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RESEARCH ARTICLE

RDEC: Routing Decisions Through Energy-Cost Estimation for IIoT and IWSNs in SDN-Managed Industry 4.0

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ABSTRACT The fourth industrial revolution has brought about automation and a shift from wireless sensor networks (WSN) to the industrial Internet of Things (IIoT), resulting in data-oriented decision-making. However, processing large amounts of data and relying on batteries can lead to communication failure, process disruptions, and even catastrophic disasters. To address this, energy-aware smart communication protocols are critical that prolong the lifespan of devices. This paper proposes a novel energy-cost-based routing protocol called RDEC: routing decisions through energy-cost estimation, which utilizes software-defined networks (SDNs) to centralize routing path decision-making. The RDEC algorithm considers the energy required to transmit data and the average battery consumption of intermediate nodes, resulting in a significant reduction in battery consumption by up to six times compared to existing solutions. Furthermore, the proposed approach reduces transmission time by over 50% and doubles the throughput over previous routing methods. Overall, the proposed RDEC algorithm increases the communication lifespan of battery-constrained devices while ensuring connectivity. In summary, the proposed RDEC algorithm provides an effective solution to address the challenges of energy consumption and communication failures in small battery-dependent devices, making it a significant contribution to the field of Industry 4.0.

INDEX TERMS Energy efficiency, industry 4.0; Industrial Internet of Things (IIoT), industrial wireless sensor networks (IWSNs), software-defined networks (SDNs).

I. INTRODUCTION

With the digitalization of manufacturing industry, the fourth generation of industry (i.e Industry 4.0) has already reduced the operational cost and it has potential to impart drastic improvement to the current production time [1]. However, smooth and effective Industry 4.0 cannot exist without integration of information and communication technologies, where there is a paradigm shift of human-to-machine interaction to machine-to-machine communications (M2M) [2]. Along with the advantage of context awareness in these devices, a huge amount of data needs to be communicated and processed in the paradigms of M2M and industrial Internet of Things (IIoT) [3], [4]. It is predicted that by the end of 2024, the number of connected devices will reach 27 billion, leading to even more data [5]. The number of active IoT devices is expected to exceed 10 billion and reach 25.4 billion by 2030 [6]. It is crucial for cyber physical systems (CPS) such as Industry 4.0 to enable flawless and error-free communications and data transfer while relying on battery- and processing-constrained devices of M2M and IIoT [7], [8]. On the other hand, industrial wireless sensor networks (IWSN) offer several advantages, including flexibility, mobility, scalability, and low maintenance [9], [10]. The international market for IWSNs is expected to reach USD 8.67 billion by 2025 [11], [12]. Straits Research forecasts this market will likely escalate to a value of around USD 8.62 billion by the year 2030 [13]. All these technological advancements make Industry 4.0 a connected, informed and autonomous paradigm. Along with data processing, several

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communication decisions can also benefit from state-of-the-art networks such as cloud computing and software-defined networks (SDN) [14], [15], [16]. These devices communicate with each other or nearby servers using wireless technologies such as Zigbee, bluetooth, Wi-Fi, Long Range Wide Area (LoRa) and Low Power Wireless Personal Area Network (6LoWPAN) [15], [17]. However, it is crucial to enable a smart but effective communication and routing paradigm that enables faster transmissions with minimum overhead to the devices.

M2M, IIoT, and IWSNs differ in terms of communication hierarchy and connectivity, but they all involve small devices with relatively smaller batteries, making them prone to traffic delays and security risks [18]. In industrial networks, data can be categorized as either persistent or transient. Transient data, which requires frequent refreshing, is crucial in various applications [19]. In the context of IWSNs, sensor nodes capture data and transmit it hop by hop to reach the destination [20]. However, the mobility of IWSN nodes leads to inefficient energy consumption as they sense, transmit, and forward data, draining their batteries [21]. Node mobility introduces complexities as it alters the network topology, requiring frequent updating of data packet routes. This route discovery and maintenance process can increase energy consumption. Additionally, when a node moves farther from a destination or relay node, the energy required for data transmission increases due to the larger distance. Thus, node mobility can result in additional energy consumption. Consequently, managing energy consumption is a challenging problem in IWSN applications due to the nature of mobile nodes and their energy consumption during data exchange and mobility [22].

In recent years, SDNs have emerged as a successful solution to meet the requirements of intelligent manufacturing [23]. By separating the control plane from the data plane, SDNs enable well-defined programming interfaces between switches and controllers, providing programmability, flexibility, scalability, and efficient network management [8], [24]. In the context of Industry 4.0, technologies such as artificial intelligence, blockchain, and SDNs have proved to be well-suited for addressing the challenges posed by wireless networks such as IIoT and IWSNs [25], [26]. They enable the efficient management of energy consumption based on routing rules established by the controller [27]. Furthermore, recent research has shown that shifting the routing decision-making from network elements (routers and switches) to the SDN controller (networking logic) improves the quality of service (QoS) in IWSNs, including energy consumption issues [28]. Figure 1 presents a generalized SDN architecture within an industrial paradigm, where the application plane accommodates various visualization, control, and monitoring applications through an application programming interface (API). The controller acts as an intermediary between IWSN/IIoT devices and the APIs, employing multiple gateways and sink nodes [29]. Efficient data transfer requires the implementation of effective message routing and communication protocols [30], [31]. However, the existing literature falls short in this respect, which is the primary objective of our research: to develop an energy-efficient routing protocol for Industry 4.0 applications. In this paper, we propose an energy and cost-efficient message routing scheme called RDEC, where a centralized SDN controller calculates the enhanced communication path for IIoT/IWSN devices, resulting in longer device lifespans. Our approach considers not only the shortest path but also minimizes battery consumption by intermediate nodes.

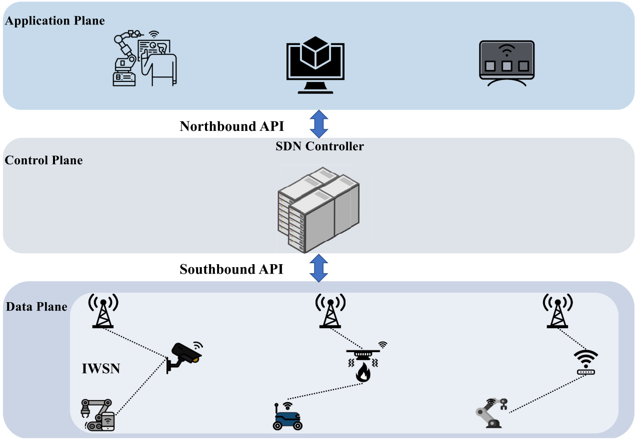


FIGURE 1. **Software-defined network-based industrial Internet of things architecture in Industry 4.0.**

The proposed routing algorithm (RDEC) offers several significant contributions to the fields of Industrial Internet of Things (IIoT), Industrial Wireless Sensor Networks (IWSNs), and Industry 4.0.

Primarily, RDEC dramatically increases energy efficiency. The algorithm achieves this by reducing energy consumption up to six times compared to existing solutions. This significant reduction in energy use extends the lifespan of battery-constrained devices, a common component in IIoT and IWSNs.

Additionally, RDEC improves network performance, effectively doubling the throughput, increasing efficiency and enhancing the productivity of IWSNs.

Finally, our research contributes substantially to the progression of Industry 4.0. By addressing the challenges related to energy consumption and communication failures in small battery-dependent devices, we can significantly improve the reliability and sustainability of industrial processes that heavily rely on these devices.

