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Scalable Emulated Framework for IoT Devices in Smart Logistics Based Cyber-Physical Systems: Bonded Coverage and Connectivity Analysis

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ABSTRACT In this research, scalable framework for Smart Logistics based Cyber-Physical System (SLCPS) is emulated for stable coverage and connectivity of Internet of Things (IoT) devices. This work is modern manifestation of three laws of computing. Moore's and Koomey's laws recommend performance gain and energy efficiency whereas Metcalfe's law imply network scalability. Combination of these laws suggests the research proposition that development of scalable and performance efficient IoT networks is inevitable. Although IoT has improved specific logistics modules considerably, but incorporation of IoT in complete supply chain of food and random placement of IoT devices due to which unstable coverage and connectivity occurred are major challenges in logistics. The proposed SLCPS framework is designed firstly, to develop apt IoT protocol stack for logistics. Secondly, for bonded connectivity and coverage, mathematical models are proposed instead of random placement and coverage map is based on binary coverage model. Thirdly, for scalability supply chain of food for smart logistics process is designed in terms of container, storehouse and warehouse comprising of varying number of IoT devices. The architecture of SLCPS framework has three modules i.e. internal IoT network, border router and external network, emulated in Cooja simulator. The contikimac protocol is used for efficient traffic flow and power consumption. Single hop, multiple hops and random IoT devices placement scenarios are used for results comparison and validation. The performance evaluation results, i.e. throughput, network convergence time, packet delivery ratio, average latency, power consumption and timeline investigation validated utilization of proposed framework in terms of enhanced network performance. Significance of proposed SLCPS framework results in cost minimization, reducing communication and computation overhead, resilience to IoT device failures and an interference free network connectivity and coverage. Coverage and connectivity are measure of quality of service in IoT network. Therefore, this research provided bonded coverage and connectivity in smart logistics using mathematical models. In addition, a baseline framework is provided for extended research in CPS and IoT applications.

INDEX TERMS Cyber-physical systems, cooja, coverage and connectivity, the Internet of Things, the IoT device placement and smart logistics.

I. INTRODUCTION

The latest up rise in Internet of Things (IoT) is smart environment, where physical objects assigned with IP addresses are incorporated with sensing and actuating abilities and connected with internet to collect, process and generate data by control and monitoring of real environment. Cyber-Physical Systems (CPS) integrate sensing, computation, control and networking into physical objects and infrastructure, connecting them to the internet and to each other. When things/physical objects speak without involvement of livings humans, the technology is termed as Internet of Things (IoT) [1]. Both CPS and IoT attempt to integrate digital capabilities, including network connectivity and computational capability, with physical devices and systems. Examples range from intelligent vehicles, smart transportation to advanced manufacturing systems, smart grids, smart agriculture, smart cities, smart health-care and most importantly smart logistics [2].

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In general, the most prevalent requirements for transportation and logistics are to have the right product at the right time at the right place and in the right state. But in percentage 33 to 35% of the food/perishable items do not arrive at the consumer's place in the right condition [3]. The basic cause of this loss is the change in environmental parameters i.e. heat, temperature and humidity etc. To solve such issues, constant monitoring of environmental parameters from farm to fork is required, but the monitoring mechanism from farm to fork i.e. in complete supply chain of food is not implemented properly. Telematics technology is used, but it measures the temperature of whole unit not of product. Similarly, radio-frequency identification (RFID) scanners and Barcode readers (line of sight necessary for barcode reader) can trace only routes and not quality of products. For the said purpose, the concept of smart logistics is used where the Wireless Sensor Network (WSN, having sensors to monitor physical/environmental conditions), IoT technologies and CPS are used. Smart logistics can be defined under the domain of smart services and smart products and termed as smart logistics, i.e. smart products and services designates that some of the control and monitoring activities of humans are distributed with products and services [4]. In addition, for complete supply chain of food for smart logistics process, scalability of nodes is required i.e. for successful performance, WSN accommodate more nodes at different upcoming stages [5]. Moreover, random deployment of WSN is non-trivial problem in smart logistics due to which difficulties of insufficient coverage and connectivity, computation and communication overhead, high battery consumption and node failures occurred. Therefore, coverage and connectivity are considered as important parameters of quality of service (QoS) in an IoT network which shows each point coverage and accuracy of information gathered by IoT devices [6]. To maintain network connectivity and coverage up to optimal level in resource constrained environment is non-trivial in IoT network. For the said resolution, bonded coverage and connectivity can be used where to keep neighboring nodes in the detection range of succeeding next node [7]. Bonded coverage and connectivity results in secure, reliable and stable connections among nodes.

The SLCPS provides the supervision of various transport parameters remotely. The CPS architecture of smart logistics consists of three modules in general: an internal network based on WSN or IoT devices scalable in terms of container, storehouse and warehouse and senses deviations in environmental parameters, a communication gateway which serves as a bridge/channel between the external network and WSN, and a web server that provides access through graphical user interface (GUI) to the data as shown in Fig. 1.

The structure of remaining paper is as follows. Section 2 explains the literature review that has been done in smart logistics and its limitations. Section 3 describes comparative analysis for appropriate IoT protocol stack development of SLCPS. The proposed framework methodology is designed in section 4. Section 5 is about results and analysis based on experiments conducted for various scenarios. Finally, conclusion and future work is expressed in section 6.

II. LITERATURE REVIEW

This section explores the previous work that has been done by researchers on smart logistics and intelligent container, IoT devices and CPS. Discussion on state-of-the-art frameworks, mechanisms in the development of framework for smart logistics and various approaches for communication of information is presented.

The "Intelligent Container" is a sensor network used for the management of logistic processes, especially for perishable goods such as fruit and vegetables. In [8], the cognitive sensor system has been developed for transport management based on taking action according to sensed data related to environmental parameters i.e. humidity and temperature. Jedermann *et al.* in [9], discussed about autonomous cooperation of constrained resources in intelligent container. To collect and evaluate sensed data simultaneously for taking decision by their own in logistics, resource constrained microcontrollers, WSN and RFIDs were used for autonomous cooperation and their effect on logistic system with limited resources has been realized. In [10], Walter explained that intelligent container is a WSN for monitoring of unpreserved items i.e. meat, fruits and vegetables. In these papers' authors discussed about incorporation of IoT for control and monitoring in logistics, lack information about simplicity and computation efficiency.

The latest research on framework development, CPS, IoT and security and privacy of IoT are as follows, in [11], Heidmann *et al.* discussed the implementation of low-power/resource constrained wireless Ultra High Frequency/Low Frequency (UHF/LF) sensor network with web-based remote supervision in the intelligent container. The system consists of wireless sensor nodes, a freight supervision unit and a web-based backend interface which is used in combination with a VPN (virtual private network) for a connection with the container and to control environmental parameters. In [12], a framework based on IoT devices is developed for handling property registration and e-stamp apparatus and also provide interface for document originality verification. The proposed framework reflects efficiency by saving network bandwidth and Central Processing Unit (CPU) computation. In [13], authors introduced CPS and IoT technologies for an intelligent transportation system (ITS) using Fog Computing (FC) for vehicular networks. The mission-critical computing needs of ITS applications are identified and proposed FC based solutions towards addressing them. In [14], authors proposed framework for security and privacy of IoT composed of a security wall between the Cloud Server and the Internet. In [15] author discussed a case study of smart medical devices in terms of general problems of assessing the quality of cyber-physical systems. [16] provided live forensics of software attacks on CPS by launching attacks and understanding its internal flows. Reference [17] compared security issues between IoT and traditional

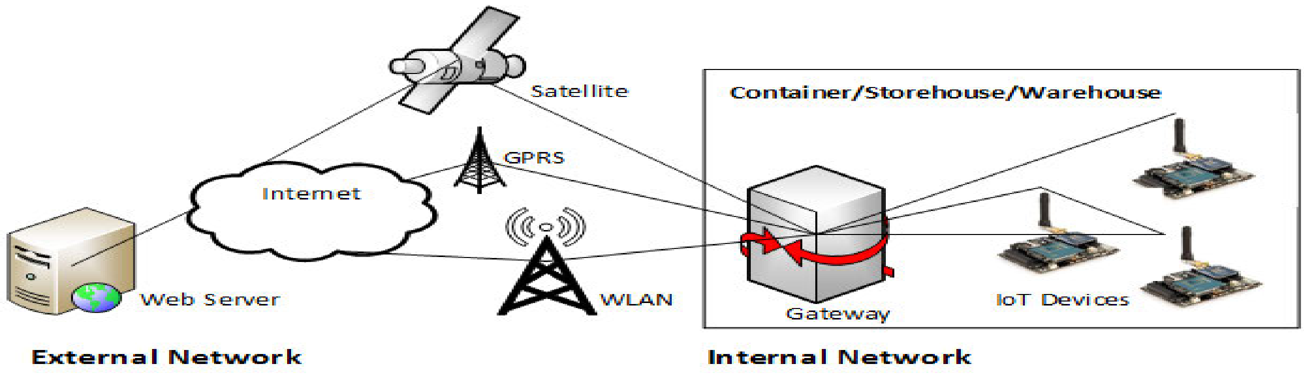

FIGURE 1. Architecture of SLCPS.

network, elaborated opening security issues in IoT, analyzed the security problems of various layers of IoT and tries to find solutions to them. In [18], latest empirical research about cloud computing, big data and IoT have been discussed.

The previous work related to IoT protocol stack i.e. appropriate protocols at various layers, use of Poisson distribution for efficient traffic flow, embedded operating system and emulator for IoT, coverage and connectivity of network, performance evaluation parameters and various scenarios in IoT frameworks are elaborated. Kuladinithi *et al.* in [19] discussed CoAP (Constrained Application Protocol) implementation and application in transport logistics. CoAP has been used as communication protocol for monitoring of environmental parameters during logistics transportation. For implementation and evaluation of communication process, embedded operating systems i.e. Contiki and TinyOs are used. The results revealed that CoAP outperformed HTTP in constrained environments. In [20], traffic flow is modeled for efficient utilization of resources in WSN. For shaping of traffic mostly Poisson distribution is used. In [21], Contiki's Cooja, a popular simulator for WSN is elaborated in terms of network lifetime and coverage evaluation in an in-building scenario. Two redundant node algorithms were used to extend the network lifetime, the tool found coverage redundant nodes, put them to sleep and automatically turned them on when active nodes failed and coverage quality decreased. Author in [22] developed the CPS for smart logistics with IoT technologies using a path decision scheme based on intelligent algorithms. In [23], authors discussed about IoT network development in a simulator that can generate realistic results for WSN. Cooja simulator was used for network planning and correct passing of physical information to higher layers. The research paper in [24] provided an overview of the 6LoWPAN standard which is an open standard developed by Internet Engineering Task Force (IETF) on top of IEEE 802.15.4 standard. It is building block for the future of IoT. Two application protocol standards i.e. CoAP and Message Queue Telemetry Transport (MQTT) for sensor networks (MQTT-SN) that are used in 6LoWPAN were also discussed. In [25], authors evaluated performance in terms of energy consumption and network traffic of two IoT application layer protocols, the CoAP, and the version of MQTT-SN using Cooja simulator. In [26], development of IoT frameworks and their complexities are discussed. The framework evolution and removal of unnecessary complexity in terms of differing objectives, interoperability, adaptability, performance, and manageability is elaborated. Authors in [27] discussed the latest developments of Application Specific Internet of Things (ASIoTs) i.e. IoTs targeted towards specific domains, communications mediums and industry sectors. In [28], authors analyzed the transmission properties and measure the performance by means of throughput, packet loss rate and latency for medical data. The healthcare scenario is based on 6LoWPAN (IPv6 over Low Power Wireless Personal Area Networks) protocol stack within the Contiki operating system and Cooja simulator. Authors in [29] discussed performance analysis of IP based WSN using simulations and experiments for flood detection scenario of smart city in Cooja simulator. In [30], authors proposed IoT-based framework for continuous monitoring of patients in healthcare.

A. LIMITATIONS IN LITERATURE VERSUS PROPOSED SOLUTION

From the literature, it is evident that CPS and IoT have enriched the existing logistics services considerably, but due to the constrained nature of devices, systems developed are either at very preliminary stage of control and monitoring, or developed schemes are complex and computationally expensive. Also, research indicate that solutions are usually proposed for some specific module of logistics and complete supply chain of food for logistics framework is not investigated. Appropriate utilization of technologies according to specific IoT and CPS applications are not revealed in literature. Also, random node/mote or IoT device placement is seen in literature. In this work, the limitations of previous work are addressed as shown in Table 1 and framework for smart logistics is emulated (simulated scenario results are closer to real deployment) by selecting suitable IoT protocol stack for specific applications. One more issue studied in this work is

TABLE 1. Limitations in literature versus proposed solution.

Current Technique	Limitations of Current Study	Proposed Scheme
IoT incorporation in logistics [8] and [9]	Preliminary level systems	Advanced techniques and CPS logic adopted in current framework
Control and monitoring in logistics [10], [11] and [13]	Complex and computationally expensive	Simplicity and computationally inexpensive CPS framework development for smart logistics based on laws of computing
Various technologies utilization and IoT protocol stack usage [15], [20] and [21]	Not for specific application according to its properties	Technologies utilization appropriately for smart logistics and IoT protocol stack development after comparative analysis
Node placement for various IoT application [6], [7], [12], [14] and [17]	Random placement of nodes	Nodes or IoT devices are deployed with proposed mathematical formulas based on simplicity, ease, scalability, connectivity, bonded coverage and low cost
Proprietary technologies and communication protocol usage in IoT [22] and [23]	Interoperability issue with internet	Interoperable communication protocols for smart logistics framework by utilizing RPL gateway to connect with external network
Frameworks for smart logistics and other IoT applications [18], [24], [25] and [26]	No surveillance of complete supply chain of food for smart logistics process	Supply chain of food for smart logistics process in terms container, storehouse and warehouse.

the improved placement of IoT devices using mathematical models for smart logistics scenarios in terms of number, simplicity, bonded coverage and connectivity (secure and stable IoT network). Another problem highlighted from related work is proprietary technologies in IoT that cause integration problem, in this work interoperable CPS for smart logistics is considered. Finally, it should be noted that no work has been done, neither on supply chain of food for smart logistics process development in terms of container, storehouse and warehouse nor on mathematical model for node placement in said process up to the authors' knowledge. Therefore, a comprehensive analysis of emulated framework for control and monitoring of cyber-physical systems in smart logistics based on scalability in addition to bonded coverage and connectivity of nodes using various performance evaluation parameters has been presented in this work.

III. IoT PROTOCOL STACK DEVELOPMENT FOR SLCPS FRAMEWORK

IoT protocol stack is a crucial part of the IoT technology as it enables hardware to exchange data in a structured and meaningful way. Nevertheless, in the past few years the IoT has seen rise in variety of applications i.e. smart home, smart health, smart agriculture and smart logistics, where each application has its own properties and requirements for communication with own protocols to suit its purposes [31]. IoT protocols can be divided in terms of the role they play within the network. Table 2 depicts the logical layering of functions as well as an actual top to bottom protocol hierarchies used today in CPS network communications.

A comparative study of the above protocols for each layer, to find which one is better for smart logistics scenario on the basis of efficiency and performance, is performed as follows.

A. APPLICATION LAYER PROTOCOLS COMPARISON FOR SLCPS FRAMEWORK

The most common application layer protocols that are used in IoT are CoAP, MQTT, MQTT-SN and Extensible Messaging and Presence Protocol (XMPP). A comparative review to determine an appropriate application layer protocol for smart logistics on the basis of their pros and cons is discussed in the following paragraphs.

TABLE 2. The IoT protocols stack for CPS.

Reference Layers for IoT Protocols	IoT Protocols
Application	CoAP, MQTT, MQTT-SN and XMPP
Network	6LoWPAN, ZigBee and BLE
Link	IEEE 802.15.4, 802.11 a/b/g/n/ad/ac and 802.15.1

CoAP was developed by the IETF Constrained RESTful Environments (CoRE) working group. It is a web transfer protocol based on Representational State Transfer (REST) on top of HTTP functionalities. CoAP runs over User Datagram Protocol (UDP), removing all the Transmission Control Protocol (TCP) overhead of Hyper Text Transfer Protocol (HTTP), this reduces requirements of bandwidth, provides more simplicity, and makes it more suitable for smart logistics. CoAP, like HTTP is based on request/response architecture and shares same methods of GET, PUT, POST, and DELETE. It supports unicast and multicast transmission. CoAP is efficient in terms of infrastructure, bandwidth and power-consumption [32].

MQTT is also designed for constraint devices by IBM and standardized at OASIS. It follows an asynchronous publish/subscribe protocol that runs over TCP. The message pattern comprises broker, publisher and subscriber. Broker controls and manages exchange of packets between subscribers and publishers. It is more reliable due to TCP but adds more latency, needs more power and bandwidth. Therefore, it is not recommended for real time application.

MQTT-SN is the version for sensor networks of MQTT. It works over UDP to reduce drawbacks of MQTT but has semantics and infrastructure same as MQTT. The only difference in the architecture is that MQTT_SN needs a gateway that translate all MQTT_SN messages over UDP to MQTT messages over TCP. Currently, brokers have this functionality integrated [25]. As MQTT-SN requires broker for their communication interpretation, therefore, it needs infrastructure environment having more complexity and power consumption.

XMPP was standardized by the IETF. XMPP supports small messages and low latency; these characteristics make the XMPP protocol a good choice for IoT messaging and communications. XMPP protocol supports both request/response and publish/subscribe models that allows bidirectional communications and multi-directional communication respectively. High scalability in XMPP is provided by decentralized architecture [33]. There are many extensions to XMPP protocol, this allows it to work on the infrastructure-less environment. XMPP protocol uses XML for text communications and this causes network traffic overhead. This also needs high consumption of bandwidth, high CPU usage and no guarantee of QoS can be given.

From the above discussion of application layer protocols, the various parameters that have been taken for comparison are power consumption, bandwidth and infrastructure. The hypothetical results of these parameters on the basis of their pros cons for SLCPS are shown in Fig. 2.

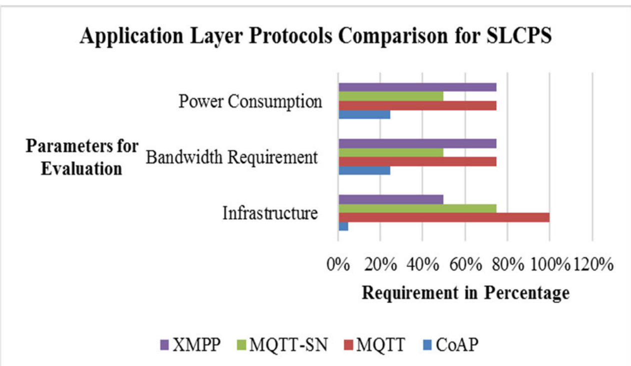

FIGURE 2. Application layer protocols comparison for SLCPS.

From the comparative analysis it is concluded that CoAP generates less overhead than other protocols. In terms of power consumption, bandwidth and infrastructure requirements and is most suitable for SLCPS framework.

B. NETWORK LAYER PROTOCOLS COMPARISON FOR SLCPS FRAMEWORK

Network layer protocols used commonly in IoT are IPv6 over Low -Power Wireless Personal Area Network (6LoWPAN), ZigBee and Bluetooth Low Energy (BLE). The comparative analysis is described as follows

6LoWPAN is based on IP version 6 (Internet Protocol version 6) having hexadecimal addresses of 128-bits and has adapted 802.15.4 radio frequency. It has enabled to use IP in low-power and lossy wireless networks i.e. WSNs (Wireless Sensor Networks), IoT, Smart Grid and M2M applications. It is the newest competitor to ZigBee now. The distinguishing features of 6LoWPAN are that it supports header compression and encapsulation approach and therefore it is more secure than ZigBee. The most prominent advantage of 6LoWPAN is that it natively supports IP networks [34].

The ZigBee is also built on the IEEE 802.15.4 standard which saves battery life of constrained networks by keeping nodes in sleep mode most of the time, but unlike 6LoWPAN which has feature of interoperability, ZigBee cannot communicate with other protocols easily.

In BLE, current version is Bluetooth 5. Like Bluetooth 4.2, Bluetooth 5 also supports IP networks (Bluetooth's IP capabilities are rarely explored by end-users). but BLE cannot form a self-healing mesh network, which is increasingly becoming a pre-requisite for IoT applications. When using ZigBee or traditional Bluetooth, a gateway is necessary to communicate with the internet, which increases overhead.

Network layer protocols comparison in terms of encapsulation, interoperability and network overhead on the basis of their pros and cons for SLCPS framework is evaluated hypothetically as shown in Fig. 3.

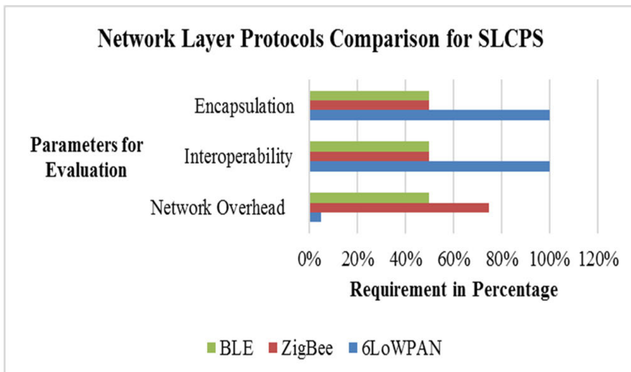

FIGURE 3. Network layer protocols comparison for SLCPS.

From results, it can be deduced that 6LoWPAN is the prime option for SLCPS with better encapsulation, interoperability and low network overhead.

C. LINK LAYER PROTOCOLS COMPARISON FOR SLCPS FRAMEWORK

Link layer protocols consist of IEEE 802.15.4 for 6LoWPAN and ZigBee, IEEE 802.11 for Wi-Fi. and IEEE 802.15.1 for Bluetooth. Rapid analysis of these protocols with respect to IoT is given below.

The IEEE 802.15.4 is the standard proposed by Institute of Electrical and Electronics Engineers (IEEE) for low power wireless networks. It has a communication range of minimum 10 meters to 100 meters. For low-data-rate and security

Wireless Personal Area Networks (WPAN), the major standard is the 802.15.4 category.

IEEE wireless communications standards WLANs/ Wireless Fidelity (Wi-Fi) is 802.11 with communication range of 40 to 90 meters. Wi-Fi (IEEE 802.11) is not battery efficient, does not cover a large area, and does not support a high number of end devices. Another WPANs standard specified by 802.15 group is Bluetooth i.e. 802.15.1 having communication range of 10 meters to 50 meters, comparatively battery efficient but less encrypted than Wi-Fi [34].

Link layer protocols comparison on the basis of security, communication range and battery consumption for SLCPS is shown in Fig. 4.

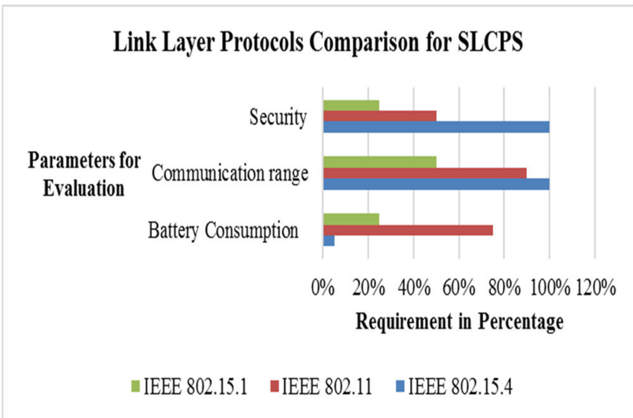

FIGURE 4. Link layer protocols comparison for SLCPS.

From the hypothetical results obtained from link layer protocols comparison, IEEE 802.15.4 appears best for SLCPS framework because it is compatible with 6LoWPAN as well as it is more secure, having low power consumption and comparatively more communication range.

In a nutshell, from comparative analysis of various protocols at different layer the IoT protocol stack for SLCPS framework is depicted in Fig. 5.

IV. METHODOLOGY FOR SLCPS FRAMEWORK DEVELOPMENT

This research work is intended to develop scalable framework for monitoring and controlling of IoT devices in SLCPS. The architecture of smart logistics framework is decoupled into three modules i.e. internal network, border router and external network with backend software for monitoring and control. The complete phenomenon is emulated in Contiki operating system and Cooja simulator. The prospective research methodology flow is shown in Fig.6.

The various steps of methodology are elucidated in the following subsections.

A. NETWORK SIMULATION AND SETUP

The network simulation and setup are the experimental process for SLCPS framework which is further divided into three modules i.e. Definition and Description, Design and Development and Operation and Procedure described in the following.

1) DEFINITION AND DESCRIPTION OF PLATFORM

This is the first phase of network simulation and setup where we will define and explain the structure of platform for smart logistics CPS framework as shown in Fig. 7.

The framework is developed using stack that is composed of personal computer where VMWare is installed for Contiki IoT based Operating System in which Cooja simulator and Wireshark is used for framework development and

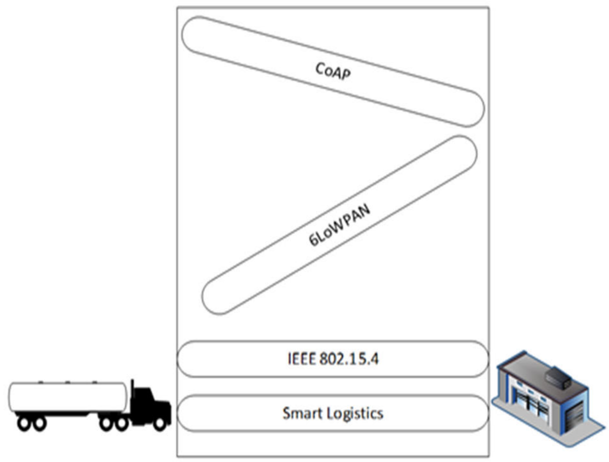

FIGURE 5. The IoT protocols stack for SLCPS framework.

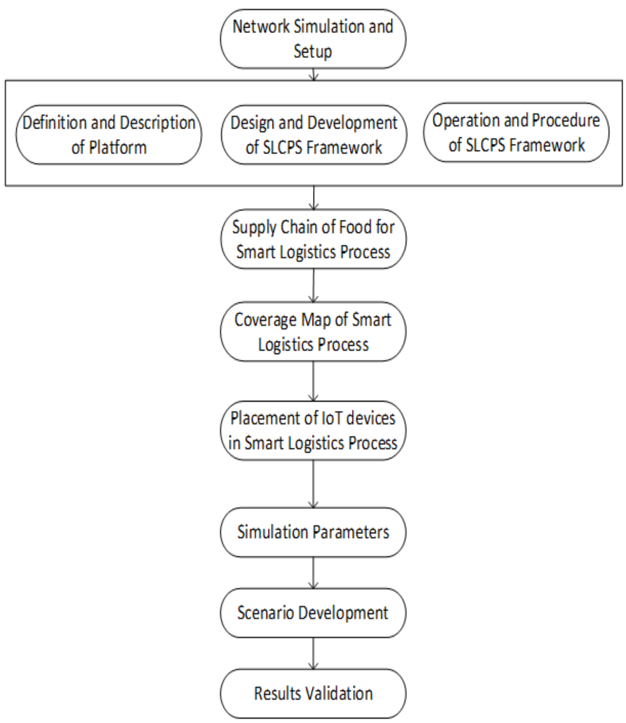

FIGURE 6. Prospective research methodology flow.

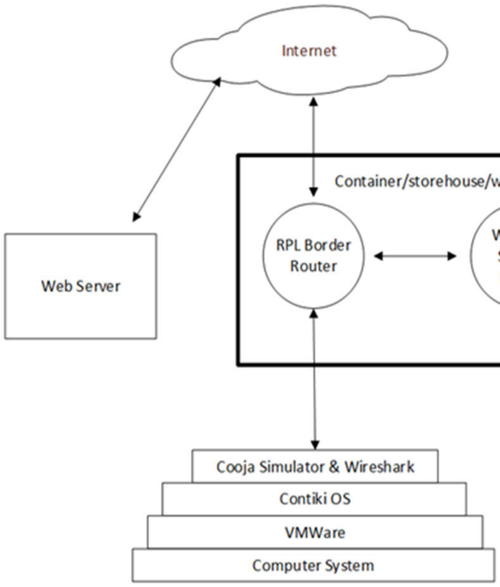

FIGURE 7. **Definition and description of platform.**

result analysis. Cooja is a useful tool/emulator for Contiki development, as it allows to test code/system before running it on the target hardware and provide realistic results [35]. The proposed framework is composed of internal network which consists of container, storehouse and warehouse having WSN or IoT devices for control, monitoring and Routing Protocol for Low-Power and Lossy Networks (RPL) border router for connectivity with external network i.e. internet and backend software/web server.

2) DESIGN AND DEVELOPMENT OF SMART LOGISTICS CPS FRAMEWORK

The second phase is based on design and development of framework for smart logistics. The comprehensive activity diagram is shown in Fig. 8. The SLCPS framework is designed and developed using Cooja simulator.

- The first activity is to open simulation, select radio propagation model i.e. Unit Disk Graph Medium-distance loss (UDGM-Distance Loss). Here the signal loss is related to distance, Received Signal Strength Indicator (RSSI) decline along with increase in distance just like real scenario. Therefore UDGM-Distance Loss is practical and also considers the radio interferences. Packets are transmitted with "success ratio T_X" probability and packets are received with probability of "success ratio R_X".
- The second thing is related to traffic of packets, in Cooja packets are generated either at periodic generation rate (packets are generated at constant frequency i.e. 1packet/second or 10packets/second) or randomly using Poisson distribution (based on discrete probability distribution where data packet generation rate will change all the time in the simulation process). In proposed SLCPS framework, as time and number of nodes are

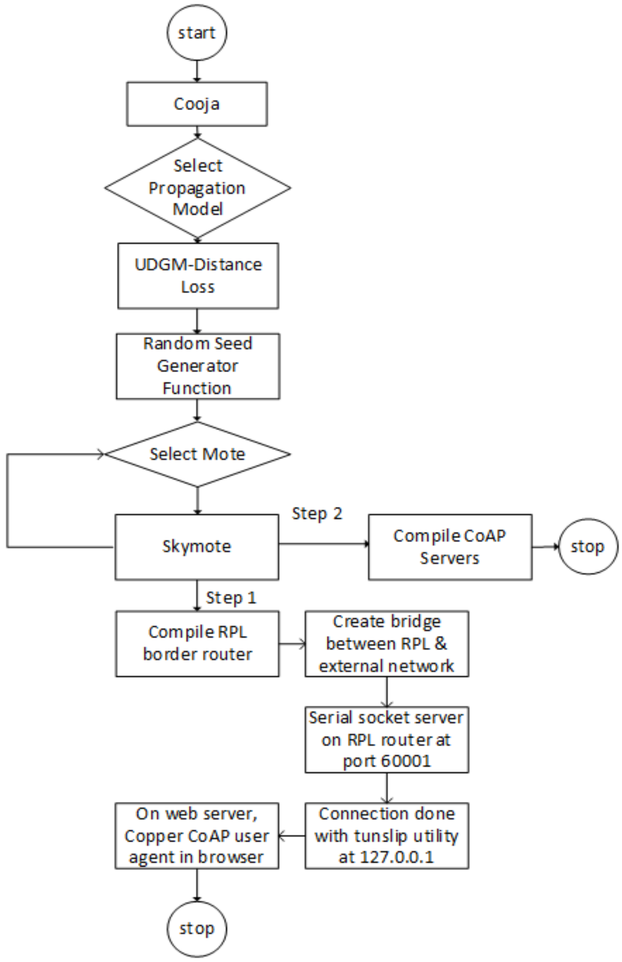

FIGURE 8. **Activity diagram for design and development of SLCPS framework.**

specific as well as each node just monitor and control environmental parameters and do not have heavy bursts of traffic. Therefore, finest option is random seed generator function, with range from 1-6 packets/second and the well-known Poisson distribution is used for random number of packets generation represented in (1).

$$P(i, \mu) = (e^{-\mu})(\mu^i)/i! \tag{1}$$

where μ is the average number of successes within a given region and i is the actual number of successes that result from the experiment.
- The next step is selection of mote where sky mote [37] (explained in section E) is selected and CoAP server is compiled on it for communication within container/storehouse/warehouse (internal network). While on another sky mote, RPL border router is compiled for connectivity with external network (internet).
- The forth coming activity is to create bridge between border router and external network, for this purpose we will open serial socket server on border router through

port 60001. Till now only RPL network is created. Now for simulation of scenario, this RPL network is connected to an external network. For this purpose, tunslip utility is used, provided in Contiki. Tunslip creates a bridge between the RPL network and the local machine i.e. 127.0.0.1. Before starting simulations, connection of RPL border router is required. For this purpose, open a new terminal in Contiki and type the following commands:
  - cd contiki/examples/ipv6/rpl-border-router/
  - make connect-router-cooja.

- Finally, for communication with web server, copper based CoAP user agent is opened in browser for control and monitoring of IoT devices in SLCPS framework. The Copper (Cu) CoAP user-agent is an add-on for the Firefox web browser, used for browsing and direct interaction with CoAP resources.

The complexity analysis of proposed SLCPS framework is as follows, in the first step, the cooja selects one out of four propagation models, in the worst case, it would execute in O(N) time. The following step UDGM-distance loss and the Random seed generation takes one process to execute i.e. O(1). The select mote is a conditional statement that executes in O(N), the result of this statement leads to either step 1 or step 2. In both cases, the remaining steps are linear i.e. it takes either O(5) for step 1 or O(1) for step 2. The proposed algorithm in the worst case will execute in O(N) time.

3) OPERATION AND PROCEDURE OF SLCPS FRAMEWORK

In this module, process and manipulation of SLCPS framework is represented in 3 modules i.e. sensor mote or IoT device, border router and internet. Sensor motes are in internal network and internet is external network as shown in Fig. 9.

The operation and procedure of SLCPS framework validates proposed IoT protocol stack where sensor motes use CoAP at application layer, a border router comprises 6LoWPAN at network layer while IEEE 802.15.4 radio at link layer and a web server using Copper based CoAP client. RPL border router is used to connect external IP network with 6LoWPAN based internal network. The working of SLCPS is to connect CoAP based sensor motes using 6LoWPAN centered border edge router with internet. Sensor mote is built on IEEE 802.15.4 radio module for logistic process.

B. SUPPLY CHAIN OF FOOD FOR SLCPS FRAMEWORK PROCESS

The supply chain of food for SLCPS framework process proposed in this work is devised into container, storehouse and warehouse consisting of 5, 10 and 15 motes for control and monitoring of environmental parameters respectively. The proposed process of transport and storage from the producer to the consumer is shown in Fig. 10.

The proposed process is Supply Chain of Food (SCF) for goods or perishable items which has been started from producer to containers for transportation to storehouse for primary storage from where it is again transported through container to warehouse for central storage. Again, it is transported using containers to storehouses for storage and finally transported through containers to consumers. These store and transport processes from farm to fork are automated using IoT devices in proposed SLCPS framework. Here, IoT devices are CoAP servers developed on proposed IoT protocol stack and placed in container, storehouse and warehouse. Each has one border router for connectivity with external network (internet). The purpose of IoT devices are control and monitoring of internal conditions of SCF and sending it to remote server to handle efficiently, to reduce wastage of perishable items inside. In this way, proposed SLCPS framework provide coverage and connectivity from producer to consumer and provide right product at the right time at the right place and in the right state.

C. COVERAGE MAP OF SLCPS FRAMEWORK PROCESS

The coverage map of SLCPS framework proposed in this work for IoT devices range detection is based on binary coverage model. In this model, target is detected by sensor motes only if it is in the transmission range of sensor, else not detected [36]. Probability of sensor mote is 1 if the distance between transmitting sensor mote and target mote is less than or equal to mote sensing range.

Let's assume that *pt* is a point on map, *m* is a sensor mote then

p_{mpt} = probability of sensor mote
d_{mpt} = distance between *m* and *pt*
d_s = mote sensing range

Then, probability of sensor motes in proposed binary coverage map for SLCPS framework is represented in (2).

$$p_{mpt} = \begin{cases} 1, & d_{mpt} \leq d_s \\ 0, & d_{mpt} > d_s \end{cases} \tag{2}$$

IoT devices are arranged according to binary coverage model in proposed SLCPS framework for bonded coverage and connectivity. Equation 2 describes general rule for bonded coverage and connectivity, then mathematical models are developed for 1hop and 5hops scenarios of SLCPS framework using this rule of binary coverage model for placement of motes.

D. PLACEMENT OF MOTES IN SLCPS FRAMEWORK PROCESS USING MATHEMATICAL MODELS

IoT devices are placed in 1 hop and 5 hops scenarios using mathematical models instead of random placement on architecture of grid in SLCPS framework process. The purpose of mathematical models is to achieve simplicity, scalability as well as bonded coverage and connectivity in both scenarios. The SLCPS framework proposed in this work consists of one RPL border router. In different scenarios, 5, 10 and 15 sensor motes are deployed along with border router for container, storehouse and warehouse according to SLCPS process. The

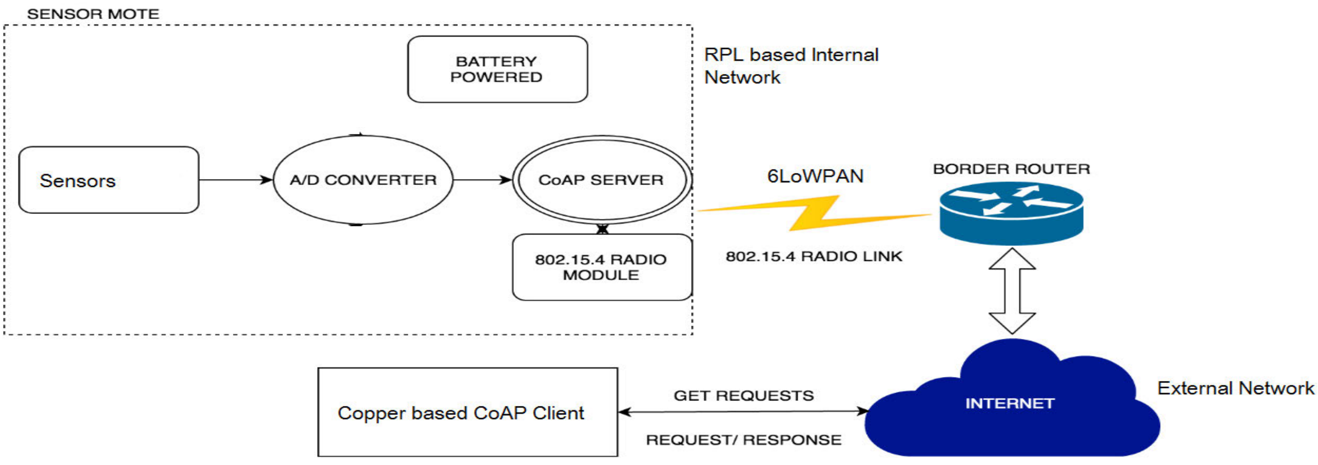

FIGURE 9. **Operation and procedure of SLCPS framework.**

FIGURE 10. **Proposed process for SLCPS framework in terms of supply chain of food.**

transmission sensing range taken in proposed process is 50 meters relative to range of 6LoWPAN. The mathematical models are discussed in the following sub sections

1) PROPOSED MATHEMATICAL MODEL FOR PLACEMENT OF MOTES ON ARCHITECTURE OF GRID FOR 1 HOP SCENARIO OF SLCPS PROCESS

In one hop scenario, all motes are placed in transmission sensing range of border router. The proposed mathematical model for 1 hop scenario is developed in such a way that let $ptn1(i, j)$ represents the position of mote for 1 hop on x and y coordinates where i is x coordinate and j is y coordinate, then proposed mathematical model for Cooja architecture of grid in 1 hop is represented in (3) as:

$$ptn1\,(i, j) = \begin{cases} (i, j), & i > 0, j > 0 \\ (-i, j), & i < 0, j > 0 \\ (-i, -j), & i < 0, j < 0 \\ (i, -j), & i > 0, j < 0 \end{cases} \tag{3}$$

Motes are placed in a loop according to range given below in meters as:

$i = 1\,0, 20, 30$

$j = 1\,0, 20, 30$

with the help of equation 3 for architecture of grid and given range, motes are placed in one hop scenarios of SLCPS framework process as shown in Fig. 11. As in 1hop maximum range is 50meters of border router for bonded coverage and connectivity therefore, equation 3 achieves proposed framework i.e. scalable up to 15 motes with range of 30meters if border router is placed at (0,0) location as shown in Fig. 11 else only range will change, equation 3 remains same i.e. proposed general mathematical model for 1hop scenario of SLCPS framework.

2) PROPOSED MATHEMATICAL MODEL FOR PLACEMENT OF MOTES ON ARCHITECTURE OF GRID FOR 5 HOPS SCENARIO OF SLCPS PROCESS

The proposed mathematical model for 5 hops scenario is designed in such a way that the motes running CoAP servers are positioned 1 to 5 hops away from the border router. Placement of motes are done by using the logic of equation 2 i.e. to keep motes in transmission sensing range of immediate previous motes, up to 5 hops from the RPL border router. The proposed mathematical model for 5 hops scenario is designed below using equation of circle as in (4).

$$(i - h)^2 + (j - k)^2 = r^2 \tag{4}$$

Here h and k are the x and y coordinates of the center of the circle. Where $i = x$ and $y = j$ while r is the radius of circle.

Then in 5 hops mathematical model

(h, k) is the position of border router

$ptn5(i, j)$ is the position of motes for 5 hops in relative transmission sensing range i.e. $0 < r^2 \leq 50$.

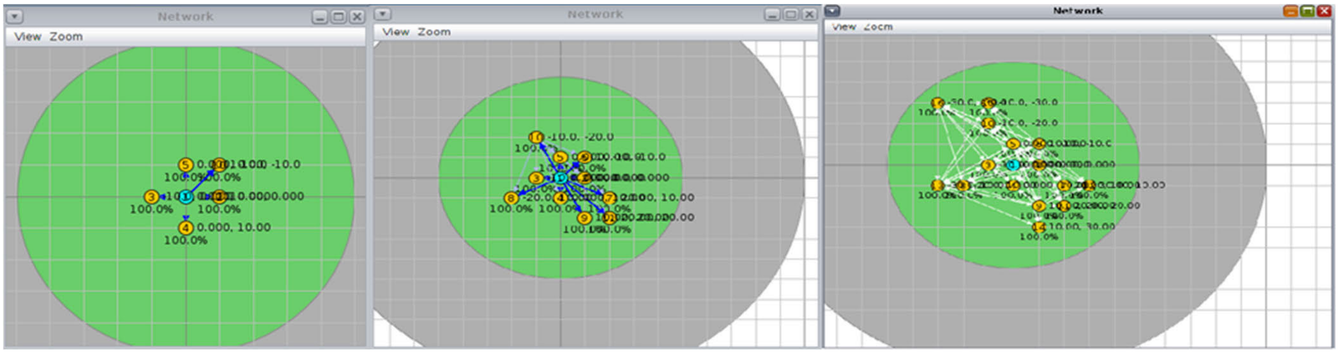

FIGURE 11. 1 Hop scenario for SLCPS framework process on Cooja architecture of grid consisting of 5, 10 and 15 CoAP motes and 1 RPL border router in each.

Then mathematical model proposed for 5 hops scenario is shown in (5) as:

$$ptn5\,(i,j) = \begin{cases} (i_1-h)^2+(j_1-k)^2=r_1^2, & 0<r_1^2\le 50 \\ (i_2-i_1)^2+(j_2-j_1)^2=r_2^2, & r_1^2<r_2^2\le 100 \\ (i_3-i_2)^2+(j_3-j_2)^2=r_3^2, & r_2^2<r_3^2\le 150 \\ (i_4-i_3)^2+(j_4-j_3)^2=r_4^2, & r_3^2<r_4^2\le 200 \\ (i_5-i_4)^2+(j_5-j_4)^2=r_5^2, & r_4^2<r_5^2\le 250 \end{cases} \quad (5)$$

Motes are placed using equation 5 for 5 hops scenarios with 5, 10 and 15 number of motes in a loop as shown in Fig. 12. As equation 5 is for 5hops scenario, so, motes of first hop are placed in range of border router i.e. 50meters while motes of second hop are in transmission range of first hop motes relatively i.e. 100meters and so on up till 5hops of 250meters. This is 5hops scenario, so, transmission range of each succeeding hop is 50 meters up to 5hops following the limitation of Table 3.

For bonded coverage and connectivity, motes are placed in 1hop and 5hops using mathematical models of equation 3 and equation 5 respectively while motes are placed randomly, neither following bonded coverage and connectivity nor in hops as shown in Fig. 13.

E. SIMULATION PARAMETERS

In this work, simulations are performed with the main objective to develop, assess and analyze proposed framework in terms of scalability, connectivity, coverage and simplicity. The parameters for simulations in Cooja are given below in Table 3.

These simulation parameters are used in Contiki, an operating system for IoT simulations. T-mote sky is used which has a RAM of 10 KB, current consumption in Radio Transmission Tx mode is 19.5mA and Radio Reception Rx mode is 20mA [37]. Mote start up delay is 1000ms for boot time randomization of motes. In low-power networks, the radio transceiver must be switched off as much as possible to save energy. In Contiki, this is done by the Radio Duty Cycling (RDC) layer where contikimac is used and the Medium Access Control (MAC) layer sits on top of the RDC layer. The MAC layer is responsible for avoiding collisions at the radio medium and retransmitting packets if there were a collision and Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) is used for efficient traffic flow and power consumption of IoT devices in WSN. NullRDC and Nullmac are active when these layer functions are disabled [38]. The Contiki commands [39] for the simulation parameters are described in Table 4.

TABLE 3. Parameters for simulation.

Parameter Name	Value
Application Layer Protocol	CoAP
Network Layer Protocol	6LoWPAN
Link Layer Protocol	IEEE 802.15.4
Border Router	RPL
Radio Propagation Model	UDGM-Distance Loss
Packets Traffic	Random
Area	$1000m^2$
Simulation Time	300000ms
Mote Type	T-mote Sky
Number of Motes	5, 10, and 15
Mote Delay	1000ms
Data rate	250kbps
Mote Transmission Tx Range	50m
Mote Interference Range/ Mote Carrier Sensing Range	100m
Tx/Rx Ratio	100%
Radio Duty Cycling (RDC) layer	Contikimac
Mac layer	CSMA/CA

F. SCENARIO DEVELOPMENT

The SLCPS Framework presented in this work is broadly divided into three scenarios i.e. 1 hop, 5 hops and random motes placement scenarios. Each scenario is further sub divided on the basis of simulator control speed into i) no speed limit constraint and ii) 100% speed limit constraint. Simulator control speed is processing capability of simulator or system

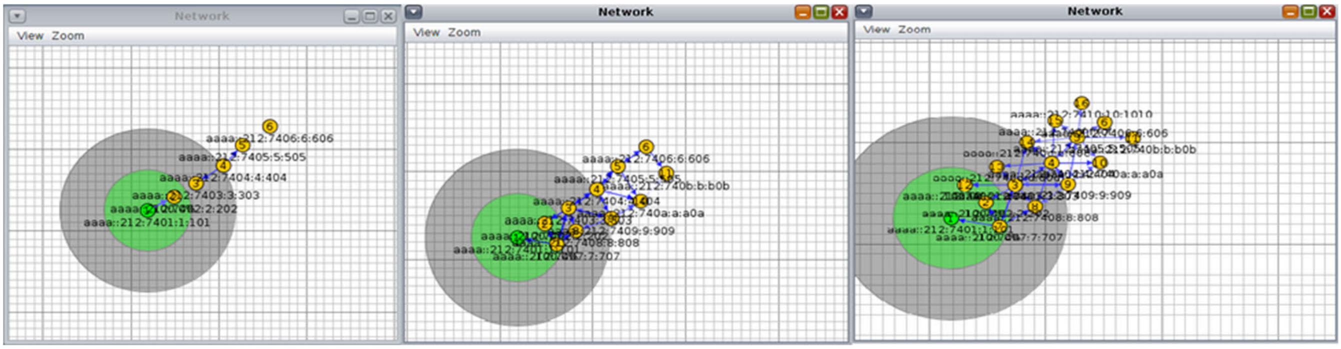

FIGURE 12. 5 Hops scenario for SLCPS framework process on Cooja architecture of grid consisting of 5, 10 and 15 CoAP motes and 1 RPL border router in each.

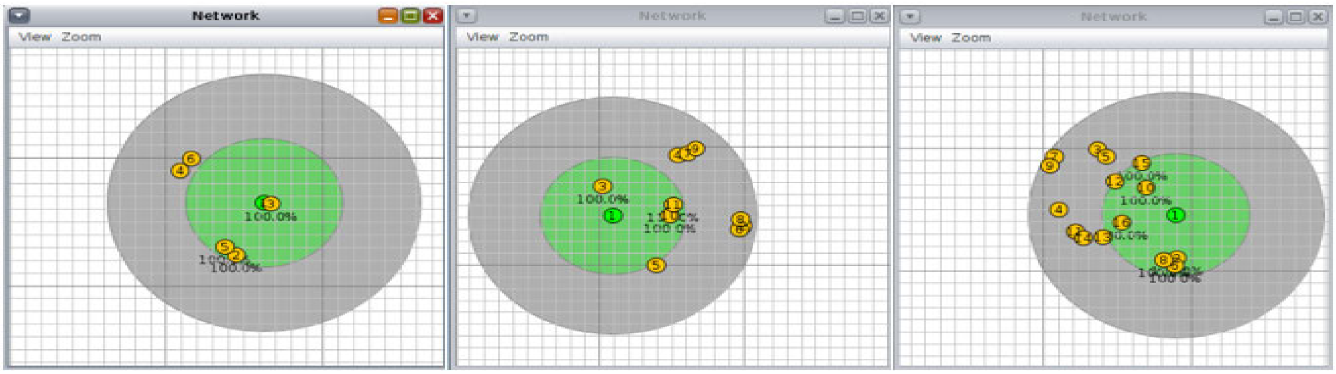

FIGURE 13. Random motes placement scenario for SLCPS framework process on Cooja architecture of grid consisting of 5, 10 and 15 CoAP motes and 1 RPL border router in each.

TABLE 4. Parameters used in contiki operating system.

Contiki Parameter Name	Value	Explanation
NETSTACK_CONF _WITH_IPV 6	1	Enables IPv6 networking configuration
NETSTACK_CONF _NETWORK	sicslopan_driver	Enables 6LoWPAN support for header compression, privacy and fragmentation
NETSTACK_CONF _RDC	contikimac_driver	Enables network communication with energy efficiency by keeping mote radio off for more than 99% of time.
NETSTACK_CONF _MAC	csma_driver	Enables MAC with Collision Avoidance
NETSTACK_CONF _RADIO	cc 2420 _driver	Enables IEEE 802.15.4 accommodating CC2420 radio transceiver with frequency of 2.4 Ghz
NETSTACK_CONF _FRAMER	framer_802154	Enables compatibility between parsing and generation of formatted packets with IEEE 802.15.4 protocol.

with respect to load of motes, where in i) if motes load is less and simulator has more processing capability then speed goes high to 200%, 300% and so on if no speed limit is enabled whereas in ii) the simulator processing capability is bound to 100% with respect to motes load. The real time duration of all scenarios are 300seconds while simulated time duration of no speed limit scenarios due to faster clock speed is less as compared to 100% speed limit constraint. The reason is, no speed limit scenarios complete activates faster due to high capability of simulator while 100% scenarios complete activities exactly in 300 seconds.

The 1 hop, 5 hops and random motes placement scenarios on the basis of proposed SLCPS framework process are divided into container, storehouse and warehouse. Here, container consists of 5 sky motes running CoAP servers and 1 RPL border router, while storehouse has 10 sky motes executing CoAP servers and 1 RPL border router. Similarly, warehouse has 15 sky motes running CoAP servers with 1 RPL border router. The border router in each scenario is also executed on sky mote. In 1hop and 5hops scenarios, motes are placed on the basis of binary coverage model explained in subsection C and mathematical models proposed for 1 hop and 5 hops scenarios. In 1 hop scenario, all motes are placed in transmission range of border router as shown in Fig. 11. In 5 hop scenario, CoAP motes are sited 1 to 5 hops away from the border router. Placement of motes are to keep CoAP motes in transmission sensing range of immediate previous motes, up to 5 hops from the RPL border router as shown in Fig. 12. In each scenario, mote 1 is border router while remaining 5, 10 and 15 motes are CoAP servers. Fig. 13. is

TABLE 5. Performance evaluation parameters and their proposed formulas in smart logistics cps framework.

Parameter Name	Proposed Formulae	Description
Throughput	$\frac{np * sp * 8}{ts}$	*np* = no. of packets delivered *sp* = size of packets in bytes, multiply by 8 to get results in bits per second *ts* = total duration of simulation, measured in bits per second (bps)
Network Convergence Time	$lDDAG - fDs$	*lDDAG* = last DIO joined DAG *fDs* = 1st DIO sent Destination Oriented Directed Acyclic Graphs (DODAGs). DODAG Information Object (DIO) (It is the carrier of information regarding the RPL instance and its configurations) measured in seconds
Packet Delivery Ratio	$\frac{pR}{pS} * 100$	*pR* = packets received *pS* = packets sent
Average Latency	$(Ave.Rx - Ave.Tx)$	*Ave.Rx* = average reception time *Ave.Tx* = average transmission time measured in millisecond
Power Consumption (Rx)	$\frac{(Rx_{end} - Rx_{start}) * 20mA * 3V}{4096 * st}$	Rx_{end} = final radio reception time Rx_{start}= initial radio reception time 20*mA* = value of current from data sheet of Tmote sky for Rx *3V* = value of operational voltage for Tmote sky (approximated) 4096 = ticks per second (considered as constant). *st* = Simulation time in seconds. (Note: Rx-time is multiplied by current and voltage, divided by constant 4096 into st to get power in milliwatt)
Power Consumption (Tx)	$\frac{(Tx_{end} - Tx_{start}) * 19.5mA * 3V}{4096 * st}$	Tx_{end} = final radio transmission time Tx_{start}= initial radio transmission time 19.5*mA* = value of current from data sheet of Tmote sky for Rx *3V* = value of operational voltage for Tmote sky (approximated) 4096 = ticks per second (considered as constant) *st* = Simulation time in seconds. (Note: Tx-time is multiplied by current and voltage, divided by constant 4096 into st to get power in milliwatt)

based on random placement of 5, 10 and 15 CoAP motes with respect of 1 border router. Random motes placement scenario is not bounded to proposed binary coverage model, mathematical models proposed and hops. The random motes placement scenario is used for results comparison and validation with proposed SLCPS framework of 1hop and 5hops.

G. RESULTS VALIDATION

The results of the proposed SLCPS framework are valued under the egis of three laws of computing in terms of IoT i.e. Moore's law, Koomey's law and Metcalfe's law. Moore's and Koomey's laws are about gain in performance as well as decrease in dimensions, power consumption, and unit costs of system. Metcalfe's law has suggested network scalability where the more motes are connected to the network, the more valuable the network becomes, and the more value can be derived from the network [40] and [41]. Therefore, by utilizing these laws framework is developed with suggested attributes of improved performance, energy efficiency and valuable network in terms of scalability, connectedness, better behavior and interoperability. The said structure is achieved using proposed IoT protocol stack, binary coverage model and mathematical models for SLCPS framework.

V. RESULTS EVALUATION AND DISCUSSION

The results of proposed framework are appraised in terms of performance evaluation parameters i.e. throughput, network convergence time, packet delivery ratio, average latency, power consumption of network in terms of transmission and reception, the overall evaluation of each parameter and timeline activities in all six scenarios are analyzed. Limitations of proposed framework are also discussed. Performance evaluation parameters and their proposed formulas in SLCPS framework are shown in Table 5.

The timeline of each mote in terms radio activity, usage, connection, LEDs and radio traffic in the proposed framework in all scenarios is analyzed using various factors shown in Table 6.

TABLE 6. Timeline parameters names and description.

Timeline Parameter Name	Description
Led Red	Interference of packets due to collisions
Led Blue	Packets sent
Led Green	Packets received
Grey Color	Radio on
No color	Radio off
Radio_on	Mote time when mote radio is on
Radio_tx	Mote radio transmission time (for how long the mote transmits physical-layer packets). Transition mode
Radio_rx	mote radio reception time (for how long the mote receives physical-layer packets). Listening mode
Radio_int	mote radio interference time

Radio traffic displays inter-mote radio communication while in radio connection events, transmissions are painted

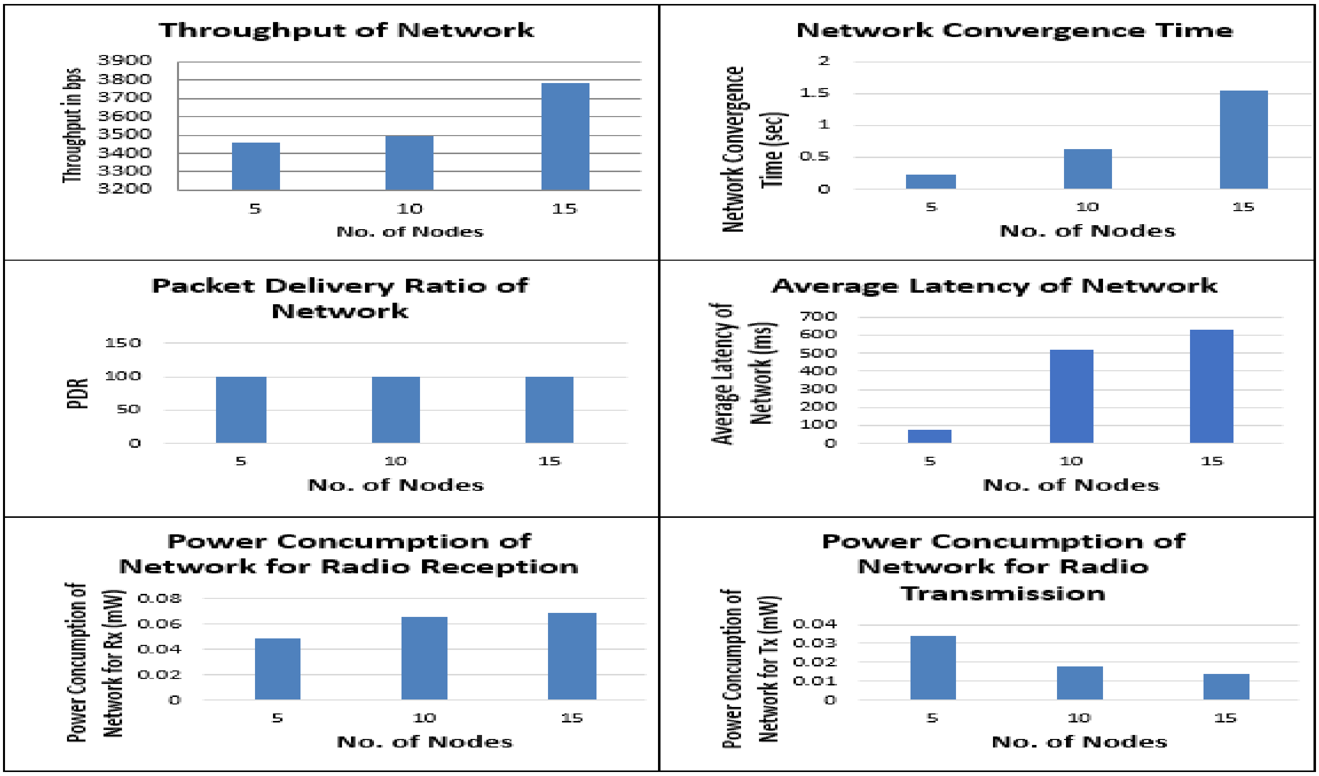

FIGURE 14. Results of throughput, network convergence time, PDR, average latency and power consumption for Rx and Tx for scenario 1.

blue, receptions are green, and interfered radios are red [42]. When the radio chip is on and neither transmitting nor receiving, the energy consumption is almost the same as in receive mode. The energy is spent on keeping the receive machinery active and continuously sampling the medium to detect start of a packet.

A. RESULTS ON SCENARIO 1 AND SCENARIO 2

Scenario 1 of SLCPS framework is based on 5 hops with no speed limit constraint from simulator control window while scenario 2 is based on 5 hops with 100% speed limit constraint. Motes are placed by proposed mathematical model of equation 5 for 5 hops SLCPS process. Scenario 1 and scenario 2 are assessed in terms of performance parameters, the throughput of network, network convergence time, packet delivery ratio, average latency of network and power consumption of network in terms reception R_X and transmission T_X using mathematical formulas given in Table 5. Fig. 14 portrays results obtained for scenario 1 and Fig. 15 depicts results obtained for scenario 2.

The scenario 1 and scenario 2 of SLCPS framework attained a low throughput, network convergence time and average latency of network with a low traffic load in terms of nodes but with the increase in network load, values of these parameters are also increased. The reason of gradual increase in throughput with increasing number of nodes up to 15 is due to the structure of 5 hops scenario which adds nodes or traffic in successive hops, keeping in consideration transmission range with proposed mathematical model for nodes placement and hence increases throughput with gradual increase in number of nodes in succeeding hops. The time for convergence of network also has a gradual accent with the increase in size of network because as nodes are increasing in 5 hops scenario, RPL border router junction time with all available nodes is increased. Similarly, for average latency increase is justified with increasing number of nodes, because packets send and receive time to or from border router increased. The PDR remained constant i.e. 100% in 5 hops scenarios because network has no losses up to 15 nodes due to proposed mathematical model and contikimac RDC mechanism. The power consumption of network for R_X is increasing while TX is decreasing with gain in network size because of contikimac RDC mechanism which keeps nodes on sleep mode for maximum time of no activity, for better power consumption. As nodes increase with respect to border router, power consumption for R_X increases and T_X decreases which showed that both activities are vice versa and validated WSN tenet that when nodes are in ON mode, it is in R_X mode. As nodes are increases in number and they are in R_X mode for maximum time So, R_X power utilization is increased. T_X power utilization is decreasing because border router is in transmission mode for maximum time and when nodes increased in number from 5 to 10 and 15 in 5 hops gradually relative to border router. So, T_X power is decreased.

From results analysis of scenario 1 and scenario 2, the following consequences are observed here:

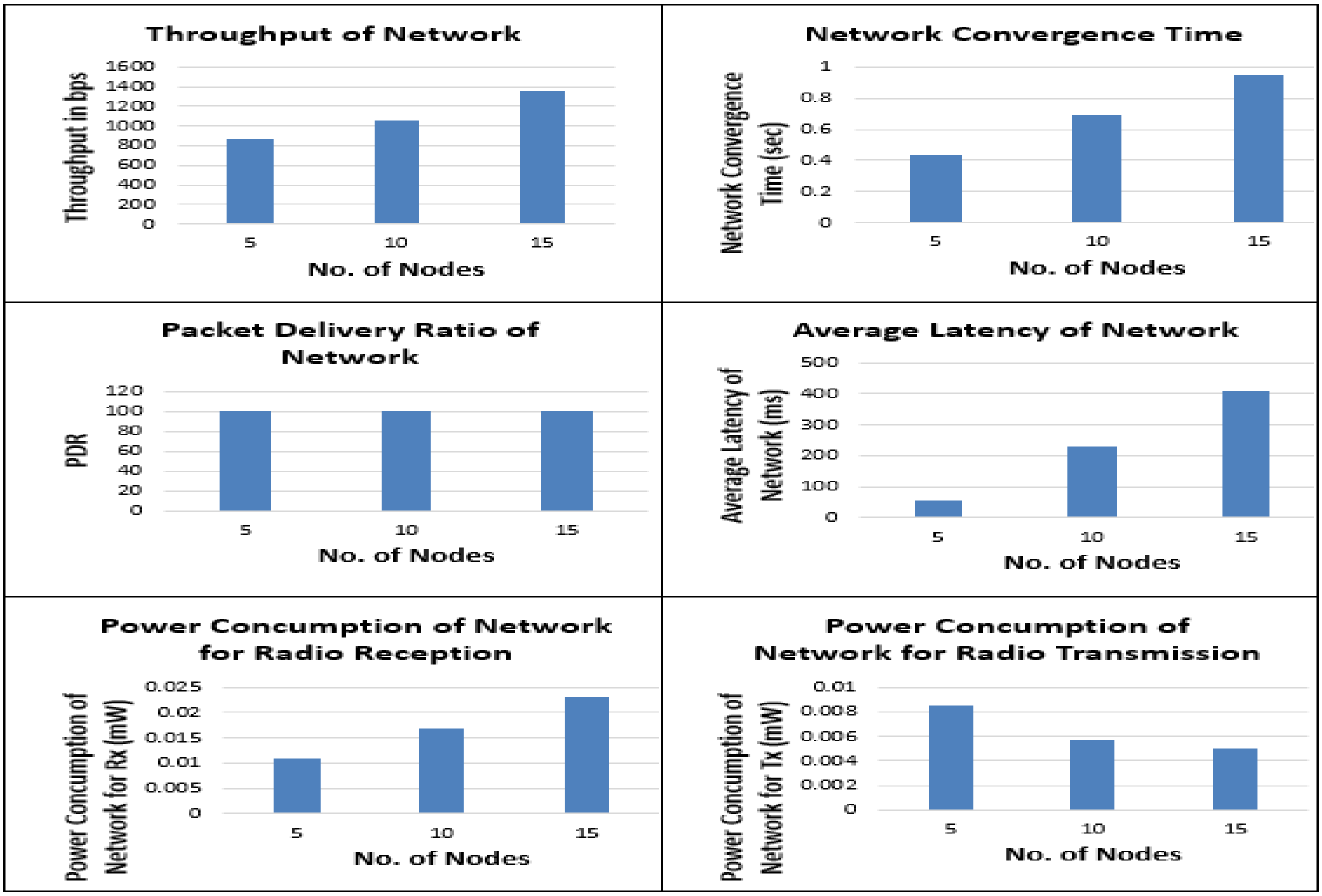

FIGURE 15. Results of throughput, network convergence time, PDR, average latency and power consumption for RX and TX for scenario 2.

- *Throughput* of network $\propto$ *No. of Nodes*
- *Network Convergence Time* $\propto$ *No. of Nodes*
- *Average Latency of Network* $\propto$ *No. of Nodes*
- *PDR* = *Constant* (100%)
- *Power Consumption* of network (*Rx*) $\propto$ *No. of Nodes*
- *Power* = *Consumption* of network (*Tx*) $\propto$ 1/ *No. of Nodes*.

B. RESULTS ON SCENARIO 3 AND SCENARIO 4

Scenario 3 of SLCPS framework is based on 1 hop with no speed limit constraint and scenario 4 is based on 1 hop with 100% speed limit constraint from simulator control window. The number of nodes is 5, 10 and 15 for container, storehouse and warehouse with 1 RPL border router in each respectively. Nodes are placed by proposed mathematical model mentioned in equation 3 for 1 hop SLCPS process. The 1 hop means that all nodes are in transmission range of border router. The scenario 3 and scenario 4 are assessed in terms of performance evaluation parameters i.e. the throughput of network, network convergence time, packet delivery ratio, average latency of network and power consumption of network in terms reception and transmission using formulas mentioned in Table 5. Fig. 16 and Fig. 17 portray results for scenario 3 and scenario 4 respectively.

The scenario 3 and scenario 4 of SLCPS framework attained increase in throughput from 5 to 10 nodes and then decreases from 10 to 15 nodes. This is due to the logic that all nodes lie in transmission range (50 meters) of border router in 1 hop i.e. $d_{mpt} \leq d_s$ (distance of motes is less than or equal to carrier sensing range of border router). Therefore, when nodes are increasing in number, packets traffic is also increased but node 10 onwards congestion occurs due to high traffic and throughput starts decreasing from 10 to 15 nodes. This shows that 1 router has maximum capacity of 10 nodes and then another border router is required. Network convergence time and average latency of the network is low with a low traffic load in terms of nodes but with the increase in network load these parameter values also increased. The reason for this increase in convergence time and average latency in 1 hop is, number of connections to or from 1 border router with increasing nodes. This give rise in time of connection with all available nodes as well as sent and receive time of network. The PDR remained constant i.e. 100% in 1 hop scenario because network has no losses and interference up to 15 motes. The reason is placement of nodes

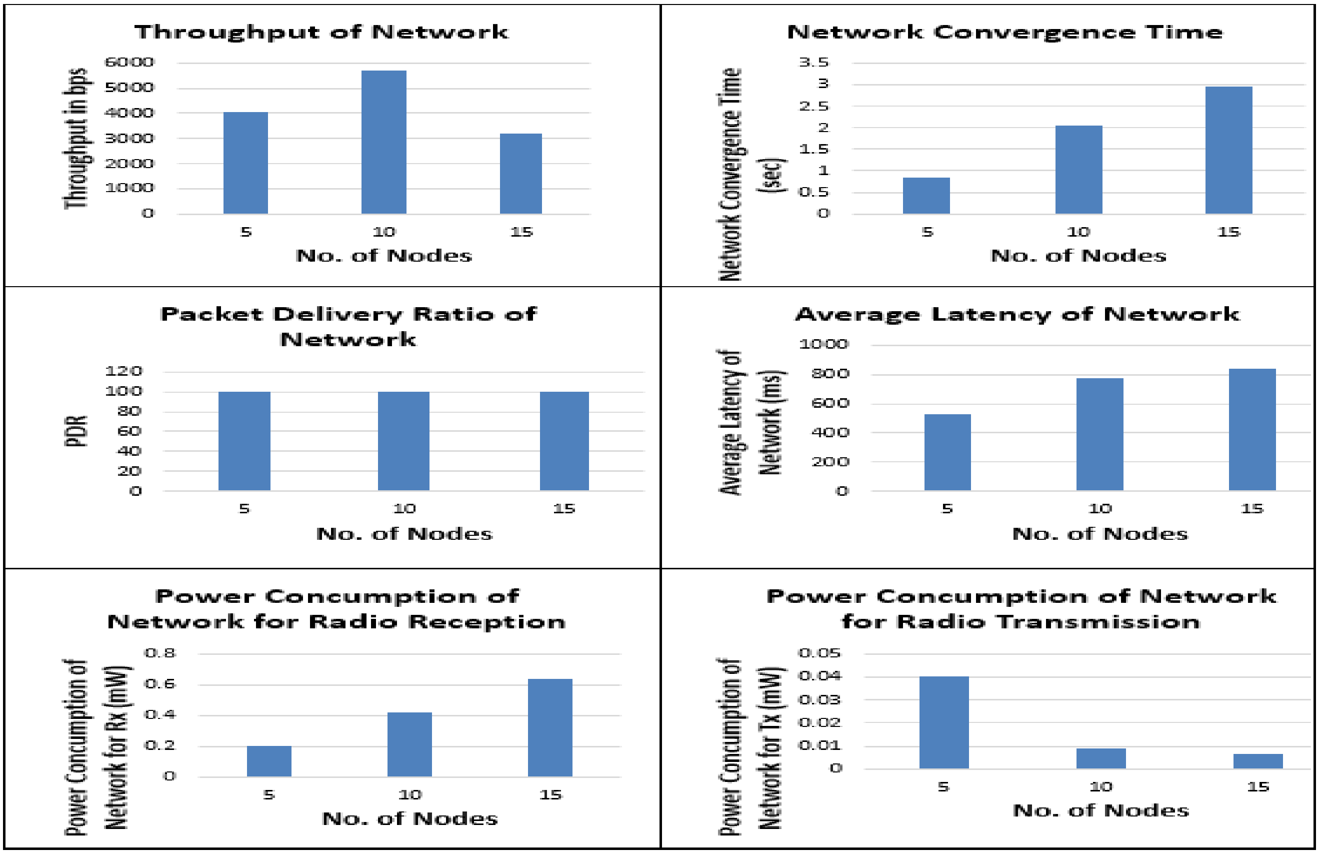

FIGURE 16. Results of throughput, network convergence time, PDR, average latency and power consumption for Rx and Tx for scenario 3.

by proposed mathematical model of equation 3, where all nodes are in transmission sensing range of RPL border router as well as contikimac at RDC layer and CSMA/CA at MAC layer. The power usage of network for R_x is increasing and T_x is decreasing due to increasing nodes which shows their reciprocal behavior because of contikimac RDC mechanism. As validated from Fig. 21. radio_R_x and radio_T_x behavior that for maximum time CoAP nodes are in R_x mode and border router i.e. node 1 is in T_x mode. So, with increase in network size, maximum nodes are in R_x mode with respect to border router hence R_x power is increasing and T_x power utilization is decreasing.

The overall results analysis of scenario 3 and 4 for 1 hop of SLCPS framework process are summarized with the following conclusions:

- *Throughput* of network $\propto$ *No. of Nodes* (from 5 to 10 nodes)
- *Throughput* of network $\propto$ 1/*No. of Nodes* (from 10 to 15 nodes)
- *Network Convergence Time* $\propto$ *No. of Nodes*
- *Average Latency of Network* $\propto$ *No. of Nodes*
- *PDR* = *Constant* (100%)
- *Power Consumption* of network (*Rx*) $\propto$ *No. of Nodes*
- *Power* = *Consumption* of network (*Tx*) $\propto$ 1/ *No. of Nodes*

C. RESULTS ON SCENARIO 5 AND SCENARIO 6

The Scenario 5 of SLCPS framework is based random placement of motes with no speed limit constraint from simulator control window while scenario 6 is based on random placement of motes with 100% speed limit constraint. Scenario 5 and scenario 6 are assessed in terms of performance parameters, the throughput of network, network convergence time, packet delivery ratio, average latency of network and power consumption of network in terms reception R_X and transmission T_X using mathematical formulas given in Table 5. Fig. 18 portrays results obtained for scenario 5 and Fig. 19 depicts results obtained for scenario 6. Both scenarios are not following proposed SLCPS mathematical models, binary coverage model and hops. Therefore, results of proposed SLCPS framework is compared and validated with these random placement scenarios.

The scenario 5 and scenario 6 of SLCPS framework has decrease in throughput with increasing number of nodes. The reason of gradual decrease in throughput with increasing number of nodes up to 15 is due to the structure of random nodes placement. Complexity and congestion in network increases with respect to border router which degrades throughput of network with increase in network load due to randomness. This behavior of throughput in random nodes

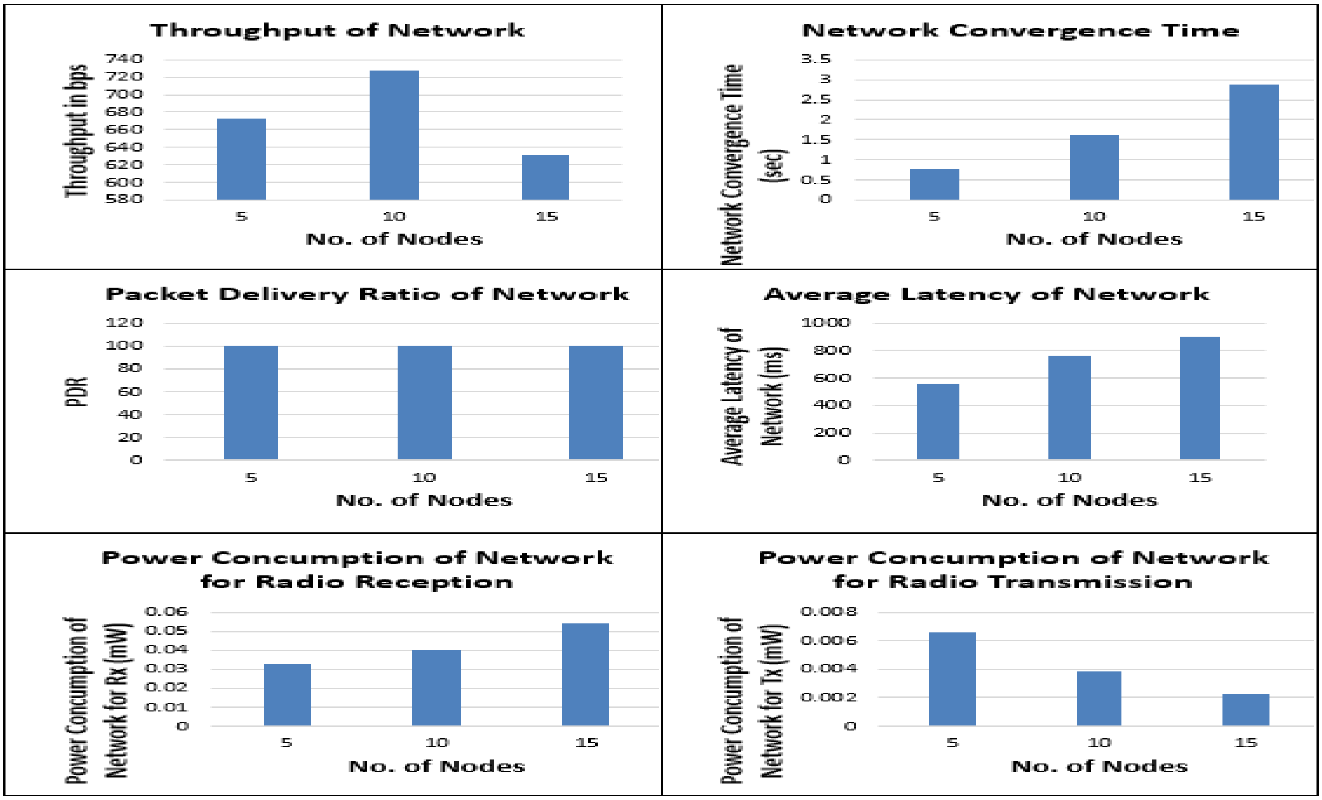

FIGURE 17. Results of throughput, network convergence time, PDR, average latency and power consumption for Rx and Tx for scenario 4.

placement scenarios is reciprocal of 1hop and 5hops scenarios of SLCPS framework.

The time for convergence of network increases with increasing number of nodes because as nodes are increasing from 5,10 to 15 nodes, the junction time of RPL border router with all available nodes is increased. The network convergence time of random node placement scenarios have premature convergence at 5nodes while it has higher values at 10 and 15 nodes as compared to 1hop and 5hops scenarios of SLCPS framework as shown in Fig. 18 and Fig. 19.

Similarly, average latency of network is low with a low traffic load in terms of nodes, but with the increase in network load, the average latency also increases. Average latency of network, is the time required for a packet to be returned to its sender and equal to Round Trip Time (RTT). Therefore, the cause of this increase in average latency with increasing number of nodes is network saturation with respect to 1 RPL border router, which produce packet queuing at border router due to traffic of nodes and increases average latency of network. The values of average latency of network in random nodes placement scenarios is high at 5, 10 and 15nodes as compared to proposed 1hop and 5hops scenarios of SLCPS framework and shows inefficiency of random behavior.

