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Internet of Things for Smart Railway: Feasibility and Applications

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***Abstract*—The explosively growing demand of internet of things (IoT) has rendered broadscale advancements in the fields across sensors, radio access, network, and hardware/software platforms for mass market applications. In spite of the recent advancements, limited coverage and battery for persistent connections of IoT devices still remains a critical impediment to practical service applications. In this paper, we introduces a cost-effective IoT solution consisting of device platform, gateway, IoT network, and platform server for smart railway infrastructure. Then, we evaluate and demonstrate the applicability through an in-depth case study related to IoT-based maintenance by implementing a proof of concept and performing experimental works. The IoT solution applied for the smart railway application makes it easy to grasp the condition information distributed over a wide railway area. To deduce the potential and feasibility, we propose the network architecture of IoT solution and evaluate the performance of the candidate Radio Access Technologies (RATs) for delivering IoT data in the aspects of power consumption and coverage by performing an intensive field test with system level implementations. Based on the observation of use cases in interdisciplinary approaches, we figure out the benefits that the IoT can bring.**

***Keywords*—Internet of Things, Smart railway, Condition based maintenance, Power consumption, Coverage**

I. Introduction

Railway has been playing a fundamental role of public transportation from 19'th century, in which a steam locomotive began to be run. From that moment, the railway was regarded as a core method to transport massive population moving along the determinant paths within and between metropolitan cities. The basic technology of the railway has been so far progressed and recently enables a high-speed railway system which satisfies the public demand on traveling a far distance. The railway possesses the inherent characteristics of high capacity and energy efficiency, and those merits motivate the governments of many countries to encourage and support the railway for public interest. Consequently, the governments consider the railway significant when they establish transport policies.

One of the important issues for railway operators is maintenance of their railway systems. As shown in Fig.1, the railway system consists of various entities including train vehicles, tracks, facilities (i.e. tunnels and bridges), catenary and electrical devices in trackside. It is essential for the railway operators to guarantee that every entity of the railway system operates in good condition. Any operational faults are supposed to be strictly prevented, because an unexpected fault may threat the safety of massive passengers. Due to this fact, the government forces the railway operators to fully engage themselves in conducting the maintenance. As a result, the operators necessarily arrange a certain amount of budget on the maintenance of the whole railway system.

Unfortunately, the railway operators are recently facing a huge challenge in conducting the maintenance. Most of the railway entities exist in an outdoor environment, which is unfavorable for keeping the condition of them in a good state. Also, the railway systems in most countries have been several decades since they were deployed and the operators are necessarily required to monitor the deterioration of the systems more carefully. For example, it is known that 42% of the railway bridges and 47% of the railway tunnels have been tolerating the weight of train vehicles for more than 30 years in South Korea. This situation presses the operators to allocate more effort to the maintenance, and eventually imposes a heavier financial burden to the operators.

In this circumstance, railway operators have begun focusing on an efficient way to accomplish the maintenance and extend the life cycle of the railway system. One promising solution is to utilize a concept of Condition Based Maintenance (CBM) ([1]-[3]). Under the concept of the CBM, maintenance actions are performed based on the status of maintenance targets. Traditionally, a maintenance action was performed periodically regardless of the condition of the targets. Although this traditional approach may assure the safety of the railway system, it makes the operators waste the financial resource on repairing or replacing the railway entities even in normal condition. By inspecting the condition of the targets, the operators can perform the maintenance actions only for the defected targets, and can consequently increase the life time of the overall railway system.

The CBM has become practical and will be able to evolve further by various enablers, such as sensing, information and communications technologies ([4]–[6]). Especially, many believe that the CBM will take a step forward by combining itself with a concept of Internet of Things (IoT). The major part of the inspection is currently performed by a human effort which is basically inefficient in a cost perspective. The IoT allows things, which are specifically maintenance targets and staffs, to be connected and to interact with each other by exchanging information. Under the IoT concept, the staffs can be easily aware of the condition of the maintenance targets and make a decision of the maintenance actions without the harsh procedure of the direct inspection.