Traditional routing schemes and their modified improvements, such as the distance-vector routing (DVR) protocol [32] and the ad hoc on-demand distance vector (AODV) routing protocol, calculate local maxima, i.e., the shortest path. However, it is crucial to consider a composite metric that takes into account not only the best path but also the longevity of the device in terms of energy consumption [33]. Additionally, most existing solutions impose the computational burden on low-power IWSN/IIoT devices, aiming to keep protocols lightweight. In contrast, our proposed

RDEC solution outperforms existing schemes by offloading the decision-making process to the SDN controller, significantly reducing battery consumption. Moreover, centralized decision-making improves routing performance by leveraging comprehensive availability of information. The major contributions of this study are discussed below.

- Our contribution lies in the development of a novel and optimized routing path selection algorithm based on two key metrics: minimal distance-related energy and average battery consumption of intermediate nodes. The inclusion of these metrics enables energy savings for both the sender and the intermediate nodes during data forwarding. By considering the estimated battery level of intermediate nodes, we ensure that the selected routing path aligns with the nodes' requirements and promotes the desired energy efficiency of the network. This approach addresses energy consumption challenges in the network and improves overall performance.
- The path calculation and selection are centralized in the SDN controller, alleviating the complexity associated with estimating the enhanced path in individual nodes. This centralized approach not only reduces the computational burden on the nodes but also leads to significant energy savings for them.
- Our approach effectively prolongs the lifetime of intermediate nodes, thereby extending the overall communication lifetime of the network. In particular, our protocol prevents the exhaustion of intermediate nodes with low battery capacity, eliminating the need for battery replacement and ensuring the continuous operation of the network.

The organization of the research article is as follows. Section II provides an overview of relevant related works. In Section III, we introduce the proposed SDN-based RDEC protocol. The experimental setup used to evaluate the proposed approach is described in Section IV, followed by the network topologies in Section IV. Section V presents and discusses the results obtained in terms of data transmission, battery consumption, total energy consumption, and network throughput. Finally, Section VI concludes our work by presenting some final remarks.

II. RELATED WORKS

There has been extraordinary achievement separately in the field of Industry 4.0, SDNs and IWSNs. However, few research contributions have incorporated SDNs for the IWSN or vice versa. A detailed discussion of the related research articles focusing on energy consumption and efficiency, IWSNs and SDNs is given below.

Several studies have focused on enhancing energy efficiency in IWSNs. In [34], a hybrid whale optimization of algorithm-simulated annealing was used to determine the optimal cluster head, resulting in enhanced WSN energy consumption. Similarly, [35] proposed an enhanced three-layer hybrid clustering mechanism that restricted control packet exchanges and balanced energy consumption between sensor nodes, leading to an extended network lifetime and reduced unnecessary communication. The routing protocol presented in [36] constructed multiple paths based on important factors, enabling the selection of optimal paths by sender sensors, thereby improving overall QoS, extending node lifetime, and reducing energy consumption. In [37], a routing protocol combined clustering and sink mobile technology to divide sensor areas into multiple sectors, achieving optimal path selection based on energy consumption and outperforming traditional routing protocols. The authors in [38] proposed a method to extend the lifetime of a wireless sensor network by reducing energy consumption. This was achieved by introducing a technique called Proactive Reduction of Idle Listening (PRIL). This technique involves deactivating the receiver when no frames are expected to be received. Energy is typically wasted when the receiver is active and no one in the network is transmitting. By using this technique, energy consumption is reduced. Additionally, [39] proposed a three-step routing protocol that divided the zone into smaller sizes, selected terrain heads using fuzzy rules, and determined nodes based on the same rules, resulting in enhanced network lifetime and energy efficiency. The authors in [40] utilize machine learning to address the problem of energy consumption in Industrial Wireless Sensor Networks (IWSNs). They propose an enhanced energy optimization model (EEOM) that enables IWSNs to minimize energy usage by identifying the most efficient transmission paths through the nodes. As a result, their model contributes significantly to energy savings.

Furthermore, SDNs have been identified as a promising approach to take over data processing and decision making, thus reducing energy consumption, in Industry 4.0 applications. In [41], a blockchain-enabled architecture of an SDN controller was presented, providing a secure and energy-efficient file transmission between IoT devices within the SDN domain. The multicast routing protocol proposed in [42] leveraged SDNs and fog computing for vehicular networks, demonstrating energy efficiency through priority scheduling and classification. The hybrid machine-learning framework in [43] utilized supervised and reinforcement learning components to achieve traffic-aware energy efficiency in SDN applications. The authors in [44] introduced a two-phase SDN-based routing mechanism that minimized energy consumption while ensuring QoS, resulting in a significant reduction in energy consumption. Lastly, [45] proposed a novel system that incorporated clustering techniques and energy-efficient routing through SDN and virtualization, leading to load balancing, reduced message transmissions, and prolonged network lifetime.

Overall, the reviewed literature highlights various approaches and techniques that contribute to improving energy efficiency in IWSNs and Industry 4.0 applications, leveraging both traditional methodologies and the capabilities of SDNs. However, there is a substantial gap where SDNs are employed to improve the life-expectancy of the IWSN/IIoT devices in Industry 4.0. We are the first to design an efficient mechanism to reduce energy consumption in low-powered devices using SDN technologies.

III. SYSTEM MODEL

Let $G\ (N,\ \ E)$ be a connected graph representing N IWSN nodes with E communication edges, where an SDN controller is connected and pervasively informed. The transmission-distance energy E_{TD} depends on the Euclidean distance between nodes i and j, calculated by the SDN controller, where each node i's location is $x_i,\ \ y_i$. The estimated distance of two nodes, i and j, is:

$$D^{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, \tag{1}$$

subsequently, E_{TD} is calculated as follows [41]:

$$E_{TD}^{ij} = \frac{B \cdot (D^{ij})^2}{V}, \tag{2}$$

where B is the packet size, D is the distance calculated in Eq. (1), and V is the domination vector used to reduce the domination of the E_{TD} metric when calculating the cost.

On the other hand, the battery level of each node is estimated as follows:

$$\begin{aligned} \mathit{Battery\ Level}^i &= \mathit{Remaining\ Battery\ Capacity}^i \\ &\quad - \mathit{Energy\ Consumption}^i, \end{aligned} \tag{3}$$

where *Remaining Battery Capacity* is the battery level of the nodes at the beginning of the communication (all sensors are assumed to be fully charged at the beginning), and *Energy Consumption* is the energy consumed while receiving and transmitting data during the communication time, calculated as follows:

$$\mathit{Energy\ Consumption} = E_{tx} + E_{rx}, \tag{4}$$

where E_{tx} is the transmission energy required for the sensor to transmit packets to the destination, while E_{rx} is the receiving energy required by the sensor to receive the packets. E_{tx} and E_{rx} are estimated as follows [46]:

$$\begin{aligned} E_{tx} &= (t_{rt} + \frac{\mathit{Data\ Length}}{\mathit{Data\ Rate}}) \cdot \mathit{Power}_{tx}, \\ E_{rx} &= (t_{rt} + \frac{\mathit{Data\ Length}}{\mathit{Data\ Rate}}) \cdot \mathit{Power}_{rx}, \end{aligned} \tag{5}$$

where t_{rt} denotes the transmission and receiving start-up time, which refers to the duration required for a node to become prepared for either transmitting or receiving packets. *Data Length* is the number of packets in the channel, Power_{tx} and Power_{rx} are the transmission and receiving power measured at the sensors' active mode, and tx and rx are the transmission and receiving status of the nodes, respectively.

TABLE 1. Symbol table.

