FTmRP-NCS: Fault-Tolerant And Reliable mRPL Routing Protocol For W-NCS Communication

Vishal Sharad Hingmire, Santosh R. Desai, Yuvraj Krishnrao Kanse

Abstract- The exponential rise in the demands for reliable and fault resilient communication over Wireless Network Control Systems (WNCS) across industrial monitoring and control ecosystems has alarmed academia-industries to develop more efficient wireless transmission solutions. On the other hand, the emergence of cloud-assisted Internet-of-Things (IoT) also has broadened the demands for reliable WNCS systems. To cope up with such irreplaceable needs, WNCS has exploited different wireless communication paradigms including IPv6 Routing Protocol for Low Power Lossy Networks (RPL) based WSN that enables reliable communication across the industrial setup to make optimal real-time process decision. However, being dynamic in nature WNCS with often undergo link-outage due to dynamic topology, node death, congestion etc. Though, a few researchers have addressed the routing problem in WNCS; however, integrating RPL with mobility to enable optimal communication has remained untouched. Additionally, no significant research addressed fault-resilient routing decision over WNCS setup, which motivates us to develop a highly robust Fault-Tolerant and Reliable mobile-RPL Routing Protocol for W-NCS (FTmRP-NCS). Unlike classical WNCS models, FTmRP-NCS employs dual objective-based routing decision by considering the Received Signal Strength Indicator (RSSI) and the number of control packets required (ETX). Here, the inclusion of RSSI ensures forwarding path formation with most reliable link condition, while ETX objective function helps maintaining low control packets and hence low energy exhaustion, low redundancy and high efficiency. FTmRP-NCS applies link-sensitive mobile node movement for data gathering across WNCS, which makes overall communication more reliable as well as time-efficient. Furthermore, fault-sensitive routing decision strengthens our proposed FTmRP-NCS protocol helps WNCS to yield optimal performance. FTmRP-NCS has been applied over standard IEEE 802.15.4 protocol stack and functions in parallel to the link and network layer, which retains backward compatibility with native RPL and hence assures easy implementation with real-time WNCS environment.

Keywords: Wireless Network Controlled System, RPL Routing, Fault Tolerant and Reliable Routing.

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I. INTRODUCTION

Development of technologies demands innovative and effective solutions for communication in various applications of industries, academia, scientific communities as well as government agencies.

Amongst major applications, industrial communication has emerged as one of the most demanding sectors where enabling reliable and fault-tolerant data transmission is inevitable [1].

Network Control Systems (NCS) being one of the most used technologies in industrial communication demand efficient and reliable transmission protocol to collect sensed data from plants and send it to the automation controller to make transient control decision [2]. Towards these objectives, wireless NCS (WNCS) has emerged as a potential solution that not only augments reliable communication but also reduces complexities [3]. The use of WNCS systems in industrial automation has strengthened industries to augment their productivity while assuring maximum fault-resilience, where the role of a robust transmission system is irreplaceable. WNCS comprises sensor nodes deployed across the physical plant to collect event information. The deployed sensor nodes transmit their targeted local information to the controller through the gateway using a wireless channel. On the other hand, controllers compute control commands on the basis of the retrieved sensor data and send it to the actuators for timely actuation control of action control in the physical plant [4, 5]. The major use of WNCS is predominantly because of the large scale rise in the embedded computing, wireless networks and cloud computing, which gets further augmented due to diverse applications such as automotive [6, 7], avionics [8], building management [9] and industrial automation [10]. In the last few years, massive use of WNCS has surfaced for Industry 4.0 assisted Smart Manufacturing [12].

In practice the cluttered and noisy network environment influence overall WNCS performance significantly. On the other hand, the classical static node deployment based Wireless Sensor Networks (WSNs) are confined to alleviate major at hand issues such as link-outage, network condition changes, node death cause packet loss etc [13]. It demands certain more efficient transmission protocols with mobility feature that could assist timely and reliable data delivery from the deployed sensor nodes to the Network Gateway (NGW), automation controllers and actuators [14]. Unfortunately, native IEEE 802.15.4 standard based WSN doesn't employ mobility model due to classical reactive routing characteristics.

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Dynamic topology and link variations are the key issues in mobile-WSN. However, introducing mobility with WSN, often called mobile-WSN has surfaced as one of the broad research areas for research communities. It can be considered as one of the prime motives of this research. Additionally, performing an in-depth study it can be affirmed that in the last few years the evolution of WNCS and cloud technologies have introduced the concept known as Smart Factory or Smart Manufacturing [15]. Smart Manufacturing exploits technologies like advanced communication system, cloud computing, BigData analysis,

Internet of Things (IoT), WNCS and advance automation control [16]. Summarily, this model requests certain robust data transmission scheme with high reliability and timely data delivery at the NGW or automation controllers to make early actuation control or allied decisions [16]. Thus it can be noted that NCS has a decisive role in achieving reliable performance in Smart Factory. Even, it has been identified as one of the inevitable needs for Industrie 4.0 assisted Smart Manufacturing concept. With this motive, in the last few years numerous international organizations such as Wireless Avionics Intra-Communications Alliance [8], International Society of Automation [17], Zigbee Alliance [18], Z-Wave Alliance [19], Wireless Industrial Networking Alliance [20] etc have been working on WNCS optimization to enhance industrial communication.

Being a large scale distributed network industrial process control or automation system demands reliable, timely [11] and fault-resilient communication across the system to meet Quality of Service (QoS) provision. However, the cluttered and noisy environment in industries confines major classical communication protocols to undergo loss condition that adversely affects overall control function, productivity and QoS provision. In such case the use of an enhanced IPv6 Routing Protocol for Low Power Lossy Network often called RPL can be of paramount significance [21].

Realizing the significance of mobility feature in sensor networks, IoT in smart factory concepts and RPL as a robust routing protocol, in this research the predominant emphasis have been made on enhancing aforesaid constructs to accomplish a novel and robust solution towards optimal WNCS communication purposes. As a contribution, to enable mobility based sensitive data gathering solution, we have applied link sensitive mobility control or mobile node positioning which ensures maximum possible or optimal data gathering from the connected wireless sensor nodes. On the other hand to ensure optimal routing decision over mobile-RPL (here onwards called mRPL), we have designed a novel multi-objective function based RPL routing decision model, which considers both RSSI as well as ETX as an objective function. Noticeably, the inclusion of RSSI ensures that the proposed WNCS routing model will constitute forwarding path with the best link quality while ETX objective function retains low computational overheads or redundant communication (of control packets) to enable communication across distributed WNCS. It makes WNCS communication cost and computationally efficient. Thus, the inclusion of link-sensitive mobility control and data gathering, multi-objective function (RSSI and ETX) based routing decision ensures QoS centric, timely and reliable data transmission across WNCS to meet real-time communication demands. As a noticeable contribution, in this research a fault-sensitive alternate forwarding concept is developed which ensures timely data delivery without imposing significant (iterative) node discovery, retransmission and resource consumption. It strengthens our proposed WNCS set up to achieve optimal communication across WNCS (distributed) nodes to make timely and efficient real-time decisions. Thus, inheriting above stated contributions (multi-objective function based routing model, link-sensitive mobility control and data gathering, and fault resilient communication), we introduce our proposed routing protocol as "Fault-Tolerant and Reliable mRPL Routing Protocol for WNCS (FTmRP-NCS)". FTmRP-NCS protocol has been applied over Contiki simulation tool where its performance has been examined in terms of Packet Delivery Ratio (PDR) and Low Packet Loss Rate (PLR) and delay. The simulation results affirm robustness of our proposed FTmRP-NCS to meet contemporary WNCS demands. Furthermore, since the proposed routing protocol is applied in parallel to the link and network layers of the native RPL, it ensures preserving backward compatibility. It confirms its suitability with real-time WNCS communication environment.

The other sections of the presented manuscripts are divided as follows. Section II discusses the related work which has been followed by the detailed discussion of the proposed system in Section III. Section IV presents the results and discussion and the overall research conclusion is given in Section V.

II. RELATED WORK

This section primarily discusses some of the key literatures pertaining to NCS communication and allied routing protocols.

In the last few years the emerging communication complexities and fault proneness has forced industries to exploit wireless networks in control applications, also called "wireless automation", which can revitalize the overall automation industry as well as smart factory paradigm [22]. Undeniably, unlike classical NCS, the use of Wireless-NCS (WNCS) delivers cost-effective, flexible and more reliable communication for transient decision process [23]. Ploplys et al [24] designed WNCS comprising a plant and a controller exhibiting point to point wireless communication between them, where they found that the overall control efficiency predominantly depends on the transmission efficacy, where wireless communication with better routing provision is a must. Ploplys et al also stressed on incorporating fault-tolerant transmission system which could perform reliably under the cluttered plant or network environment. A similar inference was made in [25] where Antsaklis et al stressed on incorporating efficient communication amongst controllers, system sensors, actuators etc. Considering the implementation of WNCS Willig et al [26] found that there the predominant issues influencing overall network performance and controllability are time delays, packet losses while during transmission [27]. With this motive, the authors recommended better network protocols, transmission scheduling [28] congestion control [29] and estimation [30] for both wired and wireless control systems. In a few kinds of literature it is found that there is an inevitable need to augment communication scheduling to retain the stability of controller [31].

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In [32] authors explored different at hand technologies and allied complexities in industrial communication and found that WNCS can be of vital significance that could support transient and reliable industrial controllability as well as home automation even with cluttered plant (say, network) conditions [22]. Furthermore, the authors focused that the predominant problem with WNCS is the uncertainty of communication, co-existence with other wireless networks and security and Quality of Service (QoS) provision. To mitigate these issues, Baronti et al [33] applied Wireless Sensor Networks (WSN) as communication technology between sensor nodes and controller or actuator.

Majority of the classical wireless communication WNCS paradigms apply wireless devices such as Bluetooth, ZigBee (based on IEEE 802.15.4 radio) and WLAN (IEEE 802.11) that often undergo link outage due to exhaustive network condition and link outage [34] and hence recommended MAC enhancement to reduce communication losses. Understanding the limitations of ZigBee [35], Neumann et al [23] recommended using certain an enhanced wireless hardware as well as heterogeneous networks; however such approaches can lead huge computational overheads and hence reduced QoS provision. As enhanced solution, Branicky et al [36] recommended augmenting both MAC as well as link layers which are highly vulnerable to getting error or vulnerabilities. With this motive, later a fault tolerance model for sensor node was proposed in [37] where Prasenjit et al applied the multipath routing scheme. Recently to achieve efficient communication in WNCS, Winter et al [38] recommended IPv6 Routing Protocol for Low Power and Lossy Networks (RPL). The noticeable inferences were found in [39], where Tsiftes et al observed that predominantly data packets are lost during selecting an alternate path. Besides, higher payloads, hop-counts, mobility and resulting topological changes were found key reasons for reduced packet delivery rate (PDR). In this relation, Pavkovi et al [40] focused on enhancing RPL path selection using an opportunistic routing protocol. To enhance the reliability of the data transmission and low delay communication authors used multipath transmission scheme over native RPL with default objective function (OF) [41]. However, this approach could not address the link outage due to rapidly changing topology. As a solution for these issues, Lee et al [42] developed mobile RPL concepts, where the prime focus was made on enabling mobility feature with native RPL. Hong et al [43] developed mobility-based RPL routing protocol using link quality index; however computational complexities and overheads could not be addressed. In their approach [44] mobile nodes find multiple paths or alternate path in case of a route failure. In [42] ETX was used as OF to perform routing decision, especially the best neighbouring node to form DAG. However, these approaches suffer significantly high control traffic and link-failure caused packet loss [47]. As a solution, Korbi et al [47] developed a dynamic DIS management model for mobile RPL protocol, where ETX was used as OF. Korbi et al [47] narrowed down their research to reduce computational overheads. RSSI was used in [48] to perform routing decision or OF for DODAG formation. In [49] CO-RPL was proposed that used the concept of Corona for mobile node placement. In these classical approaches, mobility management has always been the issue and hence in [50] Bayesian model-based mobility prediction RPL was developed. Safdar et al [44] found that the inclusion of both reactive, as well as proactive methods can be vital to augment RPL for mobile communication environment. In [51] Lee et al focused on enhancing trickle timers for DIO optimization, where they found it suitable in the range of 2-10 seconds.

By observing the above key kinds of literature, it can be found that WNCS system requires highly robust and efficient wireless routing protocol that could ensure reliable and timely data deliver (say, communication) across NCS (amongst sensors, controllers, actuators or automation controllers etc). To achieve it, classical WSN systems can't be sufficient, especially under cluttered and noisy environments such as plants. On the other hand, the use of mobility with native RPL can be vital to achieve time-efficient and reliable communication across WNCS. However, mobility management required efficient routing and hybrid network management strategy (including reactive as well as proactive node management with link-sensitive route update). Considering these facts, this research primarily focuses on developing a robust fault-tolerant and reliable mobile RPL routing protocol for WNCS communication purposes.

III.   PROPOSED ROUTING PROTOCOL

As discussed in earlier sections WNCS encompasses many sensor nodes distributed or allocated across the region of interest (say, network region), and therefore retrieving sensing data reliably from each node within deadline time becomes inevitable. On the other hand, Industrie-4.0 standard based smart factory too demands reliably and timely data delivery to the cloud infrastructures to ensure decentralized monitoring and control. Observing Fig. 1, it can also be found that to enable efficient NCS assuring optimal data transmission from sensors to the Network Gate Way (NGW) or control models is must. It needs a certain suitable networking solution, especially wireless communication paradigm to accomplish the above -stated objectives. Towards these objectives, a wireless communication protocol with fault-tolerant, reliable data transmission and internet adaptivity can be of utmost significance. With this motive, in this research paper the predominant emphasis has been made on developing fault-tolerant and reliable data transmission system between sensor nodes and the gateway (also the network controllers). Towards this objective, in this paper we have exploited IPv6 routing protocol for Low Power Lossy Networks (LLNs) also called RPL protocol which has been augmented to accomplish better performance. Noticeably, the cluttered environment with numerous noise presences across industrial scenarios, the use of LLNs becomes inevitable. On the other hand, in modern communication paradigms, mobility of nodes has broadened the horizon for reliable communication even across a large scale network. With this motive, in this paper a robust fault-tolerant and reliable data communication paradigm is developed for WNCS system. Considering RPL as a potential solution for WNCS this research intends to optimise classical or native RPL with a novel mobility feature supported by a suitable link-outage resilient routing mechanism.

As already discussed in previous sections, most of the existing approaches targeting mobile-RPL have applied timers such as handoff timers, response tracking timers, connectivity timers, etc so as to ensure that the link exists in a suitable range or appropriate. However, such inclusions make overall protocol computationally bulky and resource exhaustive and delayed, which cannot be recommended for WNCS that on contrary demands timely data delivery so as to make early control decision.

Unlike classical routing approaches, in this paper the focus is made on reducing additional components or functional entities such as the different timers, as mentioned above (except trickle timers that help scheduling network discovery at a definite interval). We intend to design an autonomous link monitoring and transmission control model over WNCS to retain QoS provision and reliable communication. Considering the fact that dynamic topology within a large scale network might cause iterative link outage or congestion, in this research a fault-tolerant and reliable link-outage repair paradigm is developed. In fact, the proposed work encompasses multiple contributions, such

as multi-objective functions based routing decision, mobility control or management under dynamic topology and QoS sensitive link-repair model. These contributions could ensure optimal data transmission over WNCS to accomplish QoS provision. The overall contribution of the proposed routing protocol can be stated as a Fault-Tolerant and Reliable mRPL Routing Protocol for WNCS (FTmRP-NCS). Our proposed FTmRP-NCS contributed the following:

1. RSSI assisted mobile-sensor node placement across WNCS to retain reliable and fault resilient data transmission,
2. Multi-objective function (RSSI and ETX) based routing decision or best parent node selection,
3. Fault-tolerant alternate path formation and link repairing model for QoS centric reliable data delivery over industrie-4.0 WNCS.

A graphical abstract of the proposed routing protocol is given in Fig. 1.
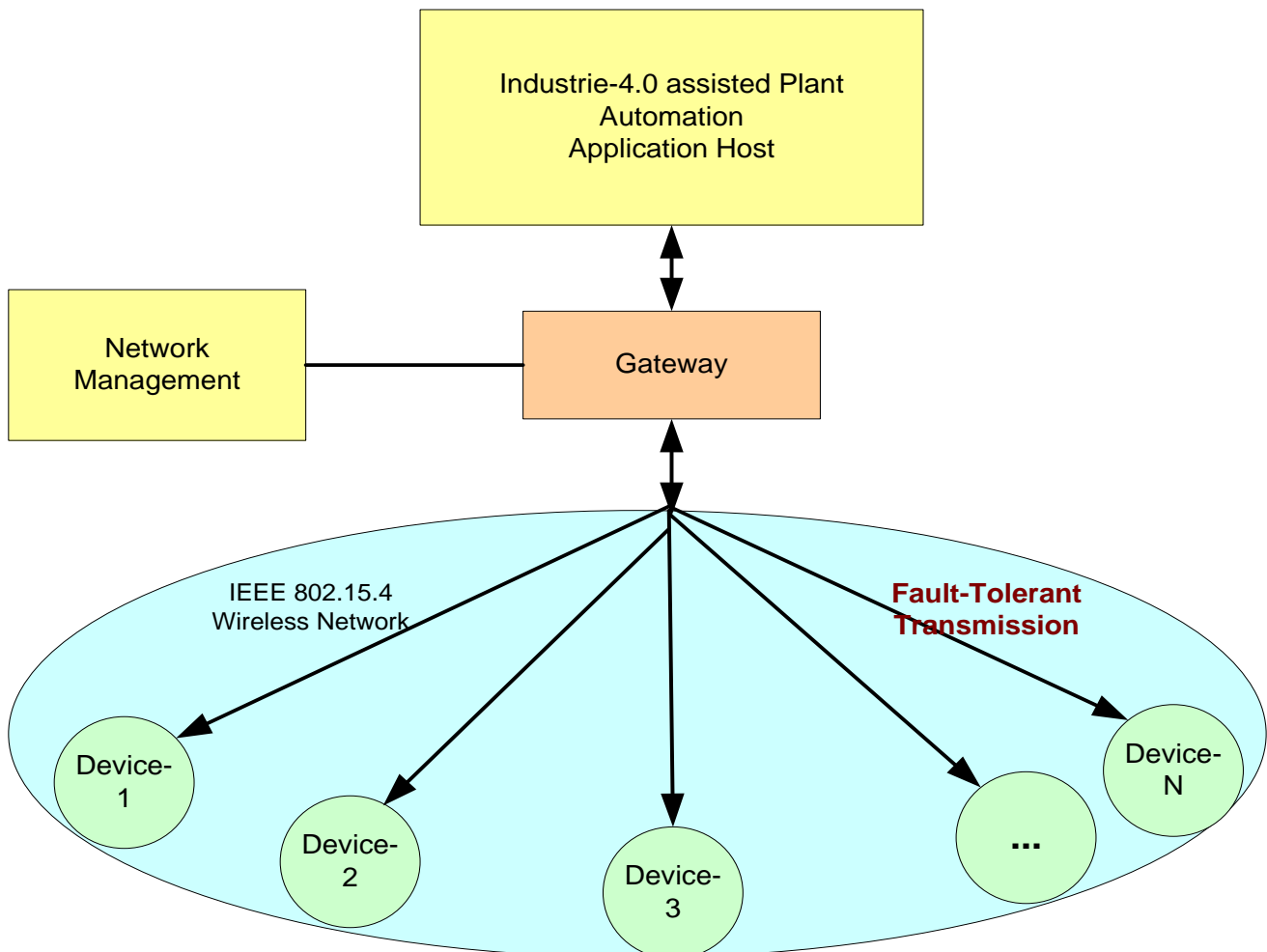

Fig. 1. An illustration of the need of fault-tolerant and reliable communication system in Industrie-4.0 assisted industrial automation

The detailed discussion of our proposed NCS routing model is given as follows:

Detecting any link-outage FTmRP-NCS routing protocol at first initiates' link repair functions that comprise two key functions named Local Link Repair (LLR) and Global Link Repair (GLR). Here, the LLR operates once identifying or detecting sensor malfunction or death and when parent node

undergoes same situation or fault. On the contrary, GLR is initiated by a parent node when the network is needed to be re-constituted after Destination Oriented Distributed Acyclic Graph (DODAG) formation. LLR operates once identifying any node failure during communication.