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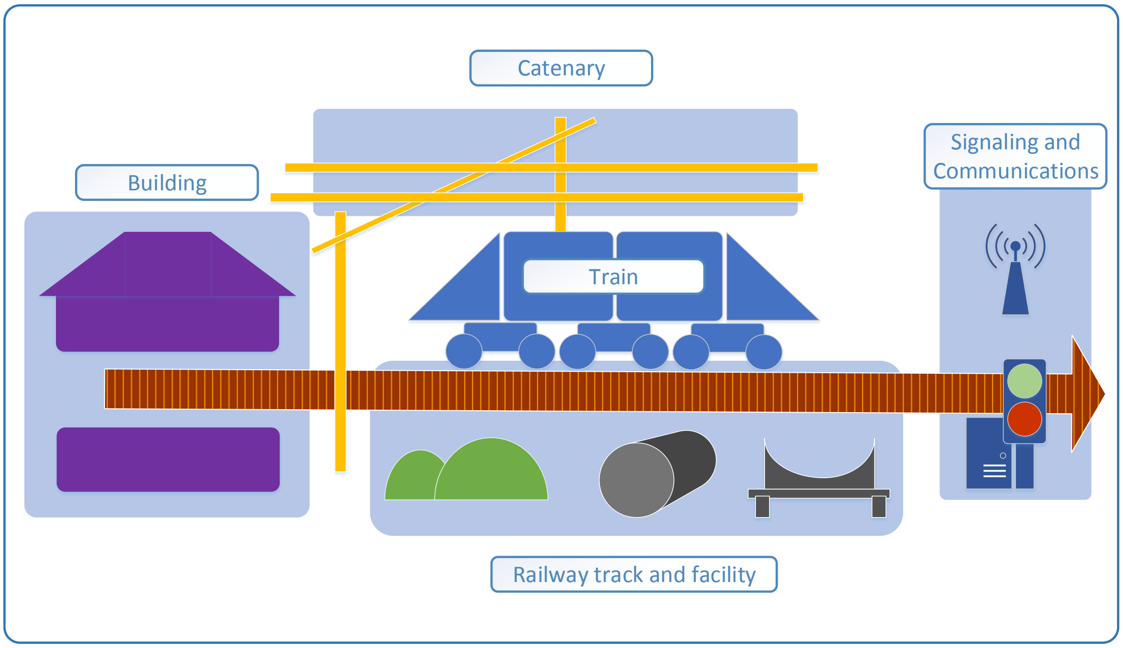

Fig. 1. The overview of a railway system: a representative IoT service scenario

To realize the IoT, the railway operators need a full scale of the base infrastructures to let the things be physically connected. In fact, many of the railway operators already have or plan to have a railway communications system, which can play the role of the base infrastructure for realizing the IoT. Currently, 66% of the European train lines utilize Global System for Mobile Communications-Railway (GSM-R) [7], and the railway operators in South Korea are considering to deploy a railway communications system based on Long Term Evolution (LTE) ([8]-[9]). The original objective of a railway communications system is to provide train control and group communication services, which utilize rather a small portion of the system capacity. Therefore, the existing railway communications system is generally capable of providing additional services with its remaining system capacity. In this sense, we can say that the railway is somewhat ready to realize the IoT concept.

From the technical aspects, IoT technology consists of three phases, which are sensing, accessing, and processing phases. In sensing phase, various sensors and devices collect the information related things and equipments such as railway, train and other infra. In accessing phase, the collected data from the things can be efficiently delivered to IoT platforms by using various wireless IoT accessing technologies without human efforts. Then, the platform analyses the data and takes a measure in processing phase. Through an in-depth and interdisciplinary study, we deduce that the IoT is a key enabling technology for realization of smart railway.

In this paper, we aim to analyze whether and how the IoT can seize a business chance by considering its suitability to the railway maintenance. We see in detail how the IoT concept can make a synergy with the CBM procedure and how the IoT can be properly implemented in a railway environment. Based on the observation on the status and use cases of the CBM, we figure out the impact of the IoT on the railway maintenance and discuss further requirements. In addition, we provide a suitable solution of the IoT which can be utilized for the railway maintenance. We analyze the technical possibility and requirements of the IoT solution in detail, and evaluate the suitability of the existing Radio Access Technologies (RATs) by comparing their performances.

II. Use Case Survey for Condition Based Maintenance in Railway

The objective of railway maintenance is to keep the railway system on performing its functions in good state during the life time. Under the aforementioned CBM concept, a maintenance staff inspects the condition of each entity in the railway system and repairs or replaces it if necessary. The upper part in Fig.2 shows the detailed procedure of the CBM. The first step is to inspect each maintenance target according to a guideline specific to the target. For each target, the maintenance staff directly visits the site and measures various indices dedicated to the target at a specific inspection period. Based on the analysis of the measurement results, the staffs decide which status each target is in and whether the target needs any maintenance actions. The candidate maintenance actions are then prioritized based on the significance and criticality, and the budget for the maintenance actions is negotiated, which bounds the range of the execution for the maintenance actions.

The railway system can be in better condition if more budget is allocated to the execution of the maintenance actions, but the financial overhead will matter to the railway operators in practical. The amount of maintenance cost is currently a

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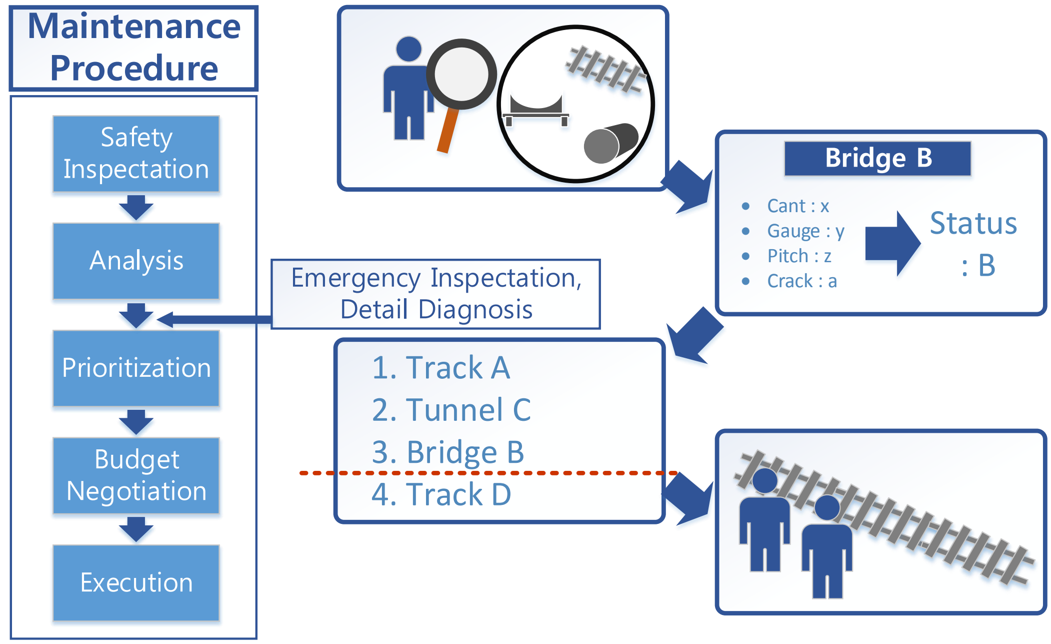

Maintenance Cost (million won)

	2009	2010	2011	2012	2013
Sum	671,909	716,038	722,527	699,606	701,647
General	593,103	619,413	613,667	601,643	601,427
High-speed	78,806	96,625	108,860	97,963	100,220

Details of the Maintenance Cost for General Railway (0.1 billion won)

	2007	2008	2009	2010	2011
Sum	5,708	5,918	5,931	6,194	6,137
Personnel	3,366	3,803	3,539	3,628	3,665
Expense	929	1,012	968	1,111	925
Repair	812	616	885	948	1,072
VAT	601	487	539	507	475

Fig. 2. The detailed procedure and cost of the railway maintenance

burden to the operators who manage the railway system with a limited amount of budget. The lower part in Fig.2 shows an example of the maintenance cost in South Korea [10]. The operator has totally consumed more than 500 million dollars per a year for the maintenance, and the scale of this expense must be a heavy burden in an operator perspective. But in other words, we can say that there is a great chance to enhance the financial condition of the operator by promoting the maintenance efficiency and reducing the cost.

Looking in the details of the maintenance expense, we can recognize that the personnel expenditure takes a great portion. The personnel expenditure occupies maximally 64.2% in 2008, and even minimally 58.5% in 2010. The portion of the cost for repair, on the other hand, has been only 10.4-17.4% in 2007-2011. This reveals that the whole maintenance procedure deeply relies on manpower, and that the railway operator injects much of the financial resource to the inspection process, rather than the repairing process. This is undesirable in the circumstance that the total budget of the railway maintenance is limited. Allocating more resource to inspection leads to consuming less resource on repair, which makes the overall system be in worse condition. After all, it is inevitable to enhance the efficiency of inspection for guaranteeing the safety of the railway system.

A. The Detailed Use Cases of the Maintenance Inspection

To grasp the details of the current inspection process, we need to go through an operator specification which clearly states the targets and methods of the inspection. Table.I shows an overview of the maintenance specification offered by Korea Rail Network Authority (KR) [11]. It is summarized with three significant targets; track, bridge and tunnels, which are the major entities in a maintenance aspect.

The table.I describes that maintenance staffs are required to perform a wide scope of measurements for the inspection. Furthermore, the number of the actual maintenance targets is very large and the targets are distributed over a wide area. In case of South Korea, the total length of the track is $3,590$km

TABLE I. DETAILS ABOUT MAINTENANCE INSPECTION

Target	Attribute	Measurement	Method
Track	Linearity	Gauge, irregularity in cross level, irregularity in longitudinal level and irregularity in line	Monthly by an inspection car (high-speed), 4 times per a year by an inspection car (general), twice per a year by men, Measurement conducted for each 10m of the track
	Surface quality	Abrasion, rail corrugation, desquamation and corrosion	0.5–2 times per a year by men
Bridge	Lower part structure (girder and supporting structures)	Crack, subsidence, displacement and corrosion	Twice a year
	Upper part structure	Slag, oscillation, curvature, damage, corrosion, abrasion, displacement and uneven pressure of bearing	
Tunnel	Lining	Long-term deformation, stress, concrete strength and surface status (crack, cave-in or displacement)	Twice a year
	Others	Drainage, joint status	
Others	The status of turnouts, rail clampings, rail joints and sleepers		Once a year or two years

and the track inspection staffs are required to measure the gauge and irregularities in cross level, longitudinal level and line for every 10m of the track. In addition, there are $3,635$ bridges and 658 tunnels for railway use, and the facility inspection staffs need to check each of them through a large amount of measurements.