Symbol	Description
G	Connected graph representing IWSN nodes
i, j	Node indices
x_i, y_i	Location coordinates of node i
D^{ij}	Estimated distance between nodes i and j
E_{TD}	Transmission-distance energy
B	Packet size
V	Domination vector
$\mathit{Battery\ Level}^i$	Battery level of node i
Remaining Battery Capacity^i	Initial battery level of node i
Energy Consumption^i	Energy consumed by node i
E_{tx}, E_{rx}	Transmission and receiving energy
t_{rt}	Transmission and receiving start-up time
Data Length	Number of bytes in the channel
Data Rate	Data transmission rate
$\mathit{Power}_{tx}, \mathit{Power}_{rx}$	Transmission and receiving power
tx, rx	Transmission and receiving status
C	Battery consumption (%)
Total Battery Capacity	Initial battery level of node's lifetime
ACBL	Average consumed battery of intermediate nodes
n	Number of nodes on the same route path
V_2	Domination reduction vector

Based on the battery level estimation for each node, the percentage of battery consumption of each intermediate node is calculated:

$$C = \frac{(\mathit{Total\ Battery\ Capacity} - \mathit{Battery\ Level})}{\mathit{Total\ Battery\ Capacity}} \times 100, \tag{6}$$

where C is the battery consumption $\in$ [0, 100%], and *Total Battery Capacity* is the battery level at the beginning of the node's lifetime. Then, the average consumed battery of intermediate nodes *ACBL* for each route is estimated as follows:

$$\mathit{ACBL} = \frac{1}{n}\sum_{k=1}^{n} C, \tag{7}$$

where n is the number of nodes located on the same route path. To reduce the domination of *ACBL*, we divide it by the domination reduction vector V_2. The vector V_2 is strategically employed to attenuate the influence of a single element, with the aim of diminishing its dominion over the decision-making process.

IV. THE PROPOSED RDEC PROTOCOL

Energy efficiency plays a critical role in the successful execution, monitoring, and improvement of activities in Industry 4.0. The interconnected devices of IWSNs/IIoTs, with their longer lifespans, facilitate communication across various applications, ranging from small temperature-monitoring devices to large car-assembly systems. Effective message communication and routing are essential for these battery-powered devices, as they not only impact the communicating devices themselves but also have implications for intermediate devices involved in relaying and routing tasks.

In an SDN-based system, communication between nodes and the SDN controller occurs via the control plane. Nodes send status updates, such as battery levels and location coordinates, to the controller. The controller uses this data to calculate transmission-distance energy and average battery consumption for each communication route. The controller also sends routing instructions to nodes, aiming for energy efficiency and load balancing. Although control messages contribute to the overall energy consumption, their impact is relatively minor, accounting for approximately 5% of the energy expended for transmitting data packets. This is

Algorithm 1 The Proposed RDEC Protocol for SDN-Managed Industry 4.0

```
Functions:
Topology Discovery (G): Build the network topology, i.e., $G(N, E)$.
Diverse Routes($src$,$dst$,$G$): For each transmission between $src$ and $dst$ in $G(N, E)$ find all possible paths.
Energy Estimation($paths$,$Batterylevel$): Calculates $E_{TD}$ and $ACBL$ for each path.
Routing Decision Maker($pathsACBP$,$E_{TD}$): The enhanced
  path selection $EN\_Path$.
Input:
G
$src \leftarrow$ Source
$dst \leftarrow$ Destination
$Battery\_Level \leftarrow$ Current battery level of each node.
$ACBP \leftarrow$ Average consumed battery level on nodes located in the same path.
$E_{TD} \leftarrow$ Transmission-distance energies
$C \leftarrow$ [Consumed battery]
Output:
$EN\_Path$
begin
    while $True$ do
        Topology Discovery(G)
        Diverse Routes($src$,$dst$,G)
        $paths$
        for $paths$ in $Paths$ do
            Energy Estimation($paths$,$Batterylevel$)
            D$\leftarrow$ Distance estimation between nodes.
            $E_{TD}$=$packet\ size * D^2$
        end
        for $Nodes$ in $Paths$ do
            $BatteryLevel$ = Battery Capacity - Energy
              Consumption
            $C$ =(Total Battery Capacity - Battery
              Level)/Total Battery Capacity*100
        end
        $ACBP$=Average($C$)
        return $E_{TD}$,$ACBP$
        Routing Decision Maker($paths$,$ACBP$,$E_{TD}$)
        for $paths$ in $Paths$ do
            for $ACBP$ in $Paths$ do
                for $E_{TD}$ in $Paths$ do
                    Path_Cost=[$ACBP$+$E_{TD}$]
                    return $Cost$
                end
            end
        end
        $EN\_Path$=Min(Cost[])
        return $EN\_Path$
    end
end
```

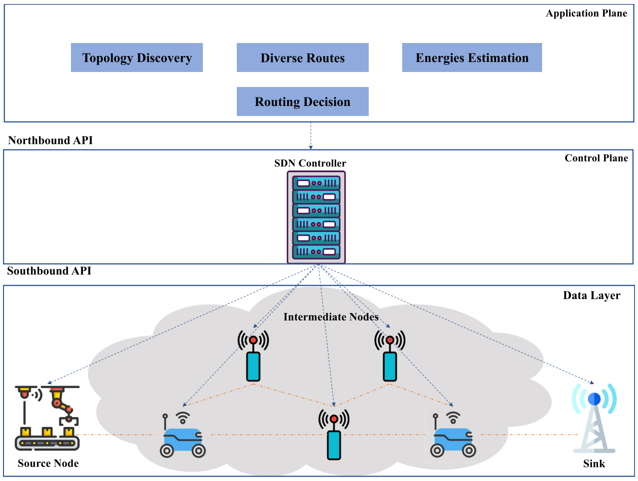
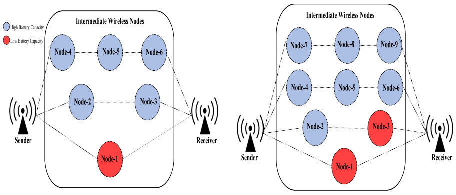


FIGURE 2. Architecture of the proposed software-defined network-based energy-cost-based routing protocol.

attributable to the smaller size of the control messages and their lower transmission frequency compared to data packets.

Existing wireless routing schemes, such as AODV, DSR, DVR, etc., often prioritize either the shortest path or the distance between the source and destination. However, the shortest path-first approach can result in repetitive utilization of the same nodes, leading to faster battery drain for those nodes while other devices remain underutilized. In contrast to previous solutions, our proposed scheme, RDEC, addresses these issues by selecting an enhanced route based on two key parameters: transmission-distance energy (E_{TD}) and average consumed battery ($ACBL$). Additionally, we leverage the capabilities of an SDN controller to make routing decisions, benefiting from centralized authority, abundant data, and enhanced processing power. Figure 2 illustrates the proposed SDN-managed Industry 4.0 architecture for our RDEC protocol, consisting of three virtual planes: the data layer, the control plane, and the application plane. In the data layer all nodes exist, such as IWSN sensors, network nodes, and the base stations (sinks). All these battery-constrained nodes are assumed to have sensory and communications modules that enable data acquisition and delivery. Moreover, a node can act as the source or destination, as well as an intermediate relay. A generic communication flow is generated by a node and communicated to either another device or a sink node. The control plane performs various actions, including node discovery, network topology, cost estimation for each communication flow, enhanced path decision making and network monitoring. On the other hand, the application plane contains the complete logic of the controller, including the four necessary routing actions: 1) topology discovery, 2) diverse route identification, 3) energy estimation, and 4) routing decision-making.

Algorithm 1 outlines the complete process of the proposed RDEC scheme. Initially, an SDN controller estimates the network topology by collecting nodes and network information to generate the graph $G(N, E)$. Each node in the graph has certain associated information, i.e., identification, location coordinates, and remaining battery levels. Along with obvious node data, the transmission-distance energy required to transmit data between nodes is calculated for each node using their location information from Equation 5. The proposed RDEC utilizes node information for better



(a) Topology A (b) Topology B

FIGURE 3. Sample topology and communication network.

path selection for data delivery, which reduces the overall energy consumption and to increase the network lifetime. For every possible communications path between any source and a destination, the controller assigns a cost metric and calculates the enhanced path that fulfils our objectives.

The application plane consists of four steps to determine the enhanced path for energy conservation.

Step 1: Network Identification. The SDN controller identifies the network components and topology at the beginning of communication, providing the number of nodes N, the number of edges (interfaces) between them E, and the graph $G = (N, E)$.

Step 2: Path Calculation. Using the output graph G from the previous step, along with the source and destination addresses, the SDN controller calculates the available routing paths between the source and destination nodes. This step provides the available paths, the number of nodes and edges in each path, and the positions of the nodes.

Step 3: Energy Estimation. The SDN controller estimates the energy consumption for each of the possible paths identified in the previous step. This estimation is based on node positions, path lengths, and battery levels of each node. The controller performs a series of calculations, including the calculation of the transmission-distance energy E_{TD} required to transmit data between nodes.

Step 4: Cost Computation. In the final step of the application plane, the routing decision-maker computes the cost for each path based on the identified routing paths from step 2, along with their corresponding transmission-distance energy E_{TD} and the average consumed battery level $(ACBL)$ of intermediate nodes calculated in step 3. The cost computation aims to minimize energy consumption during data transmission. By selecting the path with the lowest cost, intermediate nodes can maintain an acceptable battery level while successfully forwarding data to the sink node or any other destination.

Overall, the proposed scheme provides a novel RDEC scheme to substantially increase network life in SDN-managed Industry 4.0 and outperforms all existing solutions that overburden the nodes.

V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed RDEC scheme, we conducted exhaustive experiments and performed a comparative analysis. Figure 3 illustrates sample topologies that demonstrate the route selection between a random source and destination. In both samples, intermediate nodes are utilized to establish communication between two random devices. The color coding in the figure represents the available energy in each node. Nodes shown in red indicate low power, while nodes in blue have ample energy. The edges in the figure depict the communication paths between the source and the destination. Upon a quick examination, it becomes apparent that in both sample scenarios, the shortest path would exhaust the devices that are already operating at their lowest power levels, i.e., Node 1 and Node 3.

TABLE 2. Experiment emulation parameters.

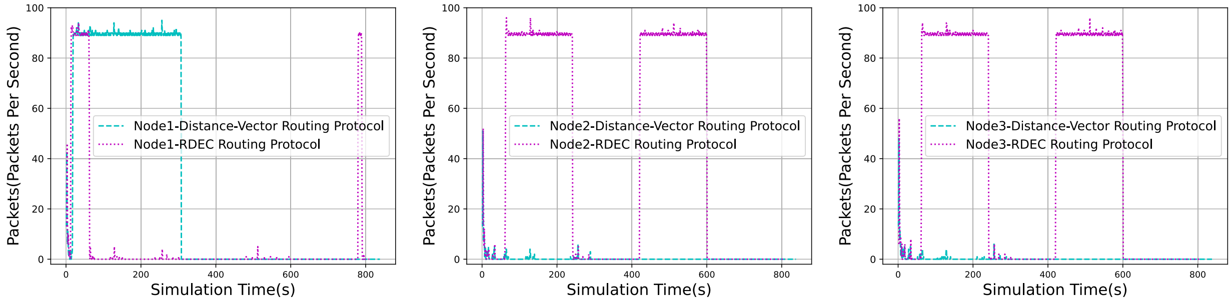
Parameters	Values
Emulator	Mininet-Wifi
Graphical simulator	NetworkX
Nodes	Equipped with communication module, network layer identification module battery (at maximum level), and application stack
Operating system	Ubuntu 20.04
Memory	9.8 GiB of RAM
CPU	i7 2.80 GHz
Data generator	*iperf* UDP application
Bandwidth	5∼10 Mbps
SDN controller	Ryu controller

The simulation of the proposed scheme and existing solutions is designed in three folds. First, a discrete-event network tool constructs the environment, including nodes and communication edges, using the NetworkX tool [47], which provides a framework for industrial network design. Every node in the network is equipped with a communication module, an identification module of the network layer, a battery at maximum level and an application stack. Each communication edge is assigned a weight, which is used later in the path selection mechanism. Secondly, the SDN controller and respective virtual nodes are imported using the open-source Mininet-Wifi tool [48]. This setup emulates SDN connectivity in the environment and establishes the communication edges between nodes. Finally, the iperf UDP application enables the transmission and reception of data packets between two randomly selected nodes.

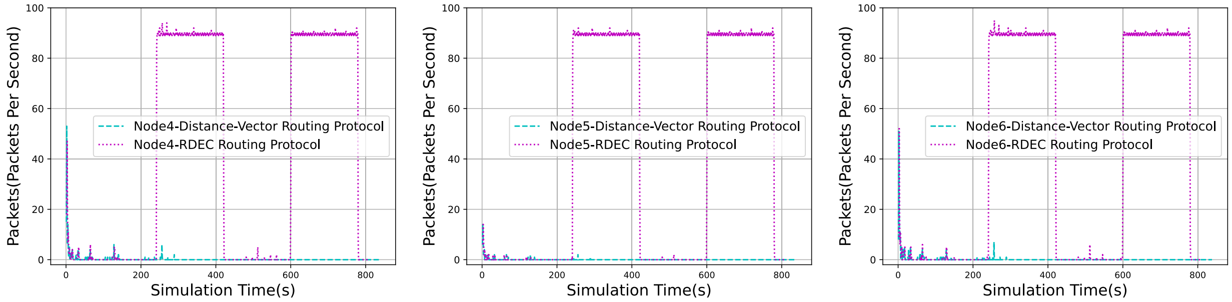
The iperf UDP application, a network testing tool, is utilized to ascertain the maximum achievable bandwidth on IP networks. This research makes use of iperf UDP to generate traffic between nodes in a simulated Industrial Internet of Things (IIoT) environment.

The SDN controller utilized in Ryu Controller is an open-source framework written in Python, which provides a platform for network applications. The communication between the Ryu Controller and the switch is facilitated through the use of the UDP transport protocol.

Each UDP data packet is generated by a sender towards a destination within the network using random distribution. Whether a node generates the packet as a sender or relays the data forward as an intermediate node, a certain amount of energy is consumed for each action. The performance of each protocol is evaluated by capturing the packets and measuring the packets received at the receiver's end. The bandwidth for each communication link is set to 5-10 Mbps.



(a) Packet flow in Node 1 (b) Packet flow in Node 2 (c) Packet flow in Node 3



(d) Packet flow in Node 4 (e) Packet flow in Node 5 (f) Packet flow in Node 6

FIGURE 4. **Packet flow in intermediate nodes.**

The complete network simulation is implemented on the Ubuntu 20.04 operating system, running on an i7 2.80 GHz CPU with 9.8 GB of RAM. Table 2 outlines the simulation parameters.

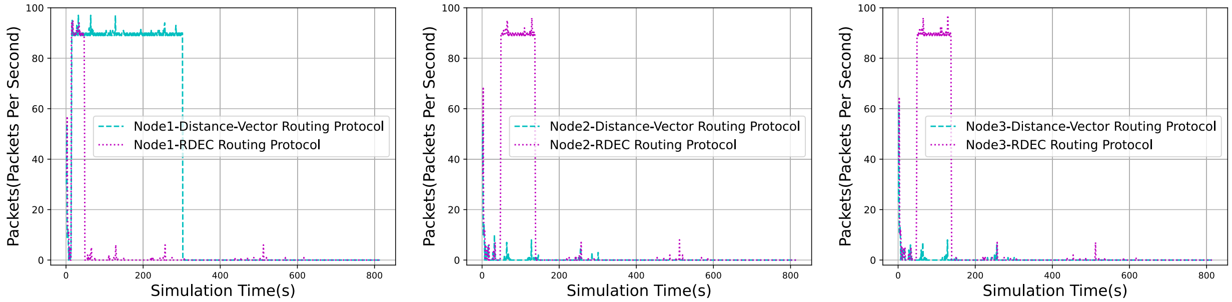
In addition to the aforementioned configurations, each node is equipped with both the proposed RDEC routing scheme and an existing DVR routing method module [32]. The inclusion of the RDEC scheme enables enhanced decision-making by considering multiple metrics that directly impact battery consumption, total energy consumption, and network throughput. For every packet transmitted between the source and destination, the SDN controller in the RDEC scheme estimates the battery usage and transmission distance energy for each possible path. This estimation takes into account the continuous nature of communication, allowing the selection of a different transmission path whenever a better alternative becomes available. It is important to note that the proposed RDEC scheme does not excessively drain any particular path. Instead, it implements a uniform load balancing strategy throughout the network, effectively distributing the communication load. This load balancing approach significantly increases the overall network lifetime, ensuring a more sustainable and efficient operation.

A. RESULTS AND OBSERVATIONS

The simulation utilized the iperf UDP application to generate a substantial number of packets from a source to a destination. Each transmission created a packet flow that followed a multi-hop routed path, with the routing protocol selecting intermediate nodes. The packet flow at each intermediate node provided insight into node utilization and subsequent battery consumption. In this simulation, the discharge lifetime was accelerated to easily observe the behavior of the network nodes and study the performance of the RDEC algorithm. The proposed RDEC routing protocol, enabled by SDN in the context of Industry 4.0, optimally selected intermediate nodes for routing based on energy consumption and battery considerations, leading to an extended network lifetime.

Figures 4 and 5 illustrate a comparative analysis of the packet flow metric, highlighting the traversal of several intermediate nodes. These figures focus only on the nodes depicted in the sample network shown in Figure 3. It was observed that the existing DVR protocol repeatedly selected Node-1 for message routing, directly impacting the exhaustion of its battery. Conversely, nodes such as Node-2 and Node-3, which were part of slightly longer routes, were underutilized. This over-utilization of Node-1 and under-utilization of other nodes can be readily identified by examining the packet flow in Figures 4a to 4f. In particular, Figure 4a clearly shows the excessive packet flow through Node-1, leading to the complete drainage of its battery at simulation time 304 seconds, when the packet reception ends.

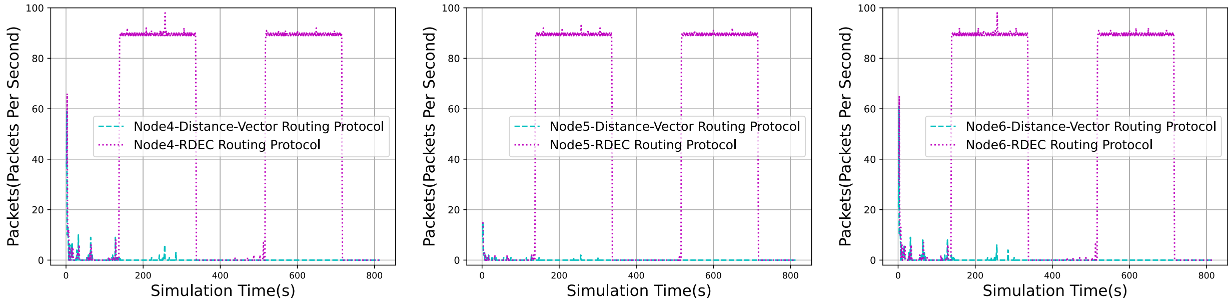
In contrast, the proposed RDEC protocol employed the SDN controller's decision-making process, which took into account battery consumption and transmission-distance energy. Initially, Node-1 was selected as the next hop for message routing. However, after assessing the battery levels of all the nodes in the network, the SDN controller chose a better route. The packet flow shown in Figure 4a demonstrates that the proposed RDEC protocol shifted to a superior route, resulting in reduced utilization of Node-1 at



(a) Packet flow in Node 1

(b) Packet flow in Node 2

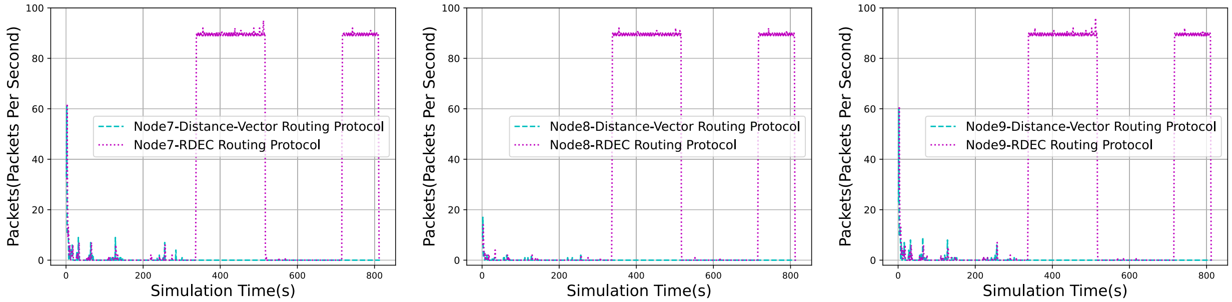
(c) Packet flow in Node 3



(d) Packet flow in Node 4

(e) Packet flow in Node 5

(f) Packet flow in Node 6



(g) Packet flow in Node 7

(h) Packet flow in Node 8

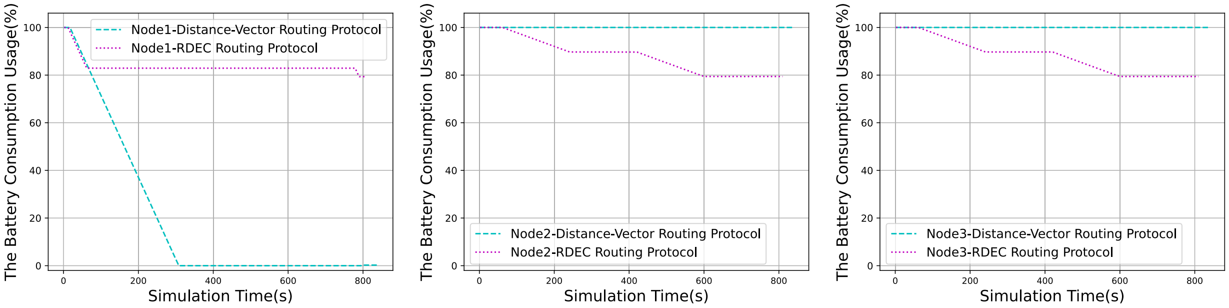
(i) Packet flow in Node 9

FIGURE 5. **Packet flow in intermediate nodes.**

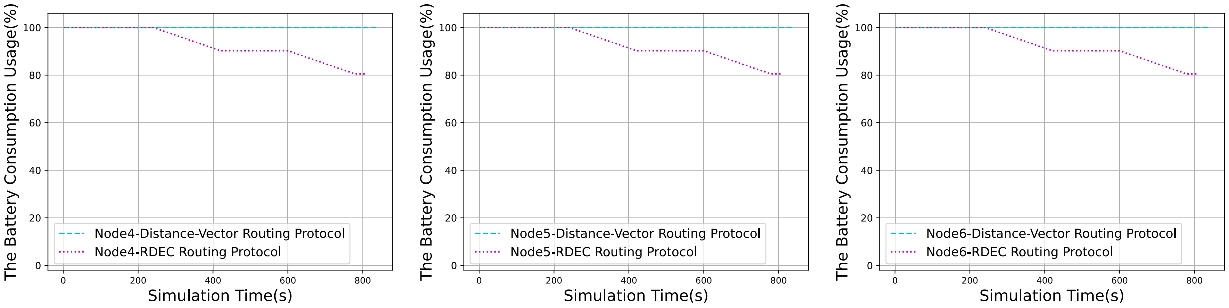
a simulation time of 60 seconds. Throughout the network simulation, the SDN controller continuously monitored the battery levels and transmission-distance energy of the nodes. Figures 4b and 4c show that the SDN controller in the proposed RDEC protocol changed the transmission route from Node-2 to Node-3 at simulation time 240. Similar behaviors can be observed in Figures 4d to 4f, indicating the adaptive nature of the proposed RDEC protocol in selecting the most efficient transmission routes based on real-time network conditions.