In this scenario, FTmRP-NCS identifies an alternate path towards the NCS-gateway or the controller to ensure reliable and QoS provision. FTmRP-NCS is designed in such a manner that even in the case when there doesn't exist any alternate node or path to accommodate NCS sensor's data, the device may function as a new node or autonomous device that could multicast DODAG Information Solicitation (DIS) to perform a suitable alternate path formation for reliable data delivery. Noticeably, our proposed routing protocol ensures that the node or network discovery during link-outage doesn't impose significantly high computational overheads.

However, in practice, especially in the network environment with mobile sensor nodes there can be iterative congestion and the link-outage probability that could force FTmRP-NCS to undergo link-outage condition regularly. To avoid such issues, in this paper, proactive network management strategy has been taken into consideration where different dynamic network parameters such as Received Signal Strength Indicator (RSSI) and Expected Number of Control Packets (ETX) have been considered for topology management. This as a result helps to ensure a reliable link for successful data delivery. In this process, once initiating node discovery often called ND the node features for each participating node is collected and stored in a priority-based hash table. In later stage, detecting any link-outage or node-failure FTmRP-NCS assesses each node in the table for its superior RSSI and ETX feature values so as to select the best parent node. Noticeably, in our proposed FTmRP-NCS routing protocol a node with the highest RSSI and the minimum ETX is selected as the parent node to constitute DODAG for successful data transmission to the NCS-gateways, here onwards called NCS-GW. To be noted, our proposed FTmRP-NCS routing protocol has been applied at the top of the native link-layer of the RPL that ensure both time efficiency, as well as backward compatibility of the IETF, recommended RPL. This approach can allow FTmRP-NCS to execute link-repair and ND (if required) once detecting any link outage at the link-layer of the IEEE 802.15.4 protocol stack. In case of a re-constituting best forwarding path, it can obtain the best possible (available in proactively managed node set) parent node. In case there is no alternate parent node available FTmRP-NCS initiates ND and thus avoids iterative ND execution for best forwarding path selection. In addition to the above stated features, recalling the fact that the proposed system employs both RSSI and ETX as an objective function to make a routing decision, FTmRP-NCS protocol exploits these link quality parameters dynamically to perform mobility management. The implementation of our proposed routing model for WNCS control is depicted in Fig. 2. Noticeably, the proposed routing model is implemented on each participating node of the network (Fig. 1.
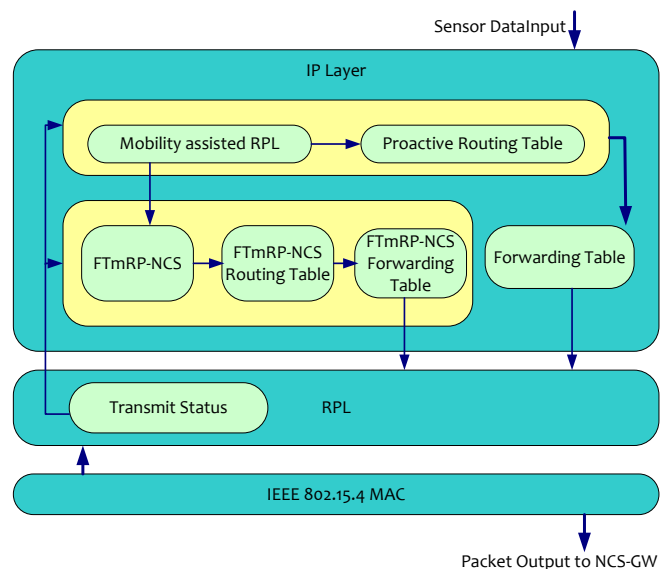

Fig. 2. Implementation schematic of the proposed FTmRP-NCS routing protocol

A. RSSI LQI assisted Topology Sensitive Route Control for Fault-Resilient WNCS

Considering the fact that the native-RPL doesn't have any sophisticated model to deal with mobility or dynamic topology conditions, we consider the sensor node's mobility as the challenge and exploit link-quality parameters such as RSSI and allied Packet Delivery Ratio (PDR) information perform mobile node localization so as to ensure outage-resilient reliable data delivery. In contrast to the conventional random movement-based mobility management model, we defined an approach called Definite Communication Range (DCR) which is used to perform mobility control. In practice, WNCSW with different autonomous operating nodes can have sensors of both static as well as mobile characteristics. Here onwards we refer static nodes as anchor nodes. Our proposed FTmRP-NCS protocol implements proactive node table management (PNTM) that estimates RSSI of each node dynamically, which is used further to decide optimal movement pattern by mobile nodes. Noticeably, such features can be easily implemented in large network region with multiple nodes and in multi-hop communication approach. In another way, there can be an open network environment where a mobile node such as Drones can be applied to collect real-time senor data to make control decision. In such an environment the use of dynamic per-node RSSI can help a network controller to assist best routing decision and forwarding path selection. PNTM executes beaconing to collect RSSI information of each node, which is updated in node table where nodes are prioritized with respect to its link quality values or RSSI.

To perform node localization FTmRP-NCS protocol exploits DCR information in which the mobile sensor node obtains its geographical location by overlapping DCR of the different anchor nodes. Here, it estimates the effect of each static or anchor node on the link reliability so as to ensure optimal forwarding path selection. It ensures reliable data transmission across the network.

Noticeably, the RSSI value obtained for an anchor close to the mobile node would always be more in comparison to the RSSI of the node existing at a farther distance. Thus, the reliability of the link with initial cases (having higher RSSI) would always be better than the other (link with lower RSSI). In such cases augmenting the mobility management by assisting mobile node to the target sensor across the network can help to avoid link outage problem due to improper path formation. Here, we hypothesize that the DCR factor functions on the basis of an assumption that the mobile node has the knowledge about the time-varying link conditions using long-distance path model. Now, applying this method, the RSSI value at a node at a certain time instant t can be obtained as (1).

$$RSSI^t = S_{1m} - 10\alpha \log_{10} d - \beta \qquad (1)$$

In (1), the variable S_{1m} states the signal obtained at the distance of 1 meter and α signifies path-loss exponent with D meter radio range. In addition, $\beta \sim \mathcal{N}(0, \sigma_\gamma^2)$ refers to the zero- mean Gaussian noise. Here, we estimated the distance between the anchor node and the mobile node using (2).

$$\widehat{D}_{RSSI}^t = 10^{\frac{RSSI^t - S_{1m}}{10\alpha}} \qquad (2)$$

Noticeably, because of the exponential relationship between distance value (2) and its link quality information (in terms of RSSI), $\widehat{D}_{RSSI}^t$ applies Gaussian distribution function. Applying log-normal distribution function for inter-node distance estimation we obtain,

$$\ln \widehat{D}_{RSSI}^t \sim \mathcal{N}(\ln D^t, \sigma_d^2) \qquad (3)$$

In (3), the variable D^t states the distance between the anchor node and the mobile node at tth time instant. Here, the standard deviation (σ_d) is obtained using (4).

$$\sigma_d = (\sigma_\gamma \ln 10) = (10\alpha) \qquad (4)$$

Now, applying the above derived values, the probability density function (PDF) has been obtained using (5).