Since the railway operator gathers the condition information on each of the numerous spots, the inspection process consumes huge human resource to accomplish it. This causes the personnel expenditure to take much portion of the overall maintenance cost, as shown in Fig.2. In addition, it is hard to say that the current inspection process allows the operator to grasp the condition of maintenance targets in real-time and to respond to errors immediately. According to the inspection periods in the table.I, most of the measurements are performed once or twice in a year, so the latest inspection result may not exactly reflect the current status of the railway system. Meanwhile, it is also a hard decision for the railway operator to reduce the inspection period due to the increase of the inspection cost. The operator therefore is forced to find an alternative way to gather the condition information in an efficient manner.

III. THE IOT SOLUTION FOR THE ENHANCED CONDITION BASED MAINTENANCE

One of the approaches for improving the efficiency of the inspection process is to utilize a concept of IoT. The IoT is considered as a good solution to provide real-time monitoring services, because it is helpful for estimating the properties of maintenance targets at remote sites. Today, the IoT technology has matured according to the recent studies and researches, and various systems realizing the IoT concept are being launched. So, it is available for railway operators to select and apply those systems to the railway maintenance.

From the statistics provided in Fig.2, we can roughly get the hang of how much benefit the IoT can bring. The yearly cost for the inspection per a kilometer is roughly estimated as 199.5 and 121.5 thousand dollars for the high speed and the general commercial railway lines, respectively, in 2011. Assuming that the IoT solution is used for at least 5 years from the deployment and a half of the budget for the inspection is allocated for deploying and managing the IoT solution, the railway operator can maximally invest 997.5 and 607.5 thousand dollars per a kilometer in deploying and managing the IoT solution for high speed and general commercial railway lines, respectively. This seems to be practically possible when considering the cost of sensors or terminal devices. As a result, the IoT is a chance to enhance financial condition in the perspective of railway operators, and is also a chance to pioneer a new market in the perspective of developers and manufacturers.

A. The Requirements for the Condition Based Maintenance

It is known from the use case survey that many kinds of sensors are utilized, so terminals of the IoT solution need to be easily equipped with various sensors. Furthermore, railway operators also expect the various sensors to be efficiently deployed and managed in a cost aspect, and require the terminals to contribute to that point. In this sense, the terminals are required to control and monitor the operation of sensors instead of human staffs. In addition, it is important to reduce the cost of the terminals, because installing the terminals will take a great portion of the overall deployment cost of the IoT solution. The sensors should be distributed over a wide area of the railway system, and a huge number of the terminals should be needed to cover the whole area. Therefore, it will be effective to reduce the unit cost of the terminals for cutting down the Capital Expenditure (CAPEX) of the IoT solution.

The terminals of the IoT installed in a railway field are also required to operate normally for a sufficient time. A railway device is typically replaced every 5–10 years after its deployment. There are two aspects which need to be considered with respect to the operational time; reliability and power consumption. Reliability represents how much time a device operates without a failure, and is generally expressed by Mean-Time-Between Failure (MTBF). Of course, railway operators require the MTBF of the terminals to be at least 50,000–100,000 hours in a severe field environment (e.g. the temperature range of -40–70°C and the vibration amplitude

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and frequency levels of $9.81m/s^2$ and 10–500 Hz, respectively).

In addition, the terminals are required to have a long battery life for covering some areas in which power supply is not available. The terminals deployed near catenary can use power supply, but there are many cases in which the terminals should rely on its battery. The terminals thus need to minimize the power consumption of the interworking sensors, as well as their own power consumption. It is noted that it is not desirable to allocate man power for replacing battery of the terminals in operator perspective. Taking into account that the expected lifetime of the terminal is 5-10 years and the operator allows to replace the battery of the terminals once, we can conclude that the battery lifetime of the terminal is required to be more than 3 years.

From the regulation perspective, it is sufficient to have the inspection data from the field side by the own period of the target referred in [10]. For instance, it is at least required to collect gauge data of tracks at once a month and the crack data of bridges and tunnels at twice a year. However, it would be more helpful to have more frequent inspection data for precise maintenance activity in some aspect. Considering the current criterion for the maintenance inspection, maintainability will be further improved if the inspection data is collected for 0.5-1 times a day. So if the IoT concept is adopted, it is needed to re-consider the requirement for the period of the maintenance inspection to be revised upward for aggressive data collection. The revision should be in proper level so that the terminal can meet the requirement of the above battery lifetime.

Railway operators also want that the condition information of maintenance targets is always available to data consumers whoever need their own data in various forms. There are various kinds of the data consumers in railway; station staffs, control staffs and maintenance staffs, and each of them needs a different kind of data for his own mission. Also, each maintenance staff in charge of different targets is interested in a different set of condition information. Therefore, the condition information gathered from the terminals needs to be properly processed and accessed so that each data consumer can get the data in his own favor. In addition, each condition information needs to be collected in the proper time, according to the characteristics of the corresponding target. Especially, a railway system generally requires to handle vital information, such as train control and safety warning data, so the IoT solution needs to guarantee the delivery of the vital information in the right time. This means that the IoT solution should have a proper priority policy for satisfying the Quality of Service (QoS) of vital services.

B. The Architecture of the IoT Solution for Practical Applications at the Civilian Stage

For the various practical applications, the IoT solution has to cover a broad scope of the role. The IoT solution therefore needs to include a combination of multiple systems having different characteristics. For instance, a mobile communications system such as LTE provides a wide coverage, but makes the terminals consume much power. A short range communications system, such as Bluetooth, promises a long battery life to the terminals, but has a limited coverage for collecting condition information. In addition, the requirements include to collect the condition information from various combinations of sensors, as well as to provide the condition information to the various data consumers. This means that various forms of platforms should be considered in terms of both device and service when composing the IoT solution.

Fig.3 shows the overall architecture of the IoT solution that we consider for the railway maintenance. It enables the efficient collection of condition information from distributed maintenance targets to a center node called *platform server* by stages [12]. Once condition information data is generated from a sensor, a *device platform* gathers and transmits the data toward the IoT network [13]. A *gateway* relays the data from the device platform which is not able to make a direct connection to the IoT network. The IoT network routes the data to the platform server which has roles of storing, processing and analyzing the condition information. The nodes in a higher stage play more significant roles to deal with the condition information, because the traffic density of the condition information increases as the stage goes up.

A basic concept of a device platform is to provide common functionality of various sensors. At the terminal side, it needs to have a flexible structure to interwork with various combinations of sensors. In this circumstance, it is structurally more beneficial for the terminals to have a platform functionality that takes care of the common functions for all kinds of sensors. As shown in Fig. 3, our proposed concept of the device platform includes a functional block, so-called as Hardware Abstraction Layer (HAL), which only conducts hardware-dependent operations. This block enables to simply interface with various sensors without modifying the main part of sensing process. Once a sensor generates raw sensing data and delivers it to the device platform which is physically attached to the sensor, the device platform processes the raw sensing data and transfers it through its communications module.

Usage of the device platform somewhat releases the financial burden of deploying and operating a large number of sensors. The device platform itself contributes to minimize CAPEX, because the unit cost of the terminals can be reduced through mass production. The developers specialized to sensors can also develop a terminal easily by utilizing the device platform, which can be an additional factor to reduce the unit cost of the terminals. Moreover, the device platform can make it easier to replace the sensors which become out of order, and this contributes to reduce the Operational Expenditure (OPEX) of the IoT solution.

According to the requirements, the device platform needs to have a sufficient level of reliability so that it properly operates till the next replacement. The device platform is also required to utilize various power management schemes for optimizing its power consumption. It should be noted that the power consumption of the device platform is closely related to its RAT. In a communications aspect, the battery life of a terminal mainly relies on the duty cycle of waking up events and the amount of power consumed during a wake-up state. An LTE terminal in IDLE mode, for example, wakes up and listens to the base station for every Discontinuous Reception

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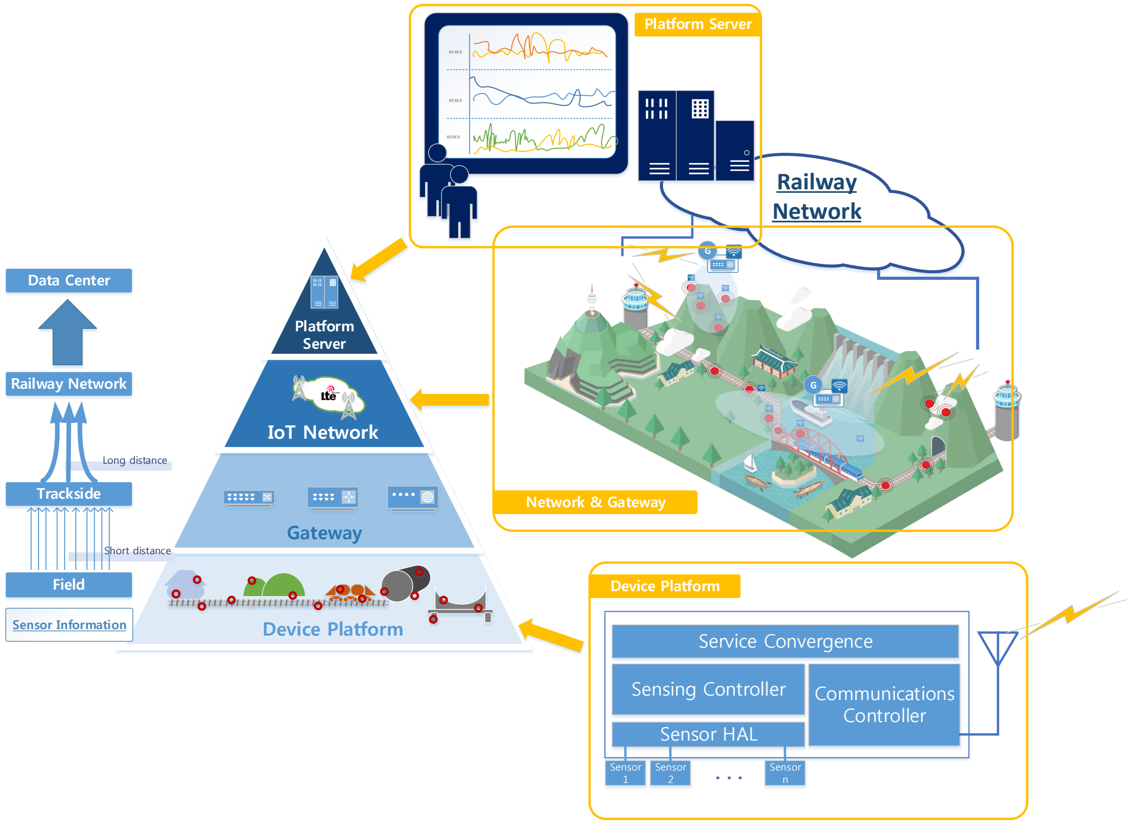