A denser sample network topology further confirms the observed behavior, as depicted in Figure 5. The DVR protocol prioritizes the shortest path and selects Node-1 and Node-3, both of which have low battery levels. Additionally, existing schemes tend to persistently favor similar routes based on positional or geographical factors, resulting in the complete drainage of the batteries of several intermediate nodes. In contrast, the proposed RDEC protocol surpasses existing schemes by considering realistic and essential metrics for decision-making. In the proposed scheme, the SDN controller initially selects Node-1 as the next hop, but quickly recognizes the energy constraints and switches to better alternatives through Node-3. Moreover, throughout the entire simulation duration, the SDN controller dynamically switches the routing path, transitioning from Node-4, 5, and 6 to eventually reach Node-7, 8, and 9. The packet flow observed at each node in Figure 5 vividly illustrates the node utilization, thereby substantiating our claim of a dynamic, efficient, and enhanced RDEC routing scheme.

The utilization of intermediate nodes for transmission, as determined by the routing decision, is reflected in the packet flow metric. However, the existing DVR protocol leads to the exhaustion of Node-1, resulting in a complete operational halt for the node. This phenomenon is evident when examining the battery levels of each node throughout



(a) Battery consumption of Node 1
(b) Battery consumption of Node 2
(c) Battery consumption of Node 3



(d) Battery consumption of Node 4
(e) Battery consumption of Node 5
(f) Battery consumption of Node 6

FIGURE 6. **Battery consumption of intermediate nodes.**

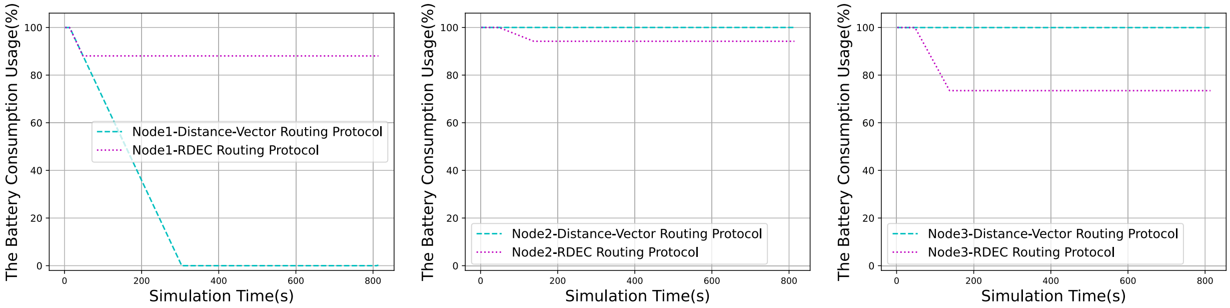
the simulation. Figures 6 and 7 depict the battery levels of each node in both sample networks, providing insights into the node utilization under each routing protocol. In our network simulation, implemented using NetworkX and Mininet-Wifi, each node consumes energy while generating network traffic and relaying data. To facilitate a comparative analysis between the proposed RDEC and existing DVR protocols, monitoring the battery levels of each intermediate node over time offers valuable insights into the routing impact. Figure 6a clearly indicates the point (at 304 seconds) when the DVR routing exhausts Node-1. The failure of an intermediate node in the selected message route not only disrupts the current transmission but also introduces data loss and additional delays. However, the remaining nodes in the network remain operational due to the under-utilization caused by the DVR routing, as depicted in Figure 6.

In contrast, the proposed RDEC protocol dynamically switches the selected route of Node-1 based on its battery level. At 60 seconds into the simulation, the protocol detects the battery drop and quickly selects an alternative route without losing any data. The SDN controller calculates the relevant metrics (E_{TD} and $ACBL$) for the available alternatives and initiates transmission accordingly. The battery levels of the nodes clearly illustrate this behavior, with Node-1 initially chosen as the enhanced path for the first 60 seconds and then switching to Node-2. After 240 seconds, the SDN controller utilizes Node-3 for transmission. A similar pattern is observed in the intermediate nodes of the other sample topology, as shown in Figure 7. In contrast, the DVR protocol exhibits no packet transmission at specific nodes for different routes, namely Node-2 and Node-3, Node-4, Node-5, and Node-6, and Node-7, Node-8, and Node-9. In contrast, the proposed RDEC scheme efficiently utilizes all nodes in the network without completely depleting the battery of any specific node.

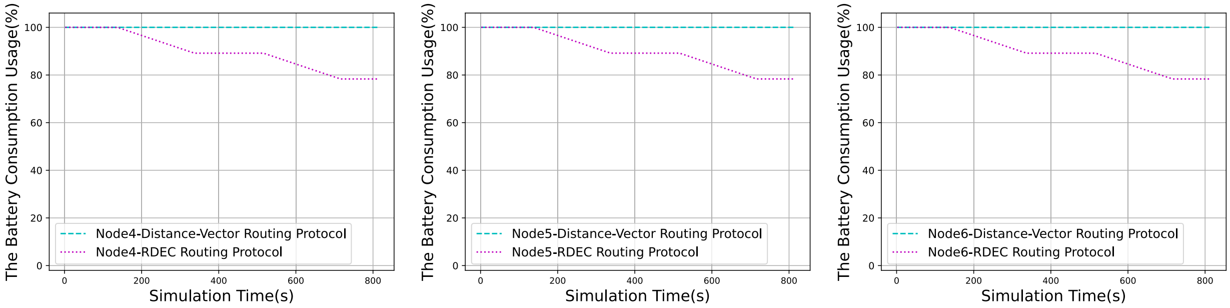
The analysis of battery consumption highlights the effectiveness of the proposed SDN-based RDEC protocol in addressing the challenge posed by the low battery capacity of Node-1. By intelligently considering battery usage and transmission-distance energy, the RDEC protocol ensures the efficient distribution of routing among multiple paths, thereby preventing node depletion. This approach not only extends the lifetime of the affected node but also eliminates the dependence on individual nodes' battery levels, promoting reliable and efficient communication throughout the network.

Energy consumption by intermediate nodes encompasses both the transmission and reception of data. The evaluation of total energy consumption takes into account two key factors: transmission energy (E_{tx}), which represents the energy expended in transmitting the packets to the destination, and receiving energy (E_{rx}), which reflects the energy consumed in accepting the packets. To compare the energy efficiency of the existing DVR protocol and the proposed SDN-based RDEC protocol, we analyze the total energy consumption (measured in Joules) of each node in our sample network topology, as illustrated in Figure 8.