$$PDF(\widehat{D}) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_d \widehat{D}} \exp - \frac{(\ln \widehat{D} - \ln D)^2}{2\sigma_d^2} & \text{if } \widehat{D} > 0 \\ 0 & \text{if } \widehat{D} \le 0, \end{cases} \qquad (5)$$

In (5) D signifies the distance. Once estimating PDF, we have derived DCR of a-th anchor node, where a new attribute C_a signifying DCR is estimated where the mobile node f is supposed to exist to gather data reliably. Let, the mobile sensor node exists within the DCR, and then the confidence likelihood be DCR_{prob}. Typically, in major NCS environment sensor nodes are armoured with omni-directional antennas that make DCR as a circular periphery with the communication range, denoted by r and centred over a-th anchor node. DCR_{prob} is obtained as (6).

$$DCR_{prob} = Pr\{D^t \le r\} \qquad (6)$$

Further,

$$DCR_{prob}(r) \simeq \int_{0+}^{r} \frac{1}{\sqrt{2\pi}\sigma_d x} \exp\left(-\frac{(\ln x - \ln \widehat{D}_{RSSI}^t)^2}{2\sigma_d^2}\right) \qquad (7)$$

In (7), m-th node defines its DCR value by overlapping different DCRs of the N closest anchor nodes. Mathematically, it can be presented as:

$$L_f = L_1 \cap L_2 \cap \ldots\ldots \cap L_N. \qquad (8)$$

In (8) N states the total DCR formed with reference to the neighbouring anchor nodes. FTmRP-NCS enables localization of the mobile node to retain reliable communication. The optimal location $\widehat{P}m$ within DCR is obtained using (9). Practically, it is achieved by identifying the location of the discrete points within L_f, as defined in (8). In our proposed routing protocol, the mobile node uses PDF value to assess the likelihood of a node to be available within L_f. Now, hypothesizing that the anchor nodes are self-directed mobile node can identify its optimal location to perform reliable data gathering from the NCS sensor nodes. The mobile node location identified would be obtained as (9).

$$\widehat{P}m = \max_c \prod_{a \in A^P} DCR_{prob}(D_{c,a}) \, \forall c \in L_m \qquad (9)$$

In (9), $D_{c,a}$ signifies the Euclidean distance in between cth and ath anchor nodes. The other attribute A^P refers to the nodes participating during mobile node localization. Thus, it becomes possible to gather NCS sensor data reliably and timely by means of inducting mobile node (for data gathering). However, such an approach often causes topological variation resulting in packet loss probability. To alleviate this problem FTmRP-NCS applies multiple OF including RSSI and ETX to decide best parent nodes dynamically. The detailed discussion is given as follows.

B. Multiple Network Parameters assisted Best Parent Node Selection for FTmRP-NCS

Considering the overall functional characteristics of the WNCS system, it can be observed that it employs two way of communication, one performing transmission between two NCS (static) sensor nodes where it intends to transmit data to the gateway for autorotation control. The other mode of communication can be from a mobile sensor to the anchor or vice versa.

In NCS systems there can be multiple anchor sensor nodes that collect real-time process or event information and passes it to the network controller or automation control system through a network gateway. This process of communication within two or multiple static nodes can be stated as inter-anchor node (IAN) communication. In this case, the static nature of nodes deployed avoids any topological changes, until a participating node doesn't die. It retains the network more stable. In this transmission mechanism, a node can assess the neighbouring node for its suitability as the best forwarding node using distance and residual energy factor.

On the contrary, the communication between the mobile sensor node and an anchor node might undergo topological changes along with link quality (i.e., strength) variations. This as a result, could cause link-outage and hence can adversely affect QoS transmission over WNCS. Considering the above-stated condition, though the native RPL can be sufficient for IAN, its efficacy remains suspicious for mobile node based data gathering over WNCS. In such cases, optimizing native-RPL can be a potential solution by incorporating dynamic best forwarding path selection measures and DODAG formation while keeping computational overheads within the cap. In this approach, DADOG is constituted by means of DIOs messages where at first the transmitter node transmits multiple messages to the neighbouring nodes across WNCS that helps it receiving single DAO messages as a unicast message from multiple nodes. In this method, DAO packets are obtained as ACK that embodies key network information comprising RSSI information and ETX values, pertaining to each possible link. Obtaining these key factors each link can be inferred in terms of certain rank information (signifying efficacy of the node to become a parent or the best forwarding node). The node-rank of each participating sensor nodes helps to make a proactive node table characterizing possible parent node where each node is ordered in the decreasing order of respective rank values.

In this manner, the node with the highest rank (characterizing higher RSSI and minimum ETX) is selected as parent node that helps to form DODAG for reliable data transmission to the gateway or eventual NCS network controller or automation units. With the estimated RSSI value of i-th node available in proactive (parent) node table, the PDR of that corresponding link can also be obtained. In addition, it can help ETX estimation using (10).

$$ETX_i = \frac{1}{PDR_{i,j}} + ETX_j \qquad (10)$$

ETX_j in (10) signifies the total number of control packets required to communicate between i-th anchor node and jth forwarding node. Similarly, ETX_j refers to overall control messages required from j-th node to the anchor node. The overall PDR value between i-th and j-th nodes within WNCS is $PDR_{i,j}$.

$$\left(ETX_{ij} = \frac{1}{PDR_{i,j}} \right) \qquad (11)$$

Thus, exploiting RSSI and ETX values for any link or node FTmRP-NCS protocol perform best parent node selection for reliable data delivery over WNCS. Now, identifying the best parent node FTmRP-NCS protocol forms DODAG towards the network gateway, where the sensed data are collected and further processed by the network controller and automation controllers to make a transient decision. Furthermore, to assist above stated transmission decision, while transmitting data from the ath anchor node the overall ETX needed to transmit data via f-th mobile node is obtained by summing it to the ETX required from a-th anchor node (denoted by $ETX_{f,a}$). Thus, the total ETX needed to be (12).

$$ETX_f = ETX_{f,a} + ETX_a \qquad (12)$$

ETX_a Can easily be estimated by using rank information of the a-th anchor node. Now, to estimate the likelihood of a node to become a parent node, DIO message is unicast by the sensor nodes that acknowledged RSSI and ETX information to the requesting node. In FTmRP-NCS PDR is estimated between mobile and the a-th anchor node at t-th time instant when the RSSI is higher than the transceiver's sensitivity ($RSSI_{th}$). In other words,

$$PDR_{f,a} = Pr\{RSSI_{f,a}^t \geq RSSI_{th}\} \qquad (13)$$

Now, with increase in inter-node distance and reducing RSSI, $PDR_{f,a}$ would be (14)

$$PDR_{f,a} = Pr\{\beta \leq S_{1m} - 10\log_{10} d_{f,a} - RSSI_{th}\}. \qquad (14)$$

Considering β as a Gaussian distribution function $\mathcal{N}(0, \sigma_\gamma^2)$, the PDR in between the anchor sensor node and the mobile node can be obtained using (15).

$$PDR_{f,a} = Pr\{\beta \leq X\} = \int_{-\infty}^{X} \frac{1}{\sqrt{2\pi}\sigma_\beta} \exp\left(-\frac{\beta^2}{2\sigma_\beta^2}\right) d\beta, \qquad (15)$$

In above derived PDR estimation model (15), the condition with X signifies higher precision than the classical $S_{1m} - 10\alpha\log_{10}\hat{D}_{f,a} - RSSI_{th}$ based approach. In our proposed FTmRP-NCS routing protocol $D_{m,a}$ has been substituted by $\hat{D}_{m,a}$. Thus, exploiting dynamic RSSI and PDR information, the $f-$th mobile sensor node performs parent node, a_f selection so as to ensure reliable and fault resilient transmission. Mathematically,

$$a_f = \arg\min_t \left(\frac{1}{PDR_{f,t}} + ETX_t\right), \quad \forall t \in \mathcal{K}_f. \qquad (16)$$

The above discussed approach enabled our proposed FTmRP-NCS routing protocol to exhibit reliable data transmission even under dynamic topology. Though, above discussed approaches strengthen FTmRP-NCS protocol to assure reliable and timely data delivery to the NCS network gateway, it requires armouring with a certain fault-resilient approach where even in case of a certain fault it may assure delivering data to the gateway timely. With this motive, in this paper, we have developed a link repair model comprising GLR and LLR concepts.

C. Link-Repair and Supplementary Path Formation for QoS provision over WNCS

In order to strengthen the robustness of the proposed routing protocol and preserve the concept of "Backward Compatibility", in this paper we have inherited native RPL protocol which has been further enhanced to achieve the targeted goal. Here, to perform IAN (Internet Area Network) communication the native RPL functions conventionally; however to perform mobile to anchor node or vice versa communication we implemented our proposed FTmRP-NCS routing protocol.

In the case of native RPL implementation we applied ETX and RSSI information to form DODAG so as to assure reliable communication. Mobile nodes require dealing with link instability due to both Spatio-temporal variations that force the link to vary over time or distance. In WNCS the environment there can be numerous sensors deployed across the network region to collect event data or process variables where it might use anchor nodes as well to forward data to the gateway for transient decision. Moreover, dynamic topology might cause insufficient information availability that might cause link outage. In addition, continuous link quality changes may also affect best parent node selection and DODAG formation that could affect overall network performance. Though reducing DIO frequency can help to minimize computational overheads, however, it may confine node information exchange so as to retain sufficient dynamic link quality monitoring. In case of insufficient information there can be iterative link outage causing QoS degradation. To adapt with such dynamism and allied link update mechanism we scheduled trickle timer at 2 seconds for DIO transmission. As stated our proposed FTmRP-NCS routing protocol is applied in parallel to the link-layer of IEEE 802.15.4, once detecting any link outage at the link layer, it executes link-repair model that helps to identify the best alternate parent node from the proactive node table to form an alternate forwarding path.

Exploiting RSSI and ETX information FTmRP-NCS ranks each node in the table and tries to select the best parent node to update DODAG for successful data delivery. Since this process doesn't execute node discovery iteratively and hence avoids computational overheads and energy exhaustion. Unlike conventional routing approaches, FTmRP-NCS protocol disables trickle timer once forming the alternate forwarding path or DODAG with suitable parent node. This, as a result, avoids resource exhaustion as well as iterative route update thus making communication more reliable even over dynamic network conditions. Considering a scenario where there is the probability of data getting dropped due to link outage, our proposed FTmRP-NCS routing protocol applies backup based supplementary data transmission where once detecting any link-outage it transmits undelivered data through the newly formed alternate forwarding path. In addition, our proposed FTmRP-NCS protocol maintains backup of the data (clone of the original data) under transmission and once detecting any packet loss or data drop it transmits a backup data without requesting native transmitter. Performing such a novel effort it not only reduced retransmission cost or delay but also avoid unwanted resource exhaustion without compromising with QoS delivery over WNCS. Thus, this approach enables fault-tolerant and reliable data transmission over WNCS.

The simulation results obtained and their respective inferences are presented in the subsequent section.

IV. RESULTS AND DISCUSSION

In this research, the predominant focus was made on developing a novel wireless routing protocol to be used in WNCS communication purposes. Realizing the fact that WNCS may often undergo cluttered and noisy environment classical noise-sensitive routing approaches could not be an optimal solution. On the other hand, realizing the need for an optimistic approach to accommodate Industrie 4.0 assisted Smart Manufacturing process, in this research RPL routing protocol was taken into consideration. Recalling the definition, RPL signifies IPv6 Routing Protocol for Low Power Lossy Networks; it seems suitable for real-time application where the sensed data can be collected to the cloud to enable decentralized monitoring and control. However, considering the fact that the native RPL can't be a suitable solution for modern NCS communication where timely and reliable data communication is inevitable, in this paper a novel Fault-Tolerant and Reliable mobile RPL (say, mRPL) Routing Protocol was developed for WNCS (FTmRP-NCS). Unlike classical WNCS routing approaches FTmRP-NCS applied multiple optimization measures such as multiple objective functions based best forwarding node (say, parent node) selection, RSSI assisted (link sensitive) mobile node localization, fault sensitive link repair model etc. In addition, the focus was maintained on retaining optimal performance without imposing any significant computational overheads, which is a common issue in major wireless communication protocols. In existing work, major efforts have been made by using either ETX or RSSI as link characterizing parameter. On the contrary, in this paper both RSSI as well as ETX was taken into consideration to perform routing decision. Recently, authors [58] tried to use this combination for routing decision; however the use of multiple timers imposed computational overheads significantly that confines its suitability for WNCS communication where maintaining minimum overheads, minimum delay and higher Packet Delivery Ratio (PDR) is a must. In addition, existing works still exploit reactive route management that seems confined, while in FTmRP-NCS protocol we have used proactive node management that updates parent nodes dynamically at the interval of defined trickle time, which is selected as 2 ms in this paper. Noticeably, FTmRP-NCS protocol uses 5kb flash memory that makes it suitable to be used under resource-constrained communication environment and even it can be cost-effective for NCS purposes. The overall proposed system has been developed using Contiki operating system with Cooja network simulator. To simulate the developed model, Ubuntoo 14.4 was considered as an operating system. Here, each node was deployed with Unit Disk Graph Medium (UDGM) radio property that follows the distance loss pattern during communication. Its consideration is well justifiable due to changing topology and respective inter-node distance variation that eventually influences signal strength or link loss. Noticeably, the proposed FTmRP-NCS protocol was applied in parallel to the link-layer of native RPL (with IEEE 802.15.4 MAC) and hence no major changes were made in IETF recommended standards [17]. Therefore, our proposed routing protocol follow backward compatibility concept and hence can be used for real-time application. Considering the mobility feature of the mobile sensor node, we assigned 5m/s as the speed of node during the simulation.

Considering the fact that so far no justifiable effort is made to exploit mobile RPL protocol for WNCS routing, in this paper to assess the efficiency of the proposed routing protocol we compared its performance with native RPL. On the other hand, in WNCS reliable data delivery and delay-resilient transmission is inevitable and therefore the performance of both FTmRP-NCS as well as (native) RPL was obtained in terms of PDR, Packet Loss Ratio (PLR) and delay.

