# Software-defined Wireless Sensor Network: WSN Virtualization and Network Re-orchestration

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Abstract: Flexible reorganization of complex IoT (Internet-of-Things)-based sensor networks is crucial for the alignment of the sensor network's operational dynamics with that of the monitored external phenomenon. Software-Defined Networking (SDN), when supported by Cloud-level Network Virtualization (NV), offers a prospective avenue for a flexible sensor network that can re-orchestrate as the monitored process demands. In order to allow for seamless softwarization of the sensor network functional entities, this paper promotes function modularization and establishment of both virtual repositories of reusable software modules as well as requisite operational software. An architectural solution that is aligned with Industry 4.0's ideology is presented in this work. This along with the software-defined resources is deemed as a viable solution to re-orchestrate the physical sensor network. By means of example simulation scenarios, this paper highlights the utility of NV for flexible soft trialling of sensor network topological re-orchestration and highlighting the possible network downtime associated with that operation. The outcome offers potential for the utilization of the virtual environment and the dynamics retained within it to offer ground for pre-planning for best possible re-orchestration scenario that comply with adaptive interaction with the dynamics of the physical environment.



## 1 INTRODUCTION

Typical IoT-based sensor network organizations entail complex architectures in provisioning the necessary internet connectivity between the physical wireless sensor network (WSN) and the remote cloud server (Ezdiani et al., 2017, Ezdiani et al., 2015). Flexible operation of such IoT-based sensor network deployments is of critical importance as it engages with its physical surroundings (Violettas et al., 2017, Ndiaye et al., 2017). Network Virtualization, in conjunction with Software-Defined Networking (SDN), holds considerable potential to unlock the requisite salience offered by a programmatic and flexible IoT-based system solution (Modieginyane et al., 2018, Ojo et al., 2016, Gupta 2018, Acharyya et al., 2016, He et al., 2019).

The core principle behind SDN is to decouple the control plane from the data plane to allow for centralised configurability of the network (via virtualizing the underlying functions and decision-making process) (Nguyen et al., 2016, Kobo et al., 2017, Mostafaei et al., 2018, Bera et al., 2017). Herein, SDN controller(s) is the essential entity, which possesses the overall (centralised) view of the network and is responsible for both management of the underlying functions as well as efficient routing of data. On its merger with Network Virtualization, the role of the SDN is that of an 'orchestrator' (e.g. between 'sliced virtual networks') (Modieginyane et al., 2018). A variety of proposals, employing SDN-based approaches, have been put forth to address issues pertaining to flexible and dynamic topological manipulation of WSNs. (Haque et al., 2019) utilise the concept of SDN within their proposed 'SDSense' architecture to devise a centralised logical controller that could preside over the configuration of software-embedded sensors residing in the data plane. Equipped with topology control modules (amongst other modules viz., routing and scheduling modules) as well as provision for user-governed addition and removal of logical modules, the central controller plays an important role in influencing the functionality and topology of the network.

Jemal et al., 2013 pursue self-adaptation within WSN by means of conventional adaptive approach.



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The paper used certain adaptive middleware control components. His paper focuses on cluster based WSN and does not emphasize upon the aspect of network re-orchestration from a topological standpoint. Results pertaining to improvement in network performance as a result of software-defined topological re-orchestration have not been included within their paper. The efficacy of establishing a singular repository catering for data storage as well as knowledge and functional (core as well as auxiliary) components in augmenting the flexibility of the network is not considered. In their approach the planning is driven via a pre-defined ruleset. Also, the authors consider a simple case of network rupture caused by sensor mobility and resolve it by means of enabling it to 'adapt' and connect to the gateway within range. The aspect of network downtime is not investigated. With the emergence of technologies like cloud-based services, software defined networks, Industrial IoT and virtualization, a more flexible and open approach could be facilitated for adaptively manipulating the sensor network. This in effect allow for open capability of accommodating knowledge acquisition and learning with time. Here the context of this paper is to highlight the potential here and suggest related architecture.

Kipongo et al., 2018 incorporate a 'Topology Management' within the SDN controller, enabling it with the capability to visualize the topology of their Software Defined Wireless Sensor Networks (SDWSN) architecture. No evaluation of the proposed work is presented. The authors acknowledge the importance of developing a topology discovery protocol that would entail minimum latency, which led them to undertake a survey of 'Topology Discovery' within the SDN domain. Galluccio et al., 2015 put forth an SDN-based solution for wireless sensor networks, namely 'SDN-WISE' wherein the 'WISE-visor' controller, consisting of a 'Topology Management' layer, is responsible for governance of the logics pertaining to network management. The role of the 'Topology Management' layer within this architecture is to a) virtualize underlying network functions, b) extract the necessary information viz., battery capacity, address, RSSI (Received Signal Strength Indication), etc. from the underlying devices and relay them over to the controller(s) and c) exert control over the stack layers denoted by the controller(s). Abdolmaleki et al. 2017 incorporate a fuzzy-based topology discover protocol on top of the SDN-WISE solution to enhance network efficiency via increasing network lifetime and decreasing packet losses. In a bid to address device and 'network topology' management issues in IoT-based WSNs, Bera et al. 2018 employ the concept of SDN to design a controller equipped with node and network-specific rule-based management policies to exert control over the respective packet formats. In another research effort to enhance software-defined control over IoT-based sensor network topologies, Theodorou et al., 2017 put forth the 'Coral-SDN architecture' wherein the centralized 'CORAL' controller is entrusted with responsibility to manage network dataflow. The 'CORAL controller' comprises of a modular 'Decision Making' subsystem (consisting of certain rules and algorithms) to allow for rule-based adaptation of network topology and routing control functionalities. The controller also consists of a 'Network Modeller' module that retains a graph-based abstracted view of the underlying network. Information pertaining to radio signal strength and link quality can be derived from here.

