

# Power optimization of Control-plane Signaling in Fog-Assisted Wireless SDN using Hybrid-Hop Transmission

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## ABSTRACT

Software-Defined Wireless Sensor Networks (SDN-WISE) provide a centralised control mechanism with flexible programmability for large IoT deployments. However, placing the SDN controller exclusively in the cloud layer introduces excessive energy consumption in the control plane signaling, especially for distant sensor nodes. The problem is exacerbated when sending control packets over long distances using single-hop transmission. To tackle this drawback, this paper presents an energy-aware hybrid-hop architecture in which a Fog-based controller is placed near the edge of the network, and a relay-assisted hybrid-hop mechanism triggered for far-off nodes. Using numerical data to study how much control signaling energy is required for Single-Hop, Relay-based Multi-Hop, and Hybrid-Hop, a Mathematical Energy Model is created to compare the respective aspects. Considering transmission, reception, and processing energy (the latter, which includes the relay node), an analytical threshold distance is obtained, which defines when the sensor node should transition from a direct transmission mechanism to a relay-based forwarding mechanism. MATLAB simulation results indicate that the proposed Hybrid-Hop Fog-based architecture reduces the power consumption for control plane signaling by an estimated (18%-20%) compared to a classical Cloud-based SDN-WISE configuration. These results demonstrate that the application of Fog computing and hybrid-hop signaling can contribute to the energy-efficient design of SