the testing area in Gjøvik. Next, the requirements and infrastructure elements will be determined to design such ad-hoc network. Furthermore, small-scale experiments will be conducted to provide representative and scalable information.

VII. CONCLUSION

IQRF is one of the most promising wireless Mesh technologies in the IoT market. However, many researchers are not aware of its benefits. Therefore, to increase the awareness about IQRF technology for smart city development, this study provides a whole picture regarding the current low-cost wireless technologies for IoT in smart cities as well as the benefits of IQRF over these technologies based on theoretical comparisons. The comparison results have shown that IQRF allows lower energy consumption than other IoT wireless technologies. However, it does not address the requirements of high data rate and low latency in short/medium range wireless communication applications. Besides, it is also possible to resolve the problems encountered in Star topology networks by means of IQMESH. Still, selecting the convenient IoT wireless technology for smart city solutions may depend on the application requirements. For this reason, a new standard is necessary to make the technologies interoperable and complementary to each other at the gateway level.

On the other hand, in this study, only the requirements to achieve low-cost communication low-power connectivity have been concerned. Yet, apart from this, there are other challenges and requirements in adopting IoT to smart cities as discussed in Section II-B. Therefore, future studies will address these challenges for the development of a sustainable IoT eco-system for smart municipality of Gjøvik in an ongoing project. It is also worth noting that currently independent research groups have been working on enhancing the implementations some of which are briefly introduced in this study. In the near future, more comprehensive studies involving case studies developed in the ecosystem are expected to be provided in detail.

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REFERENCES

[1] M. Derawi and H. Zhang, "Internet of Things in real-life—A great understanding," in *Proc. Wireless Commun., Netw. Appl.*, Shenzhen, China, 2015, pp. 337–350.
[2] L. Sánchez, L. Muñoz, J. A. Galache, P. Sotres, J. R. Santana, V. Gutierrez, R. Ramdhany, A. Gluhak, S. Krco, E. Theodoridis, and D. Pfisterer, "SmartSantander: IoT experimentation over a smart city testbed," *Comput. Netw.*, vol. 61, pp. 217–238, Mar. 2014.
[3] P. Sotres, J. R. Santana, L. Sanchez, J. Lanza, and L. Munoz, "Practical lessons from the deployment and management of a smart city Internet-of-Things infrastructure: The SmartSantander testbed case," *IEEE Access*, vol. 5, pp. 14309–14322, 2017.
[4] V. Gutierrez, "Empowering citizens towards the co-creation of sustainable cities," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 668–676, Apr. 2018.
[5] A. Zanella, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

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[4] https://www.comlight.no/
[5] https://www.telenor.no/

[6] E. Ahmed, I. Yaqoob, A. Gani, M. Imran, and M. Guizani, "Internet-of-Things-based smart environments: State of the art, taxonomy, and open research challenges," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 10–16, Oct. 2016.

[7] H. Arasteh, V. Hosseinnezhad, V. Loia, A. Tommasetti, O. Troisi, M. Shafie-khah, and P. Siano, "IoT-based smart cities: A survey," in *Proc. IEEE 16th Int. Conf. Environ. Elect. Eng. (EEEIC)*, Florence, Italy, Jun. 2016, pp. 1–6.

[8] S. Talari, M. Shafie-khah, P. Siano, V. Loia, A. Tommasetti, and J. Catalão, "A review of smart cities based on the Internet of Things concept," *Energies*, vol. 10, no. 4, p. 421, 2017.

[9] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, "Internet-of-Things-based smart cities: Recent advances and challenges," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 16–24, Sep. 2017.

[10] B. Hammi, R. Khatoun, S. Zeadally, A. Fayad, and L. Khoukhi, "IoT technologies for smart cities," *IET Netw.*, vol. 7, no. 1, pp. 1–13, Jan. 2018.

[11] A. H. Alavi, P. Jiao, W. G. Buttlar, and N. Lajnef, "Internet of Things-enabled smart cities: State-of-the-art and future trends," *Measurement*, vol. 129, pp. 589–606, Dec. 2018.

[12] C. A. Medina, M. R. Perez, and L. C. Trujillo, "IoT paradigm into the smart city vision: A survey," in *Proc. IEEE Int. Conf. Internet Things (iThings) IEEE Green Comput. Commun. (GreenCom) IEEE Cyber, Phys. Social Comput. (CPSCom) IEEE Smart Data (SmartData)*, Exeter, U.K., Jun. 2017.

[13] Z. Huang and F. Yuan, "Implementation of 6LoWPAN and its application in smart lighting," *J. Comput. Commun.*, vol. 03, no. 03, pp. 80–85, 2015.

[14] Y. Chen and D. Han, "Water quality monitoring in smart city: A pilot project," *Autom. Construct.*, vol. 89, pp. 307–316, May 2018.

[15] K. Abas, K. Obraczka, and L. Miller, "Solar-powered, wireless smart camera network: An IoT solution for outdoor video monitoring," *Comput. Commun.*, vol. 118, pp. 217–233, Mar. 2018.

[16] C. Gomez, J. Oller, and J. Paradells, "Overview and evaluation of Bluetooth low energy: An emerging low-power wireless technology," *Sensors*, vol. 12, no. 9, pp. 11734–11753, 2012.

[17] M. S. Jamil, M. A. Jamil, A. Mazhar, A. Ikram, A. Ahmed, and U. Munawar, "Smart environment monitoring system by employing wireless sensor networks on vehicles for pollution free smart cities," *Procedia Eng.*, vol. 107, pp. 480–484, 2015.

[18] D. R. Naik, L. B. Das, and T. S. Bindiya, "Wireless sensor networks with zigbee and WiFi for environment monitoring, traffic management and vehicle monitoring in smart cities," in *Proc. IEEE 3rd Int. Conf. Comput., Commun. Secur. (ICCCS)*, Kathmandu, Nepal, Oct. 2018, pp. 46–50.

[19] I. Yaqoob, I. A. T. Hashem, Y. Mehmood, A. Gani, S. Mokhtar, and S. Guizani, "Enabling communication technologies for smart cities," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 112–120, Jan. 2017.

[20] G. Pasolini, C. Buratti, L. Feltrin, F. Zabini, C. De Castro, R. Verdone, and O. Andrisano, "Smart city pilot projects using LoRa and IEEE802.15.4 technologies," *Sensors*, vol. 18, no. 4, p. 1118, 2018.

[21] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 60–67, Oct. 2016.

[22] R. Fujdiak, P. Mlynek, L. Malina, M. Orgon, J. Slacik, P. Blazek, and J. Misurec, "Development of IQRF technology: Analysis, simulations and experimental measurements," *Elektronika Elektrotechnika*, vol. 25, no. 2, pp. 72–79, Apr. 2019.

[23] M. Pies, R. Hajovsky, M. Latocha, and S. Ozana, "Radio telemetry unit for online monitoring system at mining dumps," *Appl. Mech. Mater.*, vols. 548–549, pp. 736–743, Apr. 2014.

[24] P. Bazydło, S. Dąbrowski, and R. Szewczyk, "Distributed temperature and humidity measurement system utilizing IQMESH wireless routing algorithms," *Progress in Automation, Robotics and Measuring Techniques* (Advances in Intelligent Systems and Computing), vol. 352. Cham, Switzerland: Springer, 2015, pp. 1–9.

[25] P. Bazydło, S. Dąbrowski, and R. Szewczyk, "Wireless temperature measurement system based on the IQRF platform," in *Mechatronics-Ideas for Industrial Application* (Advances in Intelligent Systems and Computing), vol. 317. Cham, Switzerland: Springer, 2015, pp. 281–288.

[26] P. Martin and H. Radovan, "Use of IQRF technology for detection of construction inclination," in *Proc. 6th Int. Eurasian Conf. Math. Sci. Appl.*, Rhodes, Greece, 2016, Art. no. 480121.

[27] S. B. Wibowo, G. D. Putra, and B. S. Hantono, "Development of embedded gateway for wireless sensor network and Internet protocol interoperability," in *Proc. 6th Int. Conf. Inf. Technol. Electr. Eng. (ICITEE)*, Yogyakarta, Indonesia, Oct. 2014, pp. 1–4.

[28] V. Sulc, R. Kuchta, and R. Vrba, "IQRF smart house—A case study," in *Proc. 3rd IEEE Int. Conf. Adv. Mesh Netw.*, Venice, Italy, 2010, pp. 103–108.

[29] M. Pies and R. Hajovsky, "Monitoring environmental variables through intelligent lamps," in *Proc. Int. Conf. Mobile Wireless Technol.*, Kuala Lumpur, Malaysia, 2017, pp. 156–158.

[30] M. Pies and R. Hajovsky, "Using the IQRF technology for the Internet of Things: Case studies," in *Proc. Int. Conf. Mobile Wireless Technol.*, Kuala Lumpur, Malaysia, 2017, pp. 274–283.

[31] *Master Plan for Smart Sustainable Cities*, International Telecommunication Union, Focus Group, ITU-T Focus Group Smart Sustain. Cities, Geneva, Switzerland, May 2015.

[32] B. N. Silva, M. Khan, and K. Han, "Towards sustainable smart cities: A review of trends, architectures, components, and open challenges in smart cities," *Sustain. Cities Soc.*, vol. 38, pp. 697–713, Apr. 2018.

[33] M. Jia, D. Li, Z. Yin, Q. Guo, and X. Gu, "High spectral efficiency secure communications with nonorthogonal physical and multiple access layers," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 5954–5961, Aug. 2019.

[34] M. Jia, Z. Yin, D. Li, Q. Guo, and X. Gu, "Toward improved offloading efficiency of data transmission in the IoT-cloud by leveraging secure truncating OFDM," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4252–4261, Jun. 2019.

[35] S. Darroudi and C. Gomez, "Bluetooth low energy mesh networks: A survey," *Sensors*, vol. 17, no. 7, p. 1467, 2017.