While the above documented state of the art presents important progress towards the WSN based cyber-physical operation, it lacks penetration towards number of operational drivers. These are relevant to the dynamics of the interaction between the cyber and physical environments when operational changes need to be physically implemented. Here, both soft trialling of various re-orchestration scenarios on a virtual platform, and examination of performance implications associated with physical WSN downtime have, to the best of our knowledge, not received significant attention. The latter is important performance measure that reflect capability of the system to cope with the real time monitoring demand of the monitored process or phenomenon.

Similar to that embodied by the concept of SDN, our work also involves virtualization of the underlying data plane (physical) functions but emphasizes upon formulation of a 'Data and Knowledge' repository of the necessary WSN core and auxiliary virtual functional modules that could reside at the cloud (or the IT-layer) as documented in a previous research work of ours (Acharyya et al., 2019). It is anticipated that interactive collaboration amongst the virtualization unit and the software repository could offer an adequate framework for requisite flexible soft trials.

This paper offers novel approach to the support of the overall process of software-defined re-orchestration and relate them to the proposed Industry 4.0-based architectural solution. Overall, the objective of this paper is to present an architectural solution capable of capitalizing on SDN-enabled virtualization technology to modularly allow for the necessary real-time interaction with the operational dynamics related to those of the prevailing service needed for the monitored phenomenon.

The rest of the paper is organized in the following manner. The proposed ideology of the 'three core modular network functions that constitute any IoT-based sensor network is spelt out in section 2. Section 3 details the proposed Industry 4.0-based architectural framework for IoT-based sensor network, which allows for the necessary flexible network re-orchestration through virtualization and software control. Example sensor network re-orchestration scenarios, along with certain simulation based flexible WSN topological re-orchestration cases, are presented in section 4. The 'network downtime' associated with the re-orchestration process is highlighted in section 5 by means of two simulation-based examples. Finally, the conclusion of this research work is presented in section 6.

## 2 FLEXIBLE WSN NETWORK FUNCTIONAL COMPONENTS

An IoT-based sensor network organization should have basic functionalities for wireless sensing, data routing and Internet gateway access (Acharyya et. al., 2019). These three key generic functions can act as standalone functions on individual devices or integrate as two or three functions on the same device depending on the ability of the hardware host to accommodate for these functions. Modern approach in offering edge computing allow for further auxiliary functional units coupled with these three generic functions in support of the system computational requirements and enhance the real time performance. Figure 1 depicts the 'core' and example 'auxiliary' roles executed by each of the three generic functions.

As shown in figure 1, core activities associated with 'Leaf function' pertain to 'Sensing and Data-acquisition' functions viz., sensor selection amongst heterogeneous sensing, and sampling rate relevant data acquisition of each type of the required sensing as well as maintenance of connectivity with router (or Gateway) node via bidirectional radio messages. On the other hand, example auxiliary activities that may be assumed by the leaf node include edge-computing-based data management tasks such as buffering, queueing, compression, and digital signal processing. Also, depending upon capabilities possessed by the hardware employed, it may assume and execute higher functional roles of 'data routing' and IoT-enabled connectivity utilizing protocol such as 6LowPAN. This, in effect, enables the node to be directly accessible through the internet. Core and auxiliary functions pertaining to 'Router node' are also depicted in figure 1. Herein, routing of sensed data (obtained from the leaf nodes) over to the 'sink' or 'Gateway nodes as well as acting as a 'cluster-head' for a group of lower level (leaf) sensor nodes are identified as two key core functions that could be attributed to a router node. Its auxiliary functions may include aggregation and processing of group of data, undertaking the role of leaf node or that of an IoT-enabled Gateway node, depending upon resources encompassed by the hardware. Finally, as depicted in figure 1, the core activities associated with the gateway node include facilitating as a local sink for the data generated by the network, escalating the accumulated data to the upper level IT-layer over the internet. The 'Edge Computing'-based tasks viz., management and processing of sensed data, buffering and/or organizing queue of sensed data, in addition to assuming the role of a leaf node, if both necessary and feasible, constitute its auxiliary activities.

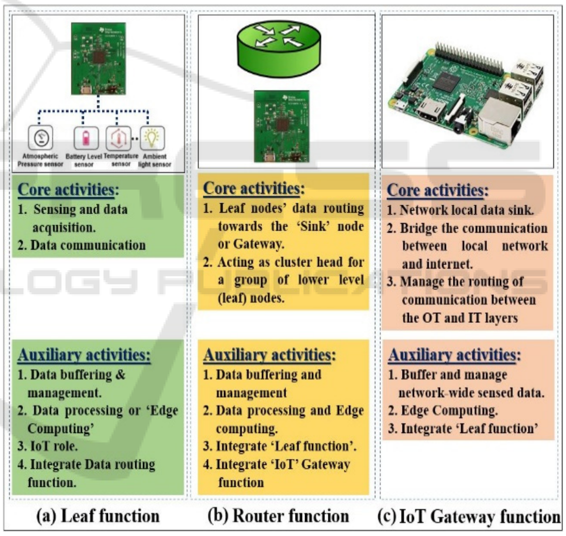



Figure 1: Example core and auxiliary activities that can be attributed to main functions composing an IoT-enabled sensor network organization viz., (a) Leaf (or end device) sensing functionality, (b) Routing functionality and (c) IoT-based WSN Gateway functionality.