Fig. 3. The architecture of the proposed IoT solution for smart railway

(DRX) cycle, which is typically 320–2560ms. Since traffic density is rather low and data transmission rarely happens in the CBM scenario, the battery life of the LTE terminal is inversely proportional to the DRX cycle. With respect to power consumption in the wake-up state, there are three dominant factors; the amount of power consumed by basic processes (P_r) including baseband H/W processes and Operating System (OS) level tasks, the amount of transmit power (P_{tx}), and the duration of transmission (T_{tx}). P_r depends on the actual implementation of the terminal, and somewhat is affected by the inherent complexity of the RAT. P_{tx} and T_{tx} depend on the transmission scheme and power control algorithm, and are not static even when using the same RAT. As a result, the power consumption of the device platform varies according to its detailed communications schemes as well as its RAT.

A gateway exists nearby the device platforms which are in a low-power operation and not capable of long range communications. As shown in Fig. 3, the data transfer in the railway IoT scenario requires both short and long range data communications. The gateway gathers data from the device platforms through short range communications and relays it to the IoT network through long range communications. Thus, the gateway is required to have a static power supply and to be capable of multiple RATs. The gateway also needs to have high computational power for operating various IoT protocols, which are heavy to be run in a device platform, as an agency. The gateway also needs to have a sufficient level of reliability so that the interworking device platforms can properly play their role of transferring condition information through the gateway.

A platform server manages the whole procedure for gathering condition information in a centralized form and processes the incoming condition information for various data consumers. The platform server remotely configures and manages the operations of the device platforms for collecting the condition information which the platform server is interested in. One point that the platform server needs to be considered specifically for the railway environment is to take care of vital information. Since the vital information in railway is critically related to the safety of passengers, the platform server needs to have QoS management schemes which can strictly guarantee the QoS of the vital services.

IV. Performance Comparison of the Candidates for the IoT Networks

An IoT network plays an important role of providing connections between a platform server and device platforms. Considering the current circumstance of the railway operators, there are two influential candidates for the IoT networks; LTE and LoRa. Many railway operators are already using GSM-R and will feel more familiar with LTE which is evolved from GSM. On the other hand, many in IoT industry keep eyes

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on LoRa, which newly arises and is specialized to serve low-power IoT devices in a wide area [14].

To estimate the suitability, we conducted a performance evaluation of LTE and LoRa through a system level field test. We observed the two indices in terms of IoT data delivery; power consumption and coverage. The system model for the field test is described in upper part of Fig.4, including the network architecture. In case of LTE, we utilized an LTE module which uses the frequency band allocated for railway in South Korea. The module inter-operates with the LTE infrastructure, including eNodeBs and an Evolved Packet Core (EPC), through full LTE stacks. In case of LoRa, we utilized a PLM100 board with an SX1276 SemTech chip which operates in 900MHz. We set the two PLM100 boards located at the eNodeBs and regarded them as the base stations of LoRa. Moving to various spots near the base stations, we have estimated the coverage of the LTE and LoRa systems, as well as the power consumption of the LTE and LoRa terminals. For each measuring spot, we evaluated whether it is in coverage by checking if packets are reliably sent from the terminals to the base stations, and measured the RSSI and packet error rate.

The table at the upper part of Fig. 4 depicts the detailed parameters of our evaluation system model. We configured the traffic model such that the terminals transfer periodical IoT data toward the network side. For each second, the transmitter terminal randomly generates and transmits a packet whose size is 30-64 bytes, and check if the packet is reached to the base station. The maximal transmit power of the terminal is 23dBm and 14dBm in case of LTE and LoRa, respectively. It is noted that the maximal transmit power of the LoRa terminal is 9dBm smaller than that of the LTE terminal, due to the regulation in South Korea.

The lower part of Fig.4 summarizes the evaluation results. In a coverage aspect, we observed whether the packets transmitted from the terminals are properly received by the corresponding base station. The result reveals that both the LTE and the LoRa cover the wide area, and the outdoor coverages of the LTE and the LoRa are almost similar. The LTE covers slightly wider area as much as about 15%, due to the lower frequency band and the higher transmit power. On the other hand, the coverage of the LoRa is comparably degraded in the indoor environment due to the poor packet reception rate in the rich scattering environment. This is because the LTE modem utilizes advanced schemes to adapt to the multipath environment, while the LoRa modem with simple structure is not sufficiently ready to combat with the multipath fading.