To present the comparative performance the log-performance obtained by Contiki simulation was processed using MATLAB and different graphs with varying network density and payload conditions were obtained. In a typical industrial application environment, a set up can be different than others, especially in terms of the number of sensors, the size of data being communicated etc. Undeniably, increasing the number of sensor nodes can have an impact on the performance of any routing protocol. Similarly, the nature of communication (i.e., data under transmission), the severity of transmission or payload condition can vary. This factor too can have an impact on the overall network performance, since higher payload often causes contention and/or congestion in the network and thus reduces overall PDR performance (due to increased packet drop or PLR). Considering this fact, in this paper we focused on assessing performance by varying node density (here, node signifies a wireless sensor node with definite radio range and memory capacity) and payload (data size/severity under transmission).

A. Performance under varying Network Density

To examine the efficiency of our proposed FTmRP-NCS routing protocol we have assessed performance by varying node density where each node was following UDGM and distance loss pattern. In addition, nodes were deployed uniform radio range of 100 meters. Here, each node was configured as T-mote sky. Simulating our proposed routing protocol, PDR, as well as PLR,

were obtained for each simulation case (by varying node size at 10, 20, 30, 40, 50 and 60). The respective PDR values were obtained from log outputs and were plotted using MATLAB 2017a tool. As depicted in Fig. 4, the maximum PDR by FTmRP-NCS was almost 98%, where the average PDR performance was obtained as 89.10% while the classical RPL could exhibit merely 72.7% of the PDR over the same simulation environment. Similarly, PLR performance by FTmRP-NCS routing protocol exhibits that it exhibits an average PLR of 10.84% which is lower than the native RPL protocol (27.13%) (Fig.4). It can be because of unavailability of mobility management feature and hence due to dynamic topology and link variations it could have undergone significantly high packet losses (Fig. 4). The effect of such unwanted packet losses can be visualized in Fig 5 where the classical RPL exhibits higher delay than the proposed FTmRP-NCS routing protocol. Noticeably, FTmRP-NCS exhibits higher PDR and hence the minimum probability of retransmission that eventually avoids any delay incurred.
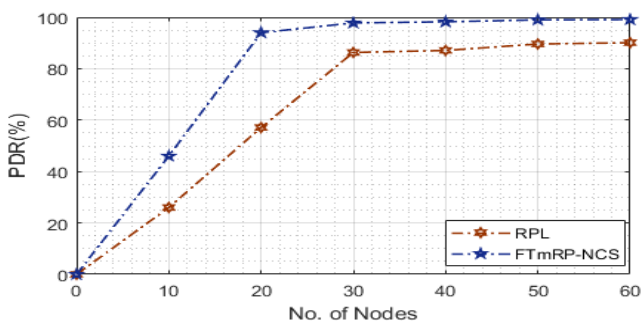

Fig. 3. PDR performance under varying network density or node of nodes

Observing overall results (Fig. 3 to Fig 4) it can be found that though both protocols undergo packet loss by increasing node density; however the proposed FTmRP-NCS protocol exhibits relatively lower PLR than native RPL. Interestingly, with increasing nodes FTmRP-NCS exhibits better PDR which can be due to the sufficient number of nodes available to form a forwarding path. In other words, there can be a scenario over NCS environment where nodes can be deployed across the network region however due to low node density mobile nodes or even anchor nodes may lack forming best forwarding path. And therefore it can undergo packet losses. On the contrary, with an increase in node density, both anchor nodes, as well as a mobile node, get sufficient nodes in proactive parent node-set (table) to form forwarding path, even under link-outage condition. It helps to enable reliable (Fig. 3) and timely (Fig. 5) data delivery over WNCS.
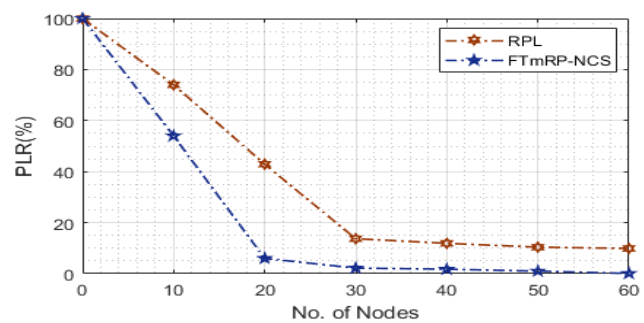

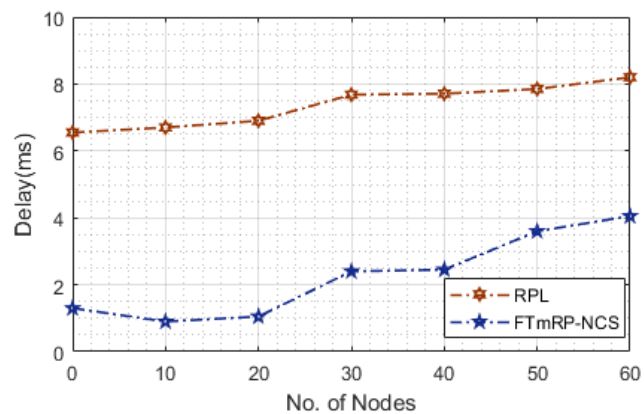**Fig. 4. PLR performance under varying network density or node of nodes**

Fig. 5. Delay performance under varying network density or node of nodes

B. Performance under varying Load Conditions

In any network, the successful data delivery often depends on network condition such as buffer availability, congestion, link quality etc. However, buffer availability at a node plays a decisive role in accommodating data to forward towards its destination. In other words, an increase in the payload can have an impact on a node whether it can transmit data successfully. The probability of congestion or resulting data drop can increase significantly due to an increase in payload or packet size. In real-time NCS environment, the dynamic payload can be a common event where a routing protocol is expected to accommodate payload without affecting overall performance.

With this motive, we examined FTmRP-NCS protocol's PDR, PLR and delay performance by changing payloads. Here, we considered payloads with 1000 bits/second (bps), 2000 bps, 3000 bps, 4000 bps and 5000 bps. The respective performance was obtained in a different payload condition. Fig. 6 presents the PDR performance by our proposed FTmRP-NCS routing where it has exhibited better performance than the native RPL. Similarly, PLR performance (Fig. 7) to confirm that our proposed routing protocol exhibits less PLR deviation due to an increase in payload. Its influence on delay performance can be observed in Fig. 8, where FTmRP-NCS exhibits lower delay than the native RPL protocol.
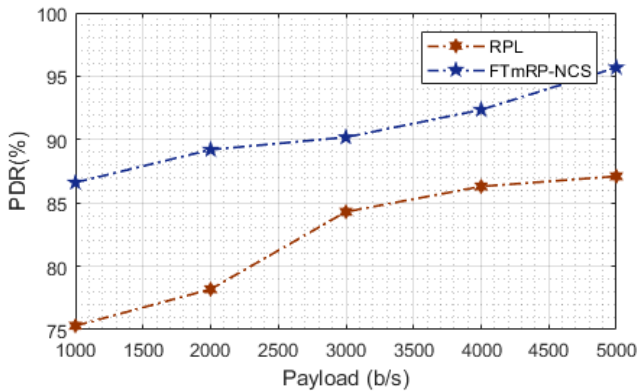
Fig. 8. Delay performance under varying payload condition