The above categorization of IoT-based sensor network functionalities allows for scalability of the network. For example, a single node system has all the functions integrated in one node. The gateway here also assumes the sensing capabilities, which is a typical IoT device. A two-node network has both the leaf and gateway functionalities. Further sizes should include two or three type of core functions involved. Typical example organizations of star, tree or multi-hop connectivity are shown by figure 2. They are quite common in sensor network organizations. Example implementation is the use of TI CC2538 as wireless sensor and/or wireless router is quite common as the device offers numerous capabilities of facilitating interaction with heterogeneous sensing, facilitating reasonable computational and storage capability and hosting wireless low-power protocol. The latter includes the IoT capability through the 6LowPAN. The Raspberry Pi is another typical example for a gateway implementation. This offers ample resources for facilitating the bridging between the low power wireless sensor network protocol and the internet protocol and facilitate the needs for the transport layer.

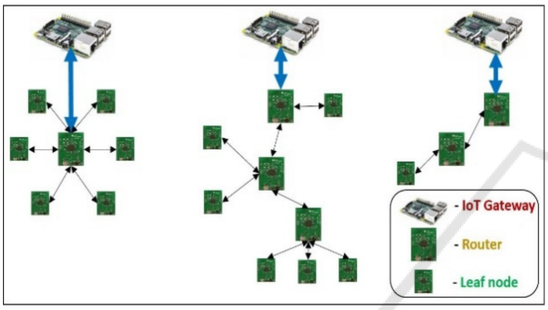



Figure 2: Example WSN implementation scenarios core (a) Star Connectivity, (b) Tree Connectivity and (c) Serial Connectivity.

Cloud-based virtualization support can be gained using operating system (OS) like Contiki. This OS offers Cooja simulation environment. Cooja is a Contiki-based simulator wherein the same Contiki-OS based C codes are used for compiling and programming the virtual Cooja nodes as that employed for the TI CC2538 wireless sensor-cum-transceivers. By virtue of this, the virtual Cooja simulator mimics the physical processes of the underlying TI CC2538-based physical sensor node or network. Such relation between the physical network entities and their virtual counterparts, enable services such as remote re-orchestration and associated performance analysis.

Defining these controls as software modules would render them capable of undergoing dynamic configurational manipulations. This is by switching over from one functional role to another and/or incorporating additional 'IoT-WSN'-centric software tasks, there by allowing for augmented flexibility of the individual functions, and hence overall WSN network. As a step to achieve this, it is deemed viable to establish a structured 'Data and Knowledge Repository, which besides accommodating for historical data as well as solution patterns, also caters for the formulation of both 'core' and 'auxiliary' software modules that could be accessed by the SDN-enabled virtualization environment. This aspect is discussed later in section 3.

## 3 PROPOSED ARCHITECTURE

The proposed architecture for IoT-based sensor networks is as depicted in figure 3. At the upper level there are two major layers. These are the 'Information Technology' (IT) and the 'Operational Technology' (OT) layers that accommodate for the virtual and physical layers respectively. The IT-layer hosts the 'Data and Knowledge' repository as well as control and virtualization management resources. This facilitate the components for establishing and managing the virtualized environment. It should also allow for performing the testing of new virtual network setting before the necessary network re-orchestrations applied on the physical network at the OT layer.

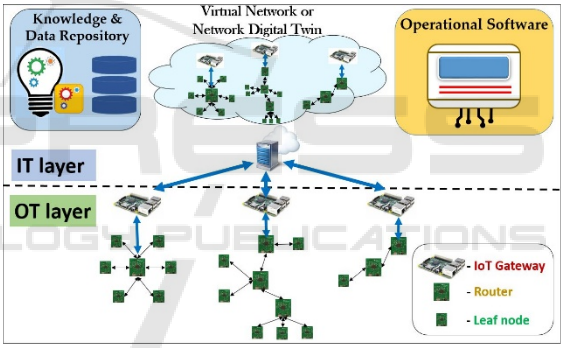



Figure 3: Proposed IoT-based sensor network organization.

The objective is for orchestration and testing of the virtual network behaviour before final reflection on the physical network. Being scalable in nature, the 'Data and Knowledge' repository could also accommodate for reusable patterns that relate to previous experiences, besides hosting the known knowledge components. Accommodation for known solutions associated with known events is one of the important features. This allow the system to retain and accumulate experiences with time. The platform also facilitates important playground for assessing any planned changes to the physical environment before actual execution of the change. This may impose real time sensitive demands especially when it comes to applications with high degree of dynamics.

The OT layer consists of the physical wireless sensor network nodes deployed for the necessary sensing and monitoring purposes. Physical data collected by the various clusters of 'leaf nodes' or 'end devices' are routed by their respective 'router' nodes which pass it over to their respective IoT-enabled gateway nodes. Certain sensor-motes as the TI CC2538 employed by us (and as previously alluded to in section 2) could be software-reconfigured to execute multi-functional tasks. For example, upon incorporation and activation of the respective software component, they could execute dual functionalities of both router and leaf node, as required. When functioning as a leaf node, the TI CC2538 can acquire heterogeneous sensor data viz., temperature of external surroundings, radio signal strength, etc. Node-operational parameters pertaining to physical layer (e.g. sensor selection, rate of sampling of the heterogeneous data, etc.), MAC layer (e.g. implementation of communication protocol viz., TDMA, CSMA, etc.) can be dictated through software control.

The ability to flexibly switch to a different functional role when required is an important feature to realize the vision of a software defined and flexible IoT sensor network organization that can be orchestrated through software control. As mentioned earlier, any IoT-based software-defined sensor network organization is composed of three key functional modules viz., Leaf function, Router function and the IoT Gateway function, that could be either switched, merged, disassembled or tweaked by means of software control. Advancements made in field of SoC technology render certain wireless-microcontroller sensor-transceiver devices to be capable of accommodating for and executing more than one of the core functionalities at a time. Such hardware sensor-cum- could be pre-configured or loaded with one or of the three functions with the help of the related software.

Equipped with protocol conversion capabilities as well as computational, IoT-enabled gateway such as the Raspberry Pi facilitates the necessary bridging of protocols. It could cater for 'Edge Computing' i.e. the requisite data processing and computation operations (viz., data compression, data buffering, queueing [1, 2], etc.) prior to escalating the sensed data (obtained from the router nodes) to the IT-layer over the internet. The IT layer could either be accessed by a single gateway that relates to all other cluster heads or by multiple gateways (governing their respective clusters) simultaneously. The ability of nodes switching functions through software allows for numerous topological scenarios and hence offer flexibility for the network to maneuver with the situation.

The IT layer is composed of three main components viz., 'Data and Knowledge Repository', 'Operational Software' as well as the 'Virtual Nework'.

The 'Data and Knowledge Repository' is responsible for storage and management of historical sensed data retrieved from the OT layer and in particular those related to important events that are associated with the virtualization of important processes. Its inherent knowledge components contribute towards formulation of core and auxiliary network functions that are meant to be accessed by the virtualization unit. Herein, historical data is deemed valuable for testing new virtual organization on the various possible process behaviour before real-life implementation on the physical network (OT layer). Finally, retaining historical solution patterns as system past experiences is another important role associated with the 'Data and Knowledge Repository' unit.

The 'Operational Software' related to the key operating tools for the development of codes relevant to the network functions. It also facilitates the development of possible training of software components or network organization for handling a given event. Contiki for example is important part of this block in generating the wireless node executable code and managing the Cooja simulator. Data processing and analytics software tool could also have important role here that supports the function of the network virtualization. Dynamic monitoring of the change in RSSI over time may for example, reveal that a given node within the network is heading towards dis-connectivity of the current associated data path. This, in turn may indicate the need for re-orchestrating the network's topology in order to avoid any subsequent issues. Similar example to analytical software like Matlab could offer the wide range of processing and soft computing capabilities.

The virtualization unit reflects the behaviour of the underlying physical network. It represents the mirror image of the physical network from both the topological organization as well as functional operational software for each node within the network. The history data represent the network performance and the extent to which it maintains the required flow of data through the network and into the sink. Another important and challenging aspect of virtualization is that of the representation of the physical environment where the physical network is located. This has an important impact on the received radio signal strength and is very difficult to be mimicked precisely. The availability of machine intelligence and learning within the cloud will play an important role here. One may initially approximate through modelling or characterization of the physical behaviour and then teach the system with more accurate behaviour with time.

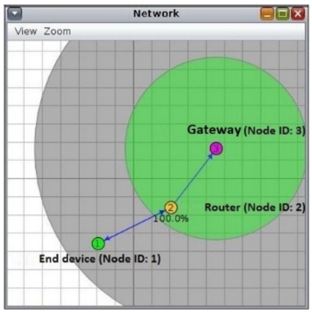
The following section offers example processes within WSN that are virtualized in the context of network topology and embedded software. The three network functions are represented within the software with an ability to get dynamically replaced as per the outcome of the re-orchestration process.

# 4 EXAMPLE NETWORK RE-ORCHESTRATION SCENARIOS

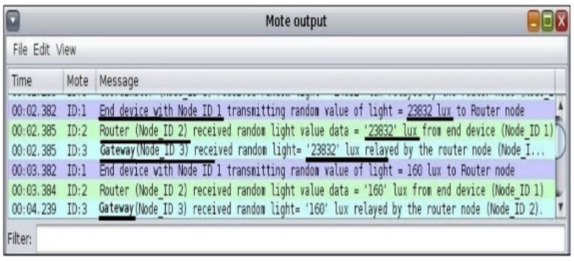
## 4.1 Simple Network Manipulation

Consider the following example wherein two different Contiki-generated, virtual 'software functional modules' are interchangeably implemented onto the same virtual network element to realize different WSN functionalities and thus, completely alter the network behaviour. This example has been performed within the virtual resource of the Cooja simulator available within Contiki. Herein, the 'broadcast_open' function presented within the Contiki-based software 'C' code was altered in a minor way to realize both the necessary functional modules, and thus, influence the communication protocol.

As shown in figure 4a, virtual Cooja node, Node ID: 1 has been configured to behave as an end device by programming as 'end device' (core) virtual software functional module. Similarly, Node ID: 2 and Node ID: 3 acts as 'router' and 'gateway' devices since they have been configured with 'router' and 'gateway' functional software modules respectively. It is important to note that since the intermediate Node ID: 2 is configured to behave as a router, the network behaves as a 'multi-hop network'. Such multi-hop network connectivity facilitates dataflow from the end-device (Node ID: 1) to the gateway (Node ID: 3) via the router (Node ID: 2). Thus, the sensed dataflow in this case, emanates from the 'end-device' function to the 'router' function, and finally to the 'gateway' function. The mote output window screenshot obtained from Cooja wherein random light data generated by the end device reaches the gateway via the router node is as shown in figure 4b.