In the perspective of error rate, the result reveals that the LTE raises packet error more frequently compared to the LoRa. In the evaluation, the block error rate in LTE is typically 5-10%, while the maximal packet error rate was 1.7% in LoRa. This is because the LTE tends to aggressively utilize the modulation and coding schemes of high data rate. Instead, the LTE compensates the error quickly by Hybrid Automatic Retransmission reQuest (HARQ) and the packet loss after the HARQ process will eventually become less than 1%. (This HARQ process also enhance the robustness of the transmission in multipath environment.) Considering that the LTE and the LoRa adopt layer 2 retransmission schemes, we can conclude that both of the system will not have a problem in transferring IoT data reliability.

In the aspect of power consumption, we let the terminals send small packets consistently and observed how much time it takes until the attached battery is exhausted. The average current of the LTE terminal is measured in the range of 333–351mA. Remarkably, the LTE terminals consume the similar amount of the power regardless of the received signal strength level, due to the unique power control mechanism in LTE. LTE specifies to control the transmit power of the control channel and the data channel independently, so the LTE terminal does not use the maximal transmit power when there is instantaneously no data to be sent. This happens frequently when the terminal sends small size packets periodically. So in the IoT scenario, the LTE terminal tends to consume a dominant amount of power on the basic processes rather than Radio Frequency (RF) transmissions. This fact gives us a guide that it is essential to lighten the basic processes, rather than to control the power amplifier exquisitely, for increasing the battery life of the LTE terminals.

On the other hand, the LoRa terminal consumes about 128mA, which is about $1/3$ level of the power consumed by the LTE terminal. This result is due to the low complexity of the baseband signal processing and the lower RF transmit power. It should be noted that the power consumption of the LoRa terminal can be further optimized by a power control mechanism. The LoRa terminal can prevent a waste of power by deciding its transmit power as a minimal level required for a data reception. The optimal transmit power can be also derived from the data rate which minimizes the overall energy consumption according to the principle in [15]. Under the existing framework for adaptive rate control in LoRa, the terminal can minimize its battery consumption by finding the optimal data rate based on the amount of power consumed in idle/transmission states, and decide the duty cycle and transmit power to achieve the data rate.

As a possible alternative for enabling the IoT applications, Narrow Band IoT (NB-IoT) is recently released by the 3GPP standard association with the mission of low-power/wide-area wireless communications, aims to reduce the complexity of its baseband process [16]. The salient point of NB-IoT lies in the use of system bandwidth as extremely narrow as 200 kHz. Table. II shows the detailed comparison of various RATs in view of the IoT network. In general, NB-IoT has the characteristics of having a compromised performance between LTE and LoRa, so that it can be a feasible alternative to have the benefits of the two RATs. One big difference between NB-IoT and LoRa in a protocol aspect is that terminal side can only trigger a connection establishment in LoRa, meanwhile both terminal and base station sides can trigger it in NB-IoT. From the perspective of the difference, LoRa is more advantageous in terms of power consumption than NB-IoT, and NB-IoT has an advantage in terms of data latency.

V. Concluding Remarks

In this paper, the major challenges and opportunities associated with the smart railway infrastructure have been investigated, and an IoT-based maintenance methodology has been