Fig. 6. PDR performance under varying payload condition
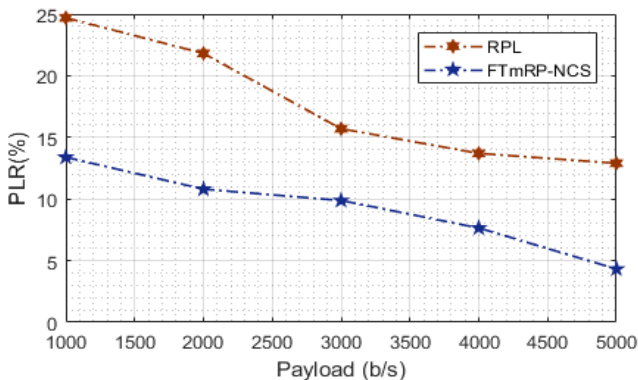
Fig. 9. Comparative performance

Fig. 7. PLR performance under varying payload condition

Thus, observing overall performance it can be found that the proposed FTmRP-NCS routing protocol exhibits better than the native RPL while preserving the concept of backward compatibility and hence can be a potential communication paradigm for WNCS applications that primarily demands high PDR (reliable data transmission) and low delay. Considering fault resiliency, FTmRP-NCS is implemented in parallel to the link-layer of IEEE 802.15.4 and hence once detecting any link outage or fault it executes link repair function where at first it tries to re-constitute alternate forwarding path by selecting the best alternate parent node from proactively arranged parent node-set. As GLR solution, once identifying that there is no sufficient alternate parent node available in the parent node-set, it executes node discovery. This overall process reduces iterative node discovery and hence computationally more efficient than the classical approaches.
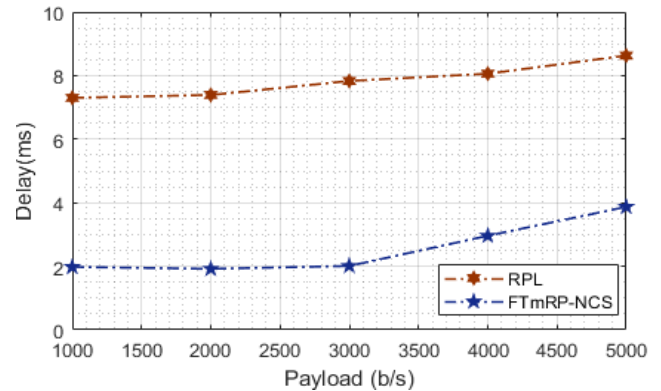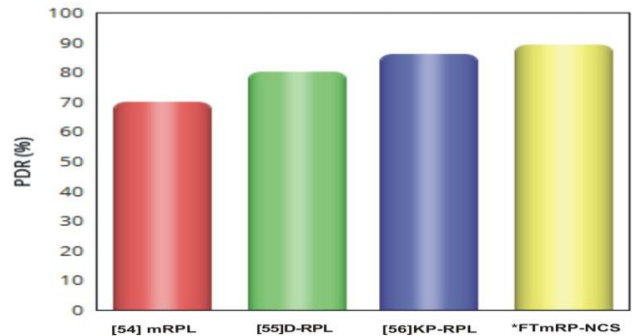
To examine the performance of the proposed FTmRP-NCS routing protocol, we have performed the qualitative assessment by reviewing other existing mobility assisted RPL protocols [52][54-56]. In [52] [54] authors applied multiple timers and handoff optimization to achieve mobility based RPL; however, authors could not address the computational overheads imposed. It confines their suitability for our intended WNCS communication. On the other hand, authors [55] developed a dynamic RPL for multi-hop routing in IoT where they used RSSI as OF to perform routing decision. Authors [55] could achieve average PDR of 80%. Similarly, in [56] authors used mobile position metrics assisted RPL routing to achieve link sensitive routing. Since, their proposed system employed multiple value additions such as dynamic mobile node localization, blacklisting it used ETX as OF to perform routing decision. Unlike [56], our proposed FTmRP-NCS protocol applies both ETX as well as RSSI to make a routing decision. In addition, we implement proactive network management followed by a computationally efficient link-outage repair system. Such novelties have augmented our proposed routing protocol to exhibit 89.1% average (Simulated) PDR which is higher than the existing KP-RPL that could achieve a maximum 86% of the PDR. It affirms robustness of our proposed model over the classical approaches. The overall conclusion of the presented research work is given in the subsequent section.

V. CONCLUSION

In the last few years, an NCS system has emerged as one of the most demanding technologies serving industrial communication and control. However, increasing complexity and allied fault proneness has alarmed academia-industries to achieve a reliable and QoS oriented wireless transmission system to enable timely network and automation control.

Considering the overall functional scenario of WNCS system, it is important to sense different process or even parameters from plant and transmit it to the network controller or automation controller. In this process, assuring timely and reliably data transmission from sensors to the gateway and automation controller is a must. On the other hand, the emergence of IoT assisted smart production system too demands timely and reliable data gathering at the automation controller in NCS. Majority of the classical routing approaches lacks incorporating mobility and internet connectivity under lossy network conditions. Considering this as motivation, in this paper a robust routing protocol named Fault-Tolerant and Reliable mRPL Routing Protocol for WNCS (FTmRP-NCS) was developed. Unlike classical routing approaches, the proposed FTmRP-NCS protocol incorporated multiple robustness such as RSSI assisted mobile-sensor node placement across WNCS, Multi-objective function (RSSI and ETX) based routing decision and QoS centric (fault-tolerant) alternate path formation and link repairing model that as a combined solution achieved better performance. Noticeably, the use of RSSI based mobile node localization enabled reliable and time-efficient data gathering from the sensor nodes across NCS. On the other hand, the inclusion of both RSSI as well as ETX accomplished routing decision by balancing the optimal trade-off between link quality as well as computational overhead.

This strengthened proposed routing approach to assure reliable communication without imposing computational costs. During the process, the use of proactive node management reduced iterative node discovery to form alternative forwarding path or DODAG during link outage. The link-outage repair model and allied efficiency strengthen FTmRP-NCS to retain computationally efficient routing which can be of great significance for WNCS system where there used to be huge cooperatively functional autonomous sensor nodes demanding timely data delivery to the network gateway and hence automation controller (or vice versa). The Contiki based simulation has exhibited that the proposed FTmRP-NCS routing protocol outperforms native-RPL in terms of Packet Delivery Ratio, Packet Loss Ratio and delay etc. Noticeably, the use of proposed FTmRP-NCS routing protocol in parallel to the link-layer of native-RPL enabled retaining backwards compatibility and hence can be applied for real-time communication.

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