4(a)

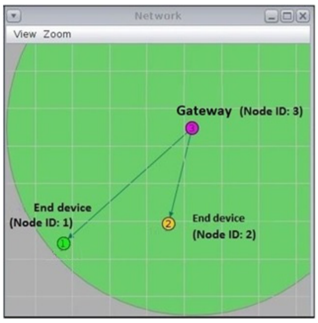



4(b)

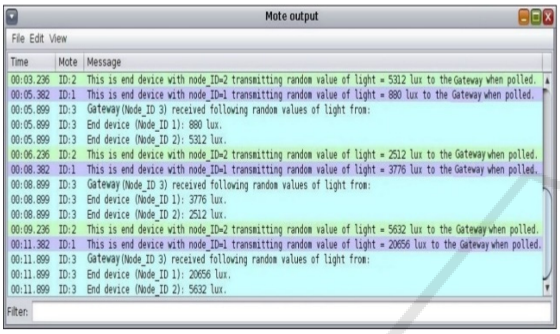
Figure 4: (a) Virtual representation of a simple multi-hop network; (b) Mote output window screenshot depicting multi-hop network behaviour.

Upon implementation of a separate virtual software 'functional module' i.e. the 'leaf node' 'functional module' on the same virtual Cooja node (Node ID: 2), it ceases to be a router and acts an end device. Without the router node, the same virtual network now behaves as a 'star network' as can be seen from figures 5a and 5b. A separate virtual 'functional module' is employed for the gateway in order to re-orient the network to follow a TDMA-based scheme, as opposed to the CSMA-based protocol implemented earlier.

This star network connectivity facilitates polling-based data flow i.e. from the end devices (Node_ID: 1 and Node: ID 2) to the gateway (Node ID: 3) is as shown in figure 5a. Thus, for providing star network service, the direction of the sensed dataflow in this case involves constant sequential switching between 'end-device 1 virtual functional module' to 'gateway' virtual functional module and 'end-device 2 virtual functional module' to 'gateway' virtual functional module. The 'mote output' window screenshot illustrating the polling-based data flow within the star-topology based network is shown in figure 5b. Thus, the above example aptly demonstrates that the network can be orchestrated to switch from case I to case II and vice-versa via implementation of the two different functional modules. This could be useful action to support (for example) reconnecting a mobile node to the network when it becomes out of the line of sight with the Gateway.




5(a)




5(b)

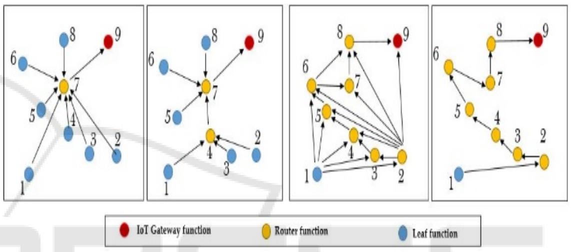
Figure 5: (a) Star implementation of the multi-hop network (shown in Fig. 4); (b) Mote output window screenshot depicting multi-hop network behaviour.

Herein, the role of software-defined re-orchestration in reformulating the functional behaviour of node 2 (originally a router function) to that of a 'leaf function' is depicted. This example, albeit simplistic, attempts to convey that such incremental re-orchestrations taking place at the individual node level are instrumental in altering the topological orientation and thereby the flow of data within the network. This also demonstrate the software defined approach in isolating the data from the control. Here, while the network offers the data path, the functions of the node are change through the software to alter the path. Multiple similar incremental actions may take place for a more complex network in re-orchestrating the topology of the overall network. The following section supported by figure 6 offers illustrations here.

Owing to the numerous flexible parameters available for software-reconfiguration within the different layers of the Contiki-stack, our IoT-WSN can possess a broad range of software functional modules that can be exploited to extract more complex network behaviour in catering for a wide range of service requirements.

## 4.2 Scenarios for Network Re-orchestration

Different sensing-based applications necessitate dynamic changes in software-defined node-function. This creates an avenue for re-orchestrating the current network topology. Irrespective of such topological variations, the three functions of 'leaf node', 'router node' and 'IoT gateway node' are indispensable with respect to execution of the mandatory tasks of 'sensing and data' acquisition, data routing and data transportation to the Cloud respectively. Figure 6 illustrates example topological variations of a stationary IoT-based sensor network that may be subjected to software-defined re-orchestration.




(a) (b) (c) (d)

Figure 6: Certain possible topological formations that an IoT-based sensor network can adapt to owing to software-defined re-orchestration: (a) Star Topology; (b) Tree Topology, (c) Mesh Topology and (d) Multi-hop Topology respectively.

For example, software-defined reformulation of Node 4 from leaf node to a router node could enable the network to re-orchestrate its topological orientation from a 'star'-based network depicted in figure 6a to a tree-based network shown in figure 6b. Through similar software-defined re-orchestration, mesh and multi-hop-based topological frameworks could be realised, as shown in figures 6c and 6d respectively.

To gauge the change in network performance derived through software-defined topological re-orchestration, consider the following experimental case. Initially, the 8-node network is assumed to operate under a multi-hop topological framework, as depicted in figure 6d. Figure 6a, on the other hand, depicts the same network re-orchestrated to operate within a star topological framework.