[36] C. Jung, K. Kim, J. Seo, B. N. Silva, and K. Han, "Topology configuration and multihop routing protocol for Bluetooth low energy networks," *IEEE Access*, vol. 5, pp. 9587–9598, 2017.

[37] A. A. Veiga and C. J. B. Abbas, "Proposal and application of Bluetooth mesh profile for smart cities' services," *Smart Cities*, vol. 2, no. 1, pp. 1–19, 2019.

[38] I. Calvo, J. Gil-García, I. Recio, A. López, and J. Quesada, "Building IoT applications with raspberry pi and low power IQRF communication modules," *Electronics*, vol. 5, no. 4, p. 54, 2016.

[39] L. Krupka, "The issue of LPWAN technology coexistence in IoT environment," in *Proc. 17th Int. Conf. Mechatronics-Mechatronika (ME)*, Prague, Czech Republic, 2016, pp. 1–8.

[40] D. Ismail, M. Rahman, and A. Saifullah, "Low-power wide-area networks: Opportunities, challenges, and directions," in *Proc. Workshop Program 19th Int. Conf. Workshops*, Varasi, India, 2018, pp. 1–6.

[41] L. Garcia, J. M. Jiménez, M. Taha, and J. Lloret, "Wireless technologies for IoT in smart cities," *Netw. Protocols Algorithms*, vol. 10, no. 1, pp. 23–64, 2018.

[42] M. Spadacini, S. Savazzi, and M. Nicoli, "Wireless home automation networks for indoor surveillance: Technologies and experiments," *EURASIP J. Wireless Commun. Netw.*, vol. 2014, no. 1, pp. 1–17, Dec. 2014.

[43] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on LPWA technology: LoRa and NB-IoT," *ICT Exp.*, vol. 3, no. 1, pp. 14–21, Mar. 2017.

[44] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, vol. 5, no. 1, pp. 1–7, Mar. 2019.

MOHAMMED BOUZIDI was born in El Mecheria, Algeria. He received the B.S. degree from the University of Science and Technology of Oran, Algeria, and the M.S. degree in automation from the University of Burgundy of Dijon, France. He is currently pursuing the Ph.D. degree with the Institute of Electrical Systems, NTNU University. His doctoral research aims to investigate the most recent IoT-communication systems for reliable, sustainable, and maintainable smart cities to provide energy-efficiency and secure communication.

YASER DALVEREN received the B.S., M.S., and Ph.D. degrees from Atilim University, Ankara, Turkey, in 2009, 2011, and 2016, respectively. He is currently pursuing the Postdoctoral studies with the Department of Electronic Systems, Norwegian University of Science and Technology (NTNU), Gjøvik. From 2009 to 2017, he was a Research Assistant with the Electrical and Electronics Engineering Department, Atilim University, where he has been an Assistant Professor with the Department of Avionics, since 2017. His research interests mainly include source localization, signal processing, wireless communications, and the Internet-of-Things.

FAOUZI ALAYA CHEIKH (Senior Member, IEEE) received the Ph.D. degree in information technology from the Tampere University of Technology, Tampere, Finland, in 2004. He has been a Researcher with the Signal Processing Algorithm Group, Tampere University of Technology, since 1994. Since 2006, he has also been an Associate Professor with the Department of Computer Science and Media Technology, Gjøvik University College, Norway. Since 2016, he has also been with the Norwegian University of Science and Technology. He teaches courses on image and video processing and analysis and media security. His research interests include e-learning, 3D imaging, image and video processing and analysis, video-based navigation, biometrics, pattern recognition, embedded systems, and content-based image retrieval. In these areas, he has published over 100 peer-reviewed journal and conference papers. He has been involved in several European and national projects, among them: ESPRIT, NOBLESS, COST 211Quat, HyPerCept, IQ-Med, and H2020 ITN HiPerNav. He is also a member of NOBIM and Forskerforbundet (The Norwegian Association of Researchers). He is on the Editorial Board of the *IET Image Processing* journal, the *Journal of Advanced Robotics and Automation*, and on the technical committees of several international conferences. He is an expert reviewer for a number of scientific journals and conferences related to the field of his research.

MOHAMMAD DERAWI received the Diploma degree in computer science engineering from the Technical University of Denmark, and the B.Sc. and M.Sc. degrees from the Technical University of Denmark, in 2007 and 2009, respectively. He is currently pursuing the Ph.D. degree in information security with the Norwegian Information Security Laboratory (NISLab). In addition, he received the title as the Youngest Engineer of Denmark, in 2009. His research interests include smart technologies, biometrics with specialization on both behavioral biometrics (gait recognition and ECG) and biological biometrics (fingerprint, face) in mobile devices, pattern recognition, and E-health. He was active in several EU-projects, including the 7th Framework European project TrUsted Revocable Biometric IdeNtitiEs (TURBINE), Erasmus Mundus. Today, he holds a full professor position and received the title as the Youngest Professor of Norway within Electronic Engineering and is specialized within Information Security, Biometrics, Smart Devices, Programming and Micro-Controllers.

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