As PDR is ratio of packets successfully received to the total packets sent. The PDR also remained constant i.e. 100% in random nodes placement scenarios because network has no losses up to 15 nodes due to CSMA/CA protocol at MAC layer and contikimac at RDC layer. Although PDR of individual nodes are not constant but to sum up packets received and packets sent of all nodes then the total PDR is constant due to mentioned protocols in all scenarios.

The power consumption of network for R_x is increasing due to increasing number of nodes and the power consumption of network for T_x is decreasing with gain in network size in random nodes placement scenarios of proposed framework because nodes has constrained nature consisting of power saving mechanisms. For this purpose, contikimac at RDC layer and CSMA/CA at MAC layer is used. As the network size increases from 5 to 15 nodes and as shown in Fig. 23 and Fig. 24 that for maximum time border router is in T_x mode and other nodes are in R_x mode. So, border router transmits and motes gathers or receives data that validates proposed network behavior that motes are increasing with respect to border router then is R_x power consumption is increasing relative to T_x power utilization. The values of power consumption of network for R_x and T_x for random nodes placement scenarios as shown in Fig. 18 and Fig. 19 are high as compared to Fig. 14 – 17 of proposed 1hop and 5hops of SLCPS framework. This shows more power consumption of network and inefficient network design in random nodes placement scenarios.

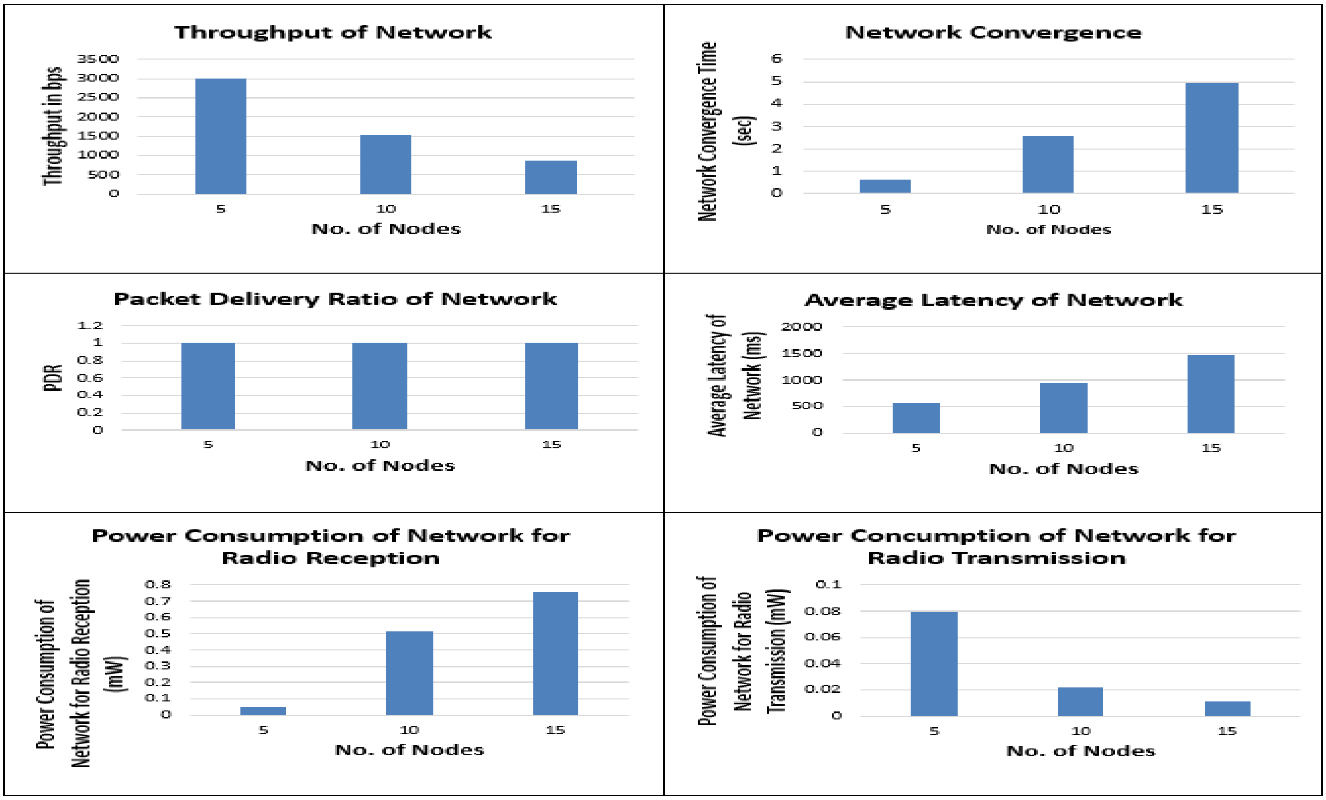

FIGURE 18. Results of throughput, network convergence time, PDR, average latency and power consumption for Rx and Tx for scenario 5.

From results analysis of scenario 5 and scenario 6, the following consequences are observed here:

- *Throughput* of network $\propto 1/$ (*No. of Nodes*
- *Network Convergence Time* $\propto$ *No. of Nodes*
- *Average Latency of Network* $\propto$ *No. of Nodes*
- *PDR* = *Constant* (100%)
- *Power Consumption* of network (*Rx*) $\propto$ *No. of Nodes*
- *Power* = *Consumption* of network (*Tx*) $\propto$ 1/ (*No. of Nodes*

It should also be noted that in all 6 scenarios of SLCPS framework, the performance parameters of no speed limit constraint scenarios i.e. Fig. 14.16 and 18 have high values as compared to 100% speed limit constrained scenarios i.e. Fig. 15, 17 and 19. The reason is high packets/second traffic due to enhanced capability of simulator or system i.e. 200%, 300% and so on in no speed limit constraint scenarios. The significance of no speed limit constraint scenarios versus 100% speed limit constraint scenarios are whether the no speed limit constraint scenarios are faster and completed in less time with mentioned low load of 5, 10 and 15 nodes as compared to 100% speed limit constraint which is completed in mentioned time of 300seconds. The proposed framework overall behavior remained same and validated stability, efficacy, consistency and reliability of SLCPS framework.

D. OVERALL RESULTS OF PERFORMANCE EVALUATION PARAMETERS FOR NO SPEED LIMIT AND 100% SPEED LIMIT CONSTRAINT SCENARIOS

Fig. 20 shows the overall results of 6 performance evaluation parameters in terms 5hops, 1hop and random placement of nodes for no speed limit constraint and 100% speed limit constraint scenarios. The first 3bars shows no speed limit constraint scenarios while the last 3bars show 100% speed limit constraint scenarios for each performance evaluation parameter for 5hops, 1hop and random placement of nodes. Performance of random nodes placement scenarios are shown by pattern filled bars and show overall worse results as compared to proposed mathematical model based SLCPS framework.

As the SLCPS framework for complete supply chain of food based on mathematical models for nodes placement is proposed for the first time up to the author knowledge, therefore, for results assessment of proposed framework is compared with random nodes placement scenarios. From comparative analysis of each parameter for proposed framework versus random nodes placement framework, it is observed that on average throughput of network improved by 223%, network convergence time of network has 667% efficacy, PDR remains constant as discussed in section V(C), average latency of network becomes better by 188%, while

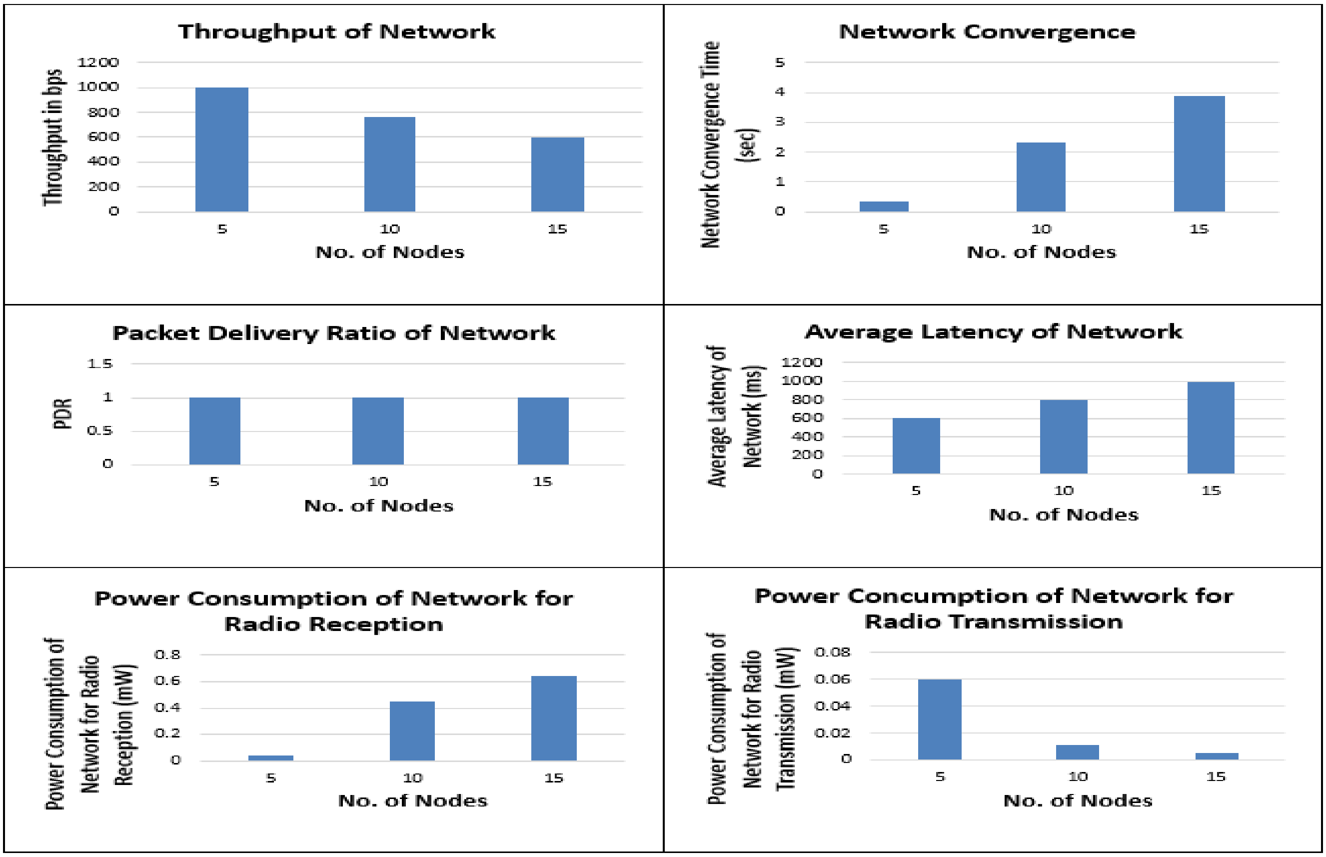

FIGURE 19. Results of throughput, network convergence time, PDR, average latency and power consumption for R_X and T_X for scenario 6.

power consumption of network for radio reception and transmission has 576% and 66% improvement respectively.

From the overall results, it is seen that on average the proposed framework based on mathematical models for nodes placement outperforms random nodes placement scenarios by using percentage increase rule [43].

E. RESULTS ON TIMELINE ACTIVITIES OF MOTES IN 1HOP AND 5HOPS SCENARIOS

The timeline of 15 motes and 1 border router in terms of radio activity, usage, connection, Light Emitting Diodes (LEDs) and radio traffic in proposed framework for 1 hop and 5 hops scenarios are analyzed using various factors shown in Table 6. Radio connection events are shown by LEDs in which transmissions are painted blue, receptions are green, and interfered or off radios are red where radio traffic displays inter-mote radio communication in which radio_on, radio_T_X, radio_R_X, and radio_int are used on physical layer for the time radio traffic is on, radio transmission, radio reception and radio interference time respectively. The results of timeline activities of 15 CoAP server on sky motes and 1 RPL border router based on sky mote for 4 scenarios are shown in Fig. 21.