The sampling rate of data being sensed by the end devices is incremented (in steps of five samples per second from one sample per second to 20 samples per second) for both network topologies to observe the implications, as depicted in Table 1. The 'packets lost' parameter is used in this experiment for the performance evaluation purposes.

Table 1: The impact of increasing sampling rates on the packet loss incurred by a network of 8 nodes for different scenarios.

| Sampling rate PPS (i.e. 'Packets per second') | Packets lost PPS Multi-hop | Packets lost PPS Star-CSMA | Packets lost PPS Star-TDMA |
|---|---|---|---|
| 1 | 0 | 0 | 0 |
| 5 | 3 | 0 | 0 |
| 10 | 5 | 0 | 0 |
| 15 | 8 | 4 | 0 |
| 20 | 10 | 0 | 0 |

Upon re-orchestrating the same network to a star topological framework, it was observed that no packet losses are incurred when the network is operated on TDMA protocol (wherein each node transmits its data during its own particular/distinct time slot). When increasing the sampling rate to 20 PPS, the multiple-hop topology reflects gradual increase in packet loss. The star network under the CSMA protocol started losing 4 PPS at the 20 PPS rate. Meanwhile, the star network under the TDMA protocol persist on passing all the packets without loss.

Thus, it could be inferred that whilst operating in service conditions demanding higher sampling rates, star-based topological frameworks fare better than multi-hop networks in terms of mitigating the overall packet losses incurred by the system. Also, by introducing the functional changes using software defined network function approach, 'multi-hop'-based topological networks could resort to star-based topological framework via software-defined re-orchestration to restrict the number of packets lost.

This example signifies the importance of embedding network behavioural knowledge within the virtual network in catering for foreseeing performance analyses prior to actual re-orchestration execution at the OT layer.

## 5 NETWORK DOWNTIME DURING RE-ORCHESTRATION

Implementation of the outcome onto the real-life physical network may temporarily entail partial or complete service disruption. However, it is viable to ascertain this through experimentation. The entire duration of the network service disruption i.e. from the first instance of breakdown of service up until the complete resumption of the normal dataflow and service post-reorchestration, is referred to as 'network downtime'. It is necessary to investigate this issue through an example scenario so as to determine the extent upon which a given software-defined reorchestration processes affect network 'uptime'.

We deem it viable to split the re-orchestration process across three phases viz., 'Data analysis and event identification phase', 'Re-Orchestration Planning phase' and lastly 'Re-Orchestration Execution phase'. These are briefly touched upon in the following paragraph but are discussed in detail in the subsequent parts of the paper.

Dynamic monitoring of network data at the cloud-level with the help of virtualization may help in revealing any important event that could potentially disrupt network operation (either partially or in complete). For example, events such as a mobile router node moves away from the connectivity chain or reaching low battery energy level may indicate that it needs to be replaced with another router node in order to sustain the flow of data for the dependent chain of nodes. Such events are continuously monitored during the on-going 'Data Analysis and Event Identification' phase by means of a knowledge component present within the 'Data and Knowledge Repository' hosted by the cloud. Upon detection or identification of any such event necessitating network re-orchestration, an alarm is triggered within this phase to initiate the next phase i.e. 'Re-orchestration Planning Phase'.

The 'Re-orchestration Planning Phase' firstly involves proactive accumulation of the essential pieces of information from the OT layer (that also influences virtual network) as required for triggering of the re-orchestration process. Based on analysis of these collected data, replacement router selection process takes place. Successful identification of replacement router set the stage for the physical re-orchestration of the physical network at the OT layer.

Progression of any re-orchestration process in this sequence ensures confinement of any downtime experienced by the network to the last i.e. 'Re-orchestration Execution Phase' alone.

With respect to the considerations stated above, consider the following example of a cloud-monitored network that is required to undergo re-orchestration. Herein, a physical network that requires election of a suitable cluster-head for a group of leaf nodes owing to a special condition causing the existing cluster-head or router to start moving out of reach of the gateway. The virtual network for this scenario is depicted in figure 8 wherein, a mobile router node (i.e. node 5) which is due to depart, acts as a cluster-head for four mobile end devices i.e. nodes 1, 2, 3 and 4 and relays the sensed data so accumulated to a Gateway represented by node 6. The four connected devices are acting as leaf nodes. Some of these leaf nodes can assume router function. For the sake of simplicity, it is assumed that leaf nodes can only communicate with the gateway though a router even if they are within the communication range of each other. However, a virtualization environment, being unbounded by the physical communicational limitations of the real world in consideration could provision for such direct communication between the leaf nodes and the gateway (and vice versa), if required.

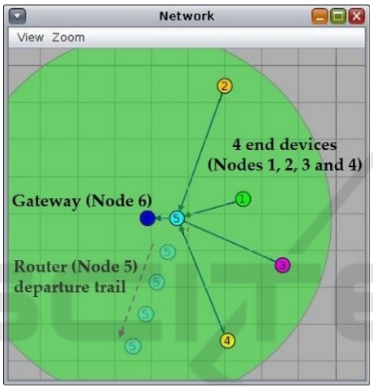



Figure 8: Simulation of network consisting of a (departing) mobile router and four end devices within Cooja.

As ‘part of the on-going monitoring activity (during the ‘Data Analysis and Event Identification’ phase) within the Cloud knowledge repository, a given knowledge component continuously monitors the radio signal strength (RSSI) between the router node 5 and the gateway node 6. By means of watching the history data of corresponding RSSI values between the router and the gateway. As it recognizes the pattern of the router departure, it raises a trigger to kick start the ’Re-orchestration Planning phase’ phase.