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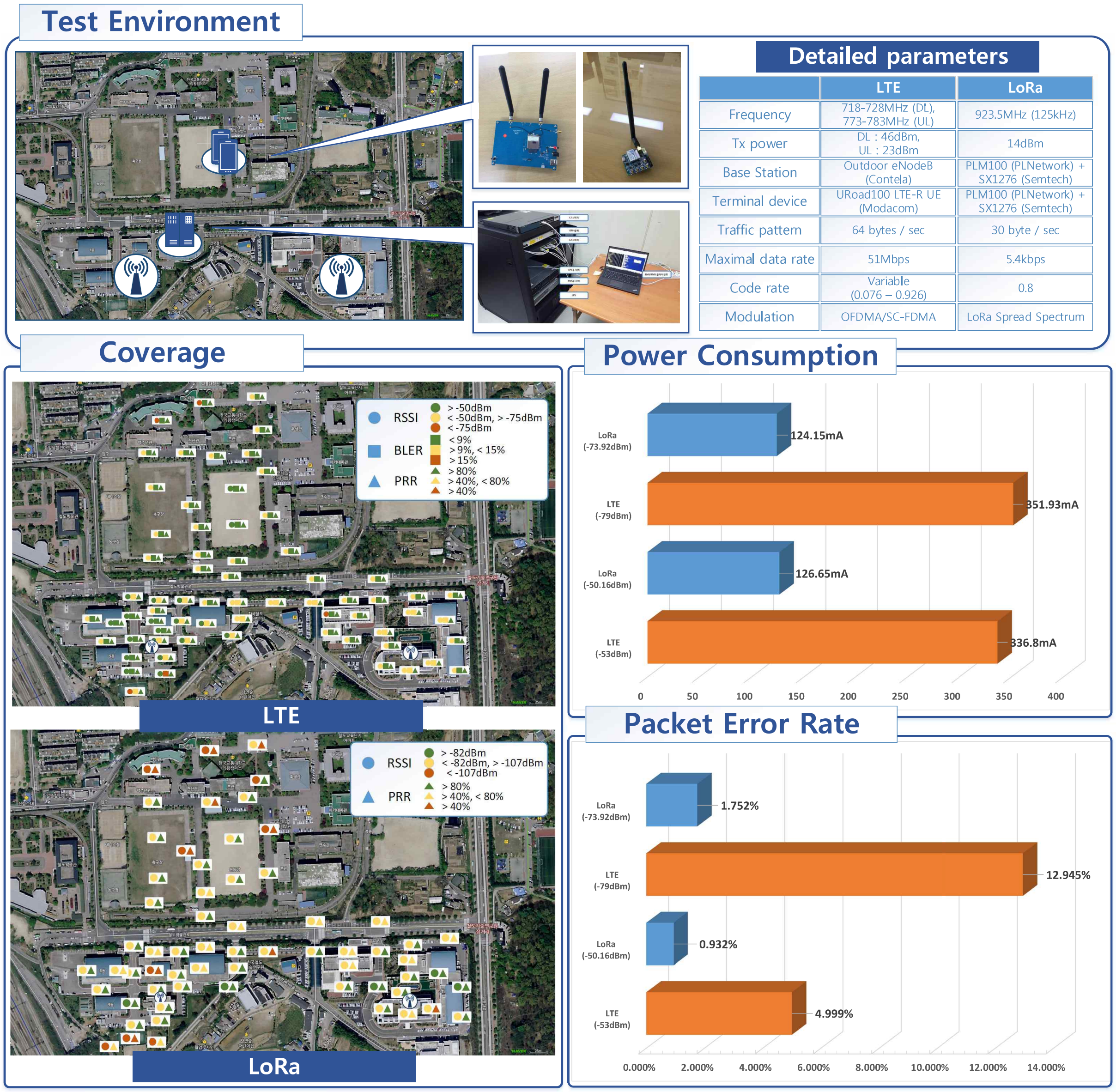

Fig. 4. Performance evaluation of LTE and LoRa.

discussed and verified. Specifically, the proposed IoT solution is the first approach dealing with holistic and interdisciplinary system level considerations in practical industry to the best of our knowledge. The analysis reveals that the IoT is an essential enabler of the CBM to enhance the efficiency of maintenance. From the fact that the IoT can bring the effect of cutting cost which can be more than hundreds of million dollars, the railway maintenance can be a great business model of the IoT application. Moreover, we are convinced that IoT will be realized in many smart city applications as well as railway for enhancing the productivity under the guideline that we have suggested.

In a technical aspect, each element of the IoT solution is ready to be applied to the field, but the following practical issues need to be considered. The device platform needs to adopt various communications schemes and a circuit design schemes to achieve low power consumption and high reliability ([17]-[21]). When using the LoRa as an IoT network, it is needed to look through various transmission and reception schemes to enhance the reliability of data transfer in multipath and interference-coexistence environments. In addition, the LoRa needs to have a capability to recognize and deal QoS of vital informations for guaranteeing railway safety.

Due to the notable advancements of IoT technologies, the information and communications community is at the midst of an ongoing major evolution. Wide scale enhancements ranging from sensing, accessing, and processing are inevitable to continuously sustain the ever increasing demands of smart

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TABLE II. COMPARISON OF THE CANDIDATE SYSTEMS FOR THE IOT NETWORK

Attribute	**LTE**	**LoRa**	**NB-IoT**
Available frequency band	718–728MHz(DL) / 773–783MHz(UL)	902–958MHz	To be decided
Coverage	$<$ 1km	$<$ 10km	$<$ 10km
Data rate	150Mbps(DL)/50Mbps(UL) (Rel.9)	$<$ 50kbps	$<$ 64kbps
Max nodes	Hundreds/cell	Millions/hub	52574/cell
Power consumption of terminals	High	Low	Moderate
Maximum transmit power of terminals	23dBm	14-20dBm	23dBm
Connection establishment triggering	Bi-direction	One-way	Bi-direction
Implementation complexity	Extremely high	Low	Moderate

IoT applications in the industry. Various IoT services and applications have been proposed and set for market readiness. However, they are still faced with numerous practical limitations at the system level during mass market user scenarios. As presented in detail in this paper for the first time, an efficient IoT solution is vital to accurately accommodate the various surrounding environments for future IoT applications. Major layers constituting the IoT solution are specifically designed and evaluated. The effectiveness of the design is corroborated by empirical results. The compelling measurement observations further ascertain the applicability and potential of the proposed IoT solution for smart railway. And the evolution of IoT technologies will continue creating new and innovative applications [22].

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