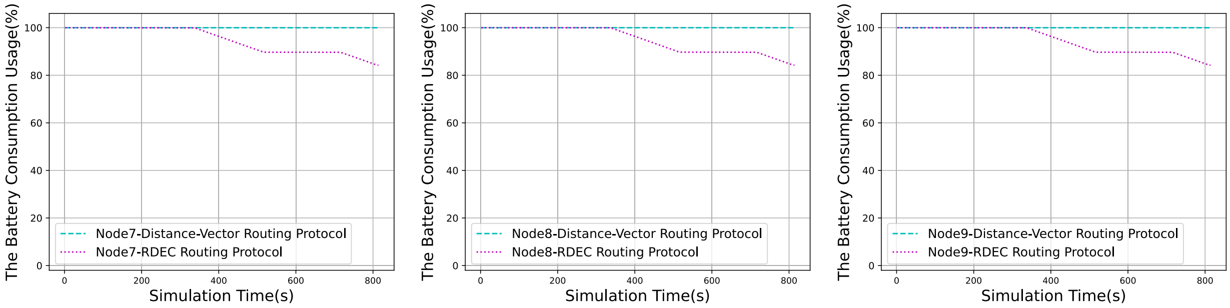
In the DVR protocol, the shortest route exclusively relies on Node-1 for forwarding, resulting in an accumulation of energy consumption until the 304th second, as depicted in Figure 8a. Subsequently, Node-1 becomes exhausted,



(a) Battery consumption of Node 1 (b) Battery consumption of Node 2 (c) Battery consumption of Node 3



(d) Battery consumption of Node 4 (e) Battery consumption of Node 5 (f) Battery consumption of Node 6

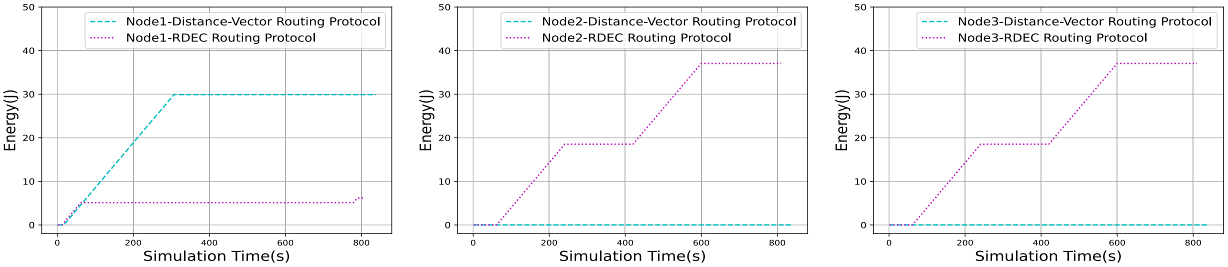


(g) Battery consumption of Node 7 (h) Battery consumption of Node 8 (i) Battery consumption of Node 9

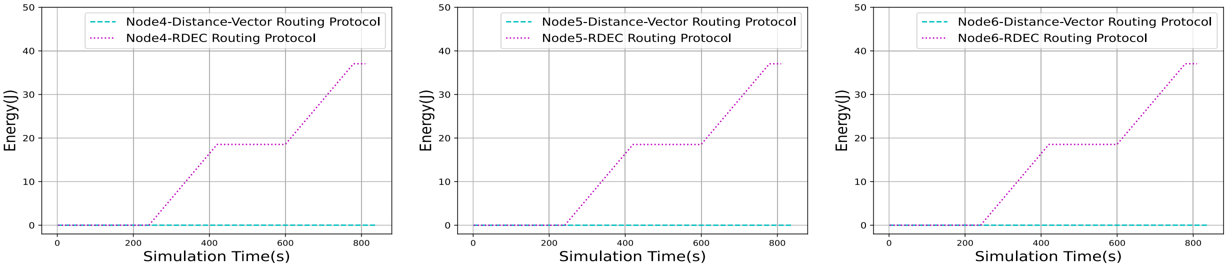
FIGURE 7. **Battery consumption of intermediate nodes.**

ceasing all forwarding activities and resulting in zero energy consumption. It is worth noting that the DVR protocol does not utilize any other nodes in the network, rendering the total energy consumption of Node-2 to Node-6 equal to zero. This pattern is similarly observed in our second network topology, where Node-1 serves as the sole forwarding node. The cumulative energy consumption of Node-1, illustrated in Figure 8g, increases until the 304th second, followed by a stable energy state due to node exhaustion. Notably, the total energy consumption of the remaining nodes (Node-2 to Node-9) is zero, as evidenced in Figure 8h to Figure 8o, respectively.

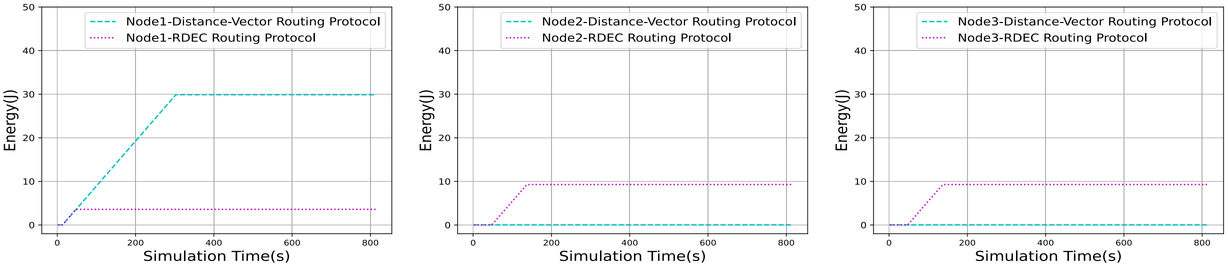
Contrasting with the DVR protocol, the proposed SDN-based RDEC protocol outperforms with a different energy consumption pattern. Initially, transmission commences at the beginning of the communication and lasts for 60 seconds. During this period, Node-1 experiences an increase in E_{tx} and E_{rx} due to the flow of packets, after which the total energy consumption stabilizes, as shown in Figure 8a. After the path switch by the SDN controller, transmission occurs from the 60th second to the 240th second and from the 420th second to the 600th second. Node-2 and Node-3 are involved in sending and receiving packets during these time intervals, leading to an increase in their respective E_{tx} and E_{rx}. The cumulative energy consumption of Node-2 and Node-3 can be observed in Figure 8b and Figure 8c for the 60th to 240th second interval and the 420th to 600th second interval, respectively. Between the 240th and 420th seconds, as well as between the 600th and 780th seconds, Node-4, Node-5, and Node-6 actively participate in transmission. Their total energy consumption corresponds to the increase in E_{tx} and E_{rx}, as depicted in Figure 8d, Figure 8e, and Figure 8f, respectively. Notably, during the 420th to 600th second interval, which encompasses route *two* transmission, the total energy consumption of Node-4, Node-5, and Node-6 remains stable. The same



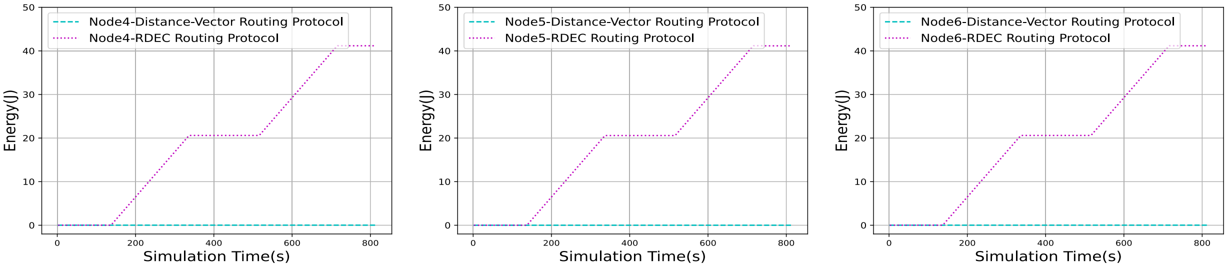
(a) Sample topology A, Node 1 (b) Sample topology A, Node 2 (c) Sample topology A, Node 3



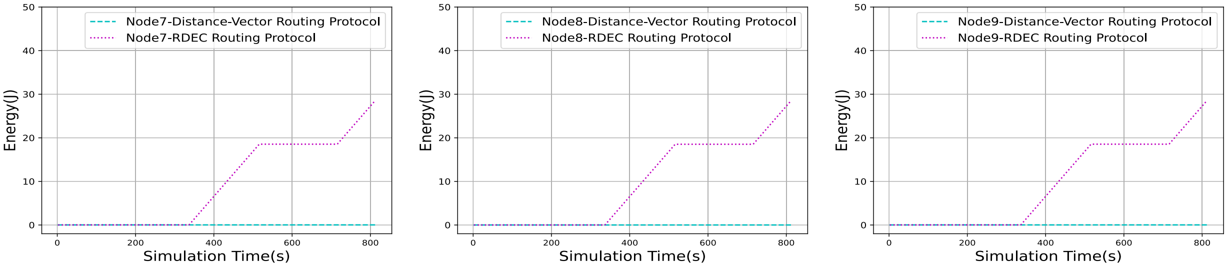
(d) Sample topology A, Node 4 (e) Sample topology A, Node 5 (f) Sample topology A, Node 6



(g) Sample topology B, Node 1 (h) Sample topology B, Node 2 (i) Sample topology B, Node 3

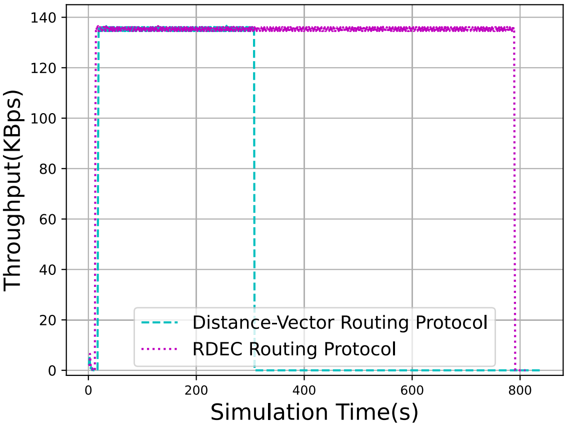


(j) Sample topology B, Node 4 (k) Sample topology B, Node 5 (l) Sample topology B, Node 6

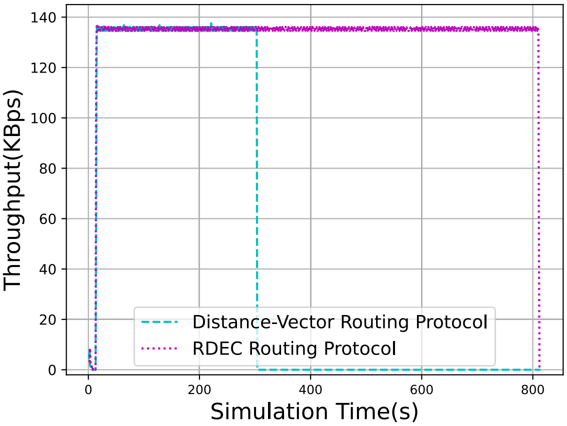


(m) Sample topology B, Node 7 (n) Sample topology B, Node 8 (o) Sample topology B, Node 9

FIGURE 8. **Total energy consumption of intermediate nodes.**



(a) Throughput of network (topology A)



(b) Throughput of network (topology B)

FIGURE 9. **Network throughput in the sample scenarios.**

efficient load-balancing can be seen in the other sample topology.

Figure 9a shows the most important metric for message routing, i.e., network throughput. In the DVR protocol, the transmission process is constrained to Node-1 as the sole intermediary for data exchange between sender and receiver nodes. Consequently, the continuity of communication hinges entirely upon the battery capacity of Node-1. Due to the limited battery capacity of Node-1, it quickly becomes depleted, resulting in the premature termination of transmission. Consequently, communication abruptly ceases not due to the absence of remaining packets to transmit, but rather due to the failure of Node-1. This leads to data loss and an incomplete communication session. Figure 9b demonstrates a similar behaviour for the DVR protocol, where Node-1 gets exhausted and results in connection and data loss.

In contrast, the proposed RDEC protocol in SDN-managed Industry 4.0 employs a more efficient approach by carefully selecting the enhanced path based on energy requirements for transmission. This selection process considers factors such as transmission-distance energy and the average battery consumption of intermediate nodes. By intelligently managing the battery consumption of intermediate nodes, the RDEC protocol prevents them from becoming depleted and extends their operational lifetime. As a result, the transmission duration is prolonged, allowing communication to continue until all packets have been successfully transmitted. This approach ensures that the communication session concludes in a controlled manner when there are no further packets remaining to be sent. The positive impact of the proposed RDEC protocol can be seen in Figure 9a and 9a.

The RDEC protocol significantly enhances network performance by effectively reducing battery consumption. It achieves this by taking into account both the energy required for data transmission and the average battery consumption of intermediate nodes. Importantly, the total energy consumption of the network is minimized, as decision-making is centralized to the Software-Defined Networking (SDN) controller. This centralization eases the computational load on individual nodes, leading to further energy savings. Additionally, the RDEC protocol successfully doubles network throughput by optimizing the selection of routing paths and promoting energy-efficient communication. Crucially, the protocol extends the lifespan of battery-constrained devices by preventing the overuse of nodes with a low battery capacity, thereby ensuring their longevity.

According to the results, the enhanced path is identified as the one producing the best outcome based on the specific metrics we have defined. These metrics include the energy expended during transmission-distance and the average level of battery consumption. Our proposed RDEC protocol leverages these metrics to select the routing path. The intent is to minimize energy consumption and equitably distribute traffic load across the network nodes, optimizing the overall network operation.

VI. CONCLUSION

The digitalization of industry has ushered in the era of Industry 4.0, where the IIoT and IWSNs play crucial roles. However, despite technological advancements and digitalization in Industry 4.0, IWSNs and IIoT face challenges due to limited battery capacity, compounded by inefficient and energy-unaware communications protocols. Traditional routing protocols, like DVR, focus solely on the shortest path, without considering energy consumption, leading to potential disruptions and power losses. In this paper, we propose RDEC, an energy-cost-based routing protocol that utilizes SDNs to centralize routing decisions. RDEC selects the enhanced route based on two energy-related metrics: transmission-distance energy and average battery consumption of intermediate nodes. By centralizing decision-making in the SDN controller, RDEC prevents energy wastage in routing tasks. Additionally, the protocol balances transmission across nodes based on their battery levels, optimizing battery usage and prolonging node and communication lifetimes.

Our realistic simulation in the industry-level Mininet-Wifi emulator with various network topologies demonstrates the efficacy of our approach in estimating transmission-distance energy and average battery consumption for each communication route, leading to efficient routing path allocation. The protocol significantly improves transmission time, network throughput, and node lifetime, while reducing total energy consumption and information loss. Compared to the baseline DVR protocol, the SDN-based RDEC protocol achieves up to six times energy savings in the shortest-path node and extends communication time from 304 seconds to 780-810 seconds, depending on the network topology.

The robustness of the RDEC protocol is underpinned by its capacity to centralize the process of enhanced path calculation and selection within the SDN controller. This strategic centralization mitigates the computational load on nodes, yielding significant energy savings. Moreover, the RDEC protocol enhances the longevity of intermediate nodes, thereby extending the overall communication lifespan of the network. These advantages position the RDEC protocol as a significant contribution to the field of Industry 4.0. It offers a robust solution to the prevalent challenges of energy consumption and communication failures in small, battery-dependent devices.

In summary, our research showcases the effectiveness of the SDN-based RDEC protocol in enhancing energy efficiency and performance in IWSNs. By considering energy-related factors and utilizing centralized routing decisions, our approach demonstrates significant improvements over traditional protocols, promising prolonged network operation and reduced energy consumption.

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