In the ‘Re-orchestration Planning phase’, another known knowledge component works on the identification of the potential nodes that could replace the current router. In this example, we have assumed that the three nodes (1, 2 & 3) can assume router function. Meanwhile, node 4 can only be a leaf function and hence will be eliminated from the competition for the router role (see figure 9). The appropriate selection of the replacement router among nodes 1, 2 and 4 follow the execution of a given fitness model. The model requires the measurement of three parameters. These are strength of the elected node to reach all the relevant leaf nodes using the RSSI reading, strength of the elected node to connect to the gateway using the RSSI readings and the elected node backup battery energy level.

Equal weightage has been assumed for each of these three parameters for this example. This, however, could change on a case-by-case basis or through long term learning process. As alluded to earlier, a software knowledge component takes the responsibility of computing and comparing the ‘normalized’ weight values for each of the participant end devices and identify the replacement router. The mathematical expression pertaining to the fitness model i.e. normalized weight i.e. ‘$W_N$’ (for each participant end device) is as follows:

$$W_N = [m_i \times RSSI_{AVG\_EDs}] + [m_{i+1} \times RSSI_{ED\text{-}G}] + [m_{i+2} \times B_{ED}],$$

where,

$m_i$, $m_{i+1}$, $m_{i+2}$ represent the weights associated with each of these three factors,

‘$RSSI_{AVG\_EDs}$’ represent the average radio signal strength of a participant end device with respect to all the other relevant end devices within the cluster,

‘$RSSI_{ED\text{-}G}$’ represent the radio signal strength of a participant end device with respect to the Gateway and

‘$B_{ED}$’ pertains to existing battery level of a participant end device.

The participant end device with superior fitness value will be elected as the replacement router. This in turn facilitates the decision for actual physical re-orchestration. The ‘execution’ phase involves several sequential transactions of message exchange amongst the nodes to attain their ‘re-orchestrated’ status within the final state of the network.

Figure 9 below provides an abstracted representation of the requisite communication messages exchanged amongst the constituent nodes across the three phases, for the execution of the necessary election process.

Herein, during the on-going ‘Data Analysis and Event Identification’ phase, the Gateway node 6 regularly transmits message ‘$M_{G\text{-}R}$’ to the router node 5 to determine its RSSI value with respect to it (at a set transmission rate). The router node, in turn, responds with the message ‘$M_{R\text{-}G}$’ to the Gateway node, along with its battery level value. This data is sent to the cloud for storing the trend. It will also be monitored at the cloud by the relevant knowledge component associated with the ‘Re-orchestration Planning’ phase.

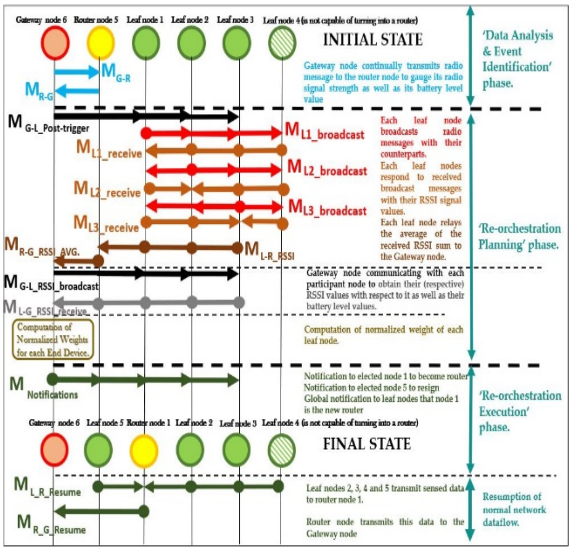



Figure 9: Abstracted representation of the exchange of communication messages across the three different phases to elect a suitable clusterhead from the constituent end devices to replace the departing clusterhead.

During the 'Re-orchestration Planning' phase, the gateway node (being capable of directly communicating with the all the leaf nodes,) broadcasts message '$M_{G\text{-}L\_Post\text{-}trigger}$' to the leaf nodes capable of turning into routers (nodes 1, 2 and 4 in this case) directing them to transform to the role of a router. These 'leaf-turned router' nodes i.e. node 1, 2 and 3 then broadcast radio messages '$M_{L1\_Broadcast}$', '$M_{L2\_Broadcast}$' and '$M_{L3\_Broadcast}$' respectively to the other leaf nodes (i.e. all the three participant leaf nodes as well as the lone, non-participant, router-incapable leaf node 4) to obtain their RSSI values with respect to each other. Upon reception of these broadcast messages, the other listening leaf nodes respond with their respective RSSI signal values, denoted by messages '$M_{L1\_receive}$', '$M_{L2\_receive}$' and '$M_{L3\_receive}$'. Through message '$M_{L\_R\_RSSI}$', each participant leaf node relays the average of the received RSSI signal values over to the router node, which in turn relays the combined information over to the Gateway node as denoted by message '$M_{R\_G\_RSSI\_AVG}$'. The Gateway node then transmits radio messages '$M_{G\_L\_RSSI\_broadcast}$' to leaf nodes 1, 2 and 3, in order to determine their radio signal strength with itself as well as acquire their battery level values. The leaf nodes respond with message '$M_{L\_G\_RSSI\_receive}$' to the gateway node.

Upon reception of the requisite parameters from all the participant nodes, the Cloud based dedicated knowledge component executes the 'planning' process wherein the normalized weight values for each of the constituent participant end devices are computed and compared. The participant end device with the most superior normalized weight will be notified of its new role as a cluster head for the remaining end devices. Figure 11 depicts the mote output screenshot pertaining to the election outcome processed at the IT-layer.

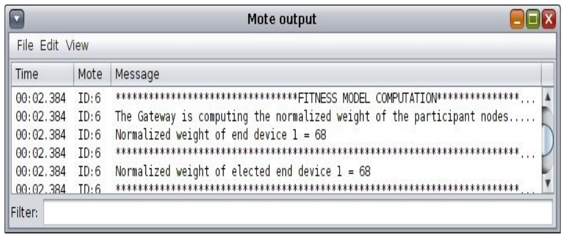



Figure 10: Screenshot of the mote output window within Cooja depicting messages pertaining to the election outcome.

This is followed by the final stage of the re-orchestration process i.e. the 'Re-orchestration Execution phase'. This proceed with implementing the above outcomes derived through the 'planning process' onto the actual physical or 'OT' layer components. Herein, a number of requisite sequential messages, represented by '$M_{Notifications}$' get executed involving the Gateway notifying the elected node of its new role as a 'router node', then notifying the departing router to resign its 'router' role and switch over to the role a 'leaf' node, then notifying all the leaf nodes about the new router i.e. node 1 and finally the resumption of the dataflow within the network i.e. gathering of all the end devices' sensed data by the newly elected router (denoted by message '$M_{L\_R\_Resume}$', upon traversal up to the approximate position of the previously existing router within the range of the gateway) and relaying it over to the Gateway node, denoted by message '$M_{R\_G\_Resume}$'.

Figure 11 depicts the instant at which the successful candidate (i.e. leaf node with node ID 1) switches over to the role of a router and commences the act of accumulating data from its leaf nodes.

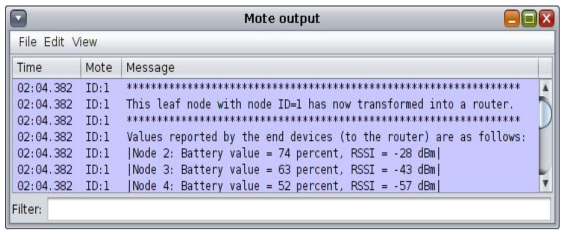



Figure 11: Screenshot of the mote output window within Cooja depicting messages pertaining to the election outcome.

As alluded to earlier, the ‘end-to-end’ downtime is calculated from the instant of time at which normal service delivery is interrupted up to the instant of time at which its normal network dataflow is restored. In our work, the network downtime incurred takes place from the instant router node 5 has been notified to become a leaf node until resumption of data flow of all leaf nodes through node 1 (as a replacement clusterhead). The instant of time wherein the normal dataflow service within the network is completely restored. Upon figuring out the number of messages getting executed within this phase from the above account, it is found that the network experiences a downtime of the order of ‘six’ communication messages for this particular case of network re-orchestration. Results such as above are only relative. Since the bulk of the re-orchestration process takes place within the virtual environment and that the motive of this exercise was to merely gauge the relative downtime incurred as a result of the network re-orchestration process, the Contiki simulator has been relied upon and employed entirely to draw tentative evaluation results. It is duly realized actual downtime incurred can only be determined through physical experimentation and forms part of the future work. At this stage, virtualization is based on real life data. Further reflection to more involved test will be consider in future work. Also, in order to obtain a more accurate network downtime value, practicalities associated with real-world communication process viz., the exact protocol being employed, persisting conditions of communication, etc. need to be factored in. This example reflects the viability of the virtualization platform (operating in conjunction with the knowledge software components within the IT-layer) in working out a suitable re-orchestration’s scenario during the first two phases before decision for re-orchestration execution phase takes place. However, although the bulk of the computation could take place at the cloud, the knowledge software components (responsible for the desired computations) could also reside at the ‘edge devices’ viz., Gateway, router nodes, etc. Herein, it is worthwhile to state that this research work solely focusses on the extent of downtime incurred as result of the network re-orchestration process whereas the future work will revolve around analysis of impact of the network parameters such as sampling rate, protocol employed, number of nodes, number of hops, topology, etc. on the re-orchestration latency. However, the aspect of data loss too (as a result of the network re-orchestration process) is an interesting research proposition that could be pursues as part of the future work.

# 6 CONCLUSIONS

This research work attempts at addressing the aspect of software-defined functional and topological re-orchestration of sensor networks through modularization and virtualization of the WSN functions within an architectural organisation based on the Industry 4.0-based ideology. Downtime suffered by the network as a result of the re-orchestration largely depends on the structural arrangement i.e. topological orientation, density of nodes, number of hops, number of messages to be exchanged amongst the various constituent nodes (as per the re-orchestration strategy obtained from the ‘Re-orchestration Planning’ phase), etc. While majority of WSN systems have the ability for absorbing this down-time without any significant impact, high dynamic applications involving mobile sensor nodes could be quite critical towards such down-time. Further work will involve determination of the actual downtime incurred during the ‘Re-orchestration phase’ using the real-life hardware nodes. Furthermore, analysis of impact of the network parameters such as sampling rate, protocol employed, number of nodes, number of hops, topology, etc. on the re-orchestration latency will also be pursued.

The paper has emphasized upon the significant role of WSN virtualization and software repository of knowledge components in offering the necessary environment for monitoring, and if necessary, re-orchestrating the dynamics of the physical network. This introduction should stimulate the research in this novel and important area of WSN.

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