Fig. 21 demonstrates timeline activities of LED red, green, blue, radio_on, radio_T_X, radio_R_X, and radio_ int of network in 4 scenarios of SLCPS framework. Mote 1 is RPL border router and mote 2-16 are CoAP servers. The timeline activities are based on protocol stack used in proposed framework as well as contikimac and CSMA/CA protocols for efficient utilization of power. The red, green and blue LED shows synchronized power off or interfered i.e. neither transmitting nor receiving, reception and transmission events of motes in all scenarios with difference of few micro-seconds. Motes are off on average of 10720μ s, reception events on motes are for 53000μs on average while transmission events are for 300μs on average. This justifies our proposed framework results that motes spend maximum time in reception events. For communication between motes and their radio traffic, radio_on for 299200000μs on average which validate 3000000ms simulation time of proposed framework. Radio_T_X is transmission traffic which is high on mote 1 (border router) and comparatively less on remaining CoAP motes as well as Radio_R_X, which is low on border router and high on remaining motes that validates results of power consumption in R_X and T_X mode of proposed framework. Also, standard behavior of border router is validated, which has high transmission and CoAP motes having high reception or listening traffic. The radio_int is interference between motes which exists in 5 hops scenarios because in multiple hops only motes in next intermediate hop is in transmission range not of others hops due to which interference exists while interference is almost

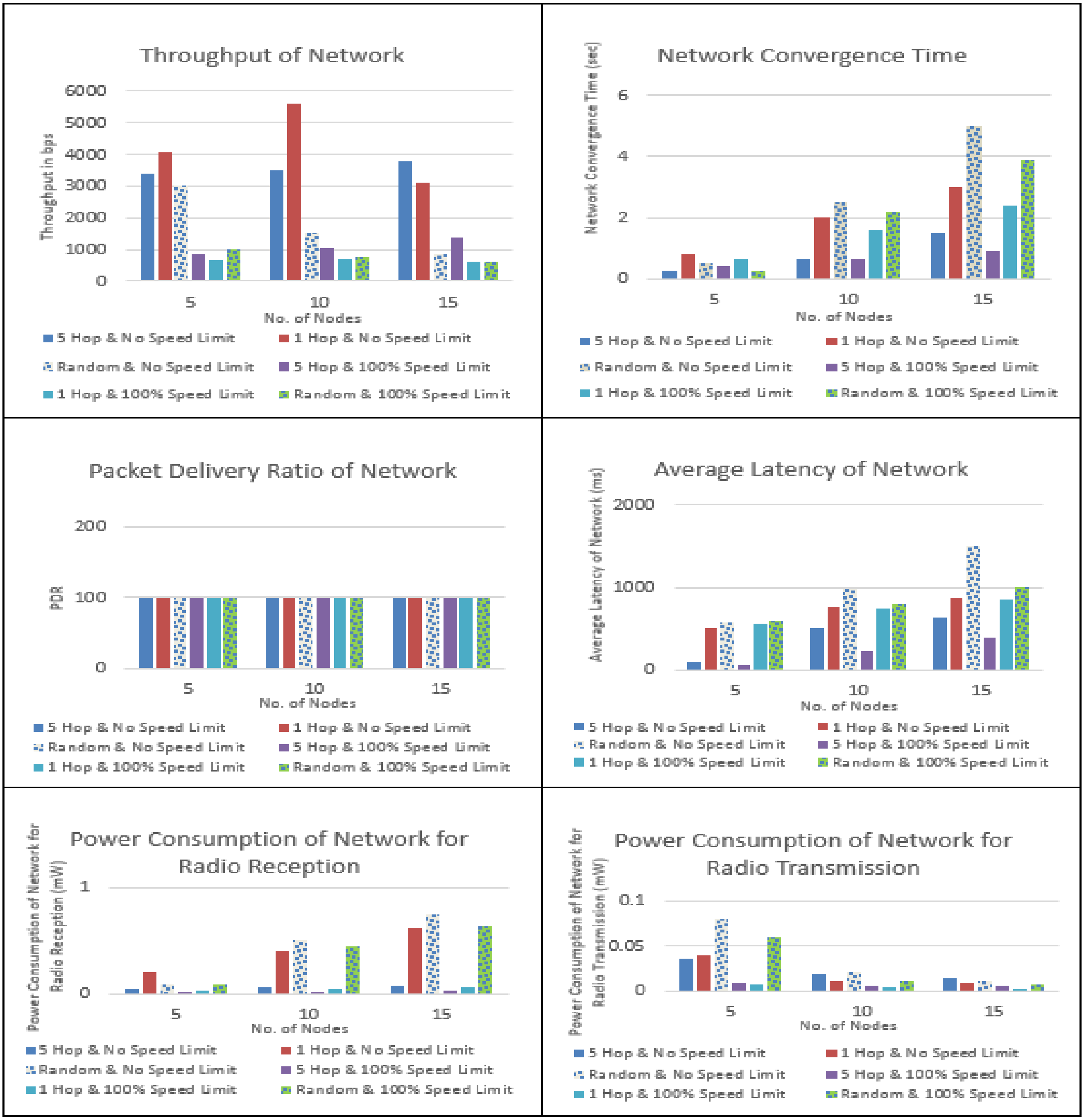

FIGURE 20. Overall results of performance evaluation parameters in terms 5hops, 1hop and random placement of nodes for no speed limit and 100% speed limit constraint scenarios of SLCPS framework.

zero in 1 hop scenarios as all motes are in transmission range of border router.

F. RESULTS ON TIMELINE ACTIVITIES OF MOTES IN RANDOM MOTE PLACEMENT SCENARIOS

Fig. 22 demonstrates timeline activities of LED red, green, blue, radio_on, radio_Tx, radio_Rx, and radio_ int of network in 2 scenarios of random placement of nodes of SLCPS framework for validation and comparison with proposed mathematical model based SLCPS framework. Mote 1 is RPL border router and mote 2-16 are CoAP servers. The timeline activities are based on protocol stack used in proposed framework as well as contikimac and CSMA/CA protocols for efficient utilization of power. It has been observed that the all radio connection events i.e. red, green and blue LED while one of inter-mote radio communication parameter i.e.

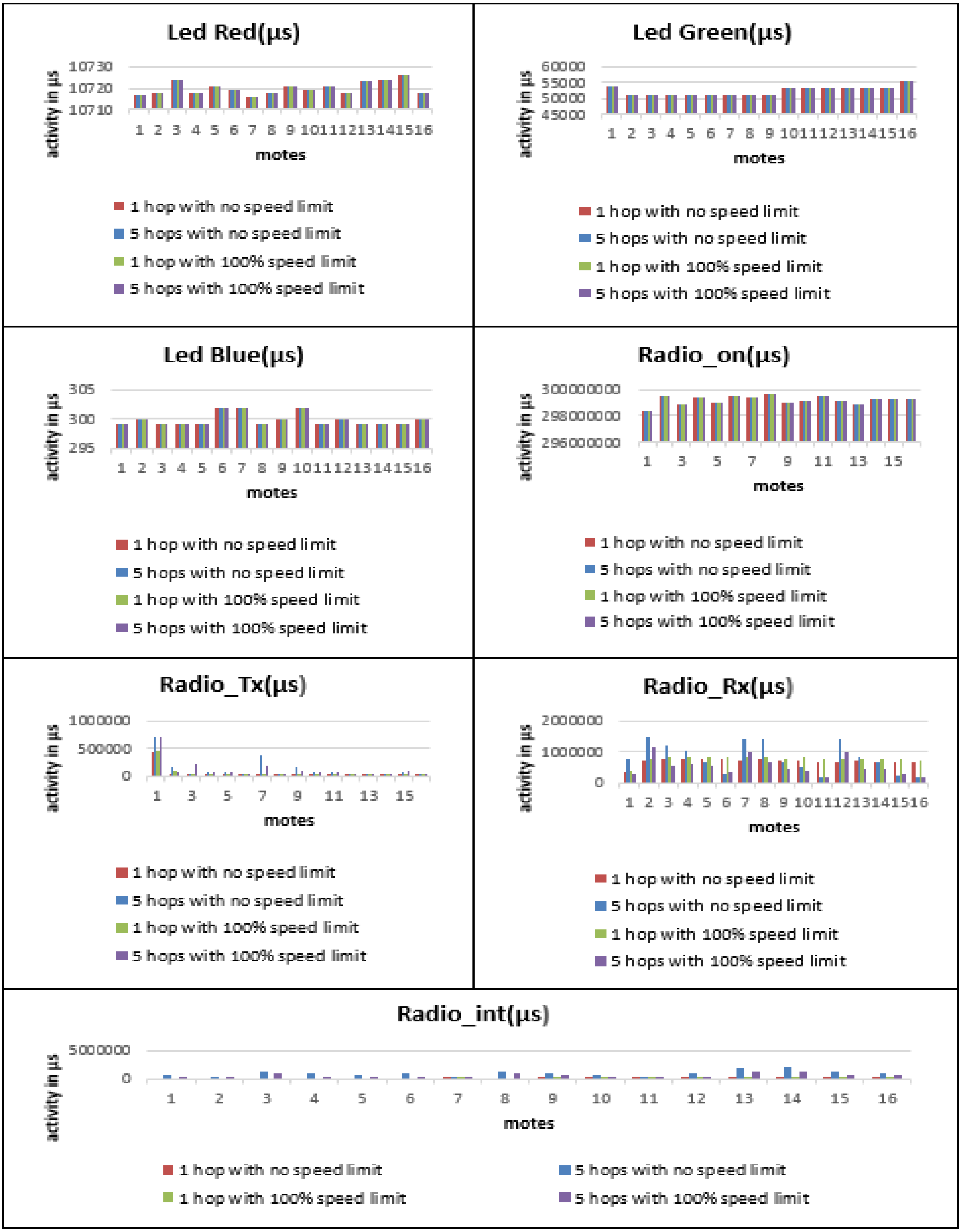

FIGURE 21. Motes timeline activities of LED red, green, blue, radio_on, radio_Tx, radio_Rx and radio_ int in 4 scenarios of SLCPS framework.

FIGURE 22. Motes timeline activities of LED red, green, blue, radio_on, radio_Tx, radio_Rx and radio_ int in random motes placement scenarios of SLCPS framework.

radio_on have similar values with proposed mathematical model based SLCPS framework. The reason is similar time duration of simulation, IoT protocol stack, contikimac and CSMA/CA protocol which showed each mote capability under said similar parameters. Radio_Tx and Radio_Rx is transmission and reception traffic among motes on physical layer respectively while the Radio_int is interference between motes. The Radio_Tx and Radio_Rx have same behavior like proposed mathematical model based SLCPS framework but their values are comparatively low on average, showing inefficiency of random motes placement scenarios in SLCPS framework. Similarly, Radio_int is interference among motes which exists on all motes in random motes placement scenarios. The reason is motes are neither bounded to proposed binary coverage model nor mathematical models instead motes are placed randomly as shown in Fig. 13. Therefore, interference exists at very high that effects transmission and reception of motes in random motes placement scenarios of SLCPS framework. Whereas bonded coverage and connectivity based on proposed mathematical models and binary coverage model gives a single, reliable, high speed and secure SLCPS framework.

G. LIMITATIONS OF SLCPS FRAMEWORK

The proposed SLCPS is baseline framework for bonded coverage and connectivity of IoT devices limited by various resources i.e. number of IoT devices are limited up to 15, mathematical models are only provided for bonded coverage and connectivity of 1hop and 5hops scenarios and the interference is minimized in these scenarios. The security and reliability are achieved in proposed SLCPS framework by bonded coverage and connectivity using mathematical models instead of security algorithms due to constrained nature of IoT devices in terms of memory, processing power and battery life. The framework is proposed for short range link layer protocols where the maximum transmission range is 50meters. Overall, a novel and naive SLCPS is proposed for complete supply chain of food in terms of container, storehouse and warehouse which can be enhanced in future.

VI. CONCLUSION AND OUTLOOK

In this paper, the issues related to complete smart logistics process in terms of IoT and CPS scalability, bonded connectivity and coverage, sensor placement and simplicity have been addressed under the umbrella of 3 laws of computing for IoT i.e. Moore's, Koomey's and Metcalfe's laws. Although, CPS and IoT have supplemented the existing logistics services considerably, but due to constrained nature of IoT devices, systems developed are either at very preliminary stage of control and monitoring, or developed schemes are complex, computationally expensive and for some specific module of logistics. Mechanisms formulated in the past are conventional that have proven to be unfitted to controlled sensor-based data traffic environment. Conventional methods are either human based or constructed on random behavior of WSN that give rise to interference and degrade scheme performance in critical environment of control and monitoring of goods conditions in logistics. Real time surveillance and information sending of environmental parameters within logistic processes for reduction of goods and perishable items wastages is a critical issue, if handled by conservative human methods or preliminary WSN approaches. Therefore, to cope with such issues, a framework was proposed in this paper for reliable coverage and connectivity of IoT devices in SLCPS.

The proposed framework for SLCPS was emulated based on mathematical models for placement of IoT devices instead of random placement for the first time up to the authors' knowledge. Also, the proposed SLCPS framework is compared with random motes placement framework. With mathematical models, the proposed framework achieved better scalability, reliable coverage, stable connectivity and simplicity. Similarly, IoT protocol stack and apt utilization of interoperable technologies were used for this specific IoT application after thorough comparative analysis. In this work, a novel smart logistics process in terms of container, storehouse and warehouse has been developed based on supply chain of food. Simulation results were acquired using Cooja and Wireshark simulator in Contiki operating system after an ample analysis of SLCPS framework for IoT devices using various performance evaluation parameters in different scenarios. The results of proposed framework were based on the throughput, network convergence time, packet delivery ratio, average latency, power consumption of network in terms of transmission and reception, the complete evaluation of each parameter and the timeline of each mote in terms radio activity, usage, connection, LEDs and radio traffic. The results validated efficacy of the framework proposed in this work in different scenarios as compared to random motes placement framework. The framework also provided baseline rubrics for extended research in smart IoT and CPS applications.

The proposed framework has provided real-time analysis of comprehensive supply chain data, increased dependability, distribution planning and delivery reliability, reduction of food/goods losses through better synchronization of dynamic logistics processes, optimized processing time and labor costs, minimized storage and transport costs and overall platform provides a constantly updated situation picture to gain new customers.

The aim in the future would be to boost and extend the existing framework for other IoT applications. The existing work status can be improved by stretching it further to analyze mobility in scenarios of transport and logistics. The current framework has provided bonded communication mechanism in smart logistics but in future enhanced security can be incorporated for more trustworthy environment. Hence, it is stated that SLCPS framework can generate a valuable contribution to the subject of food/goods waste and will be profitable in the future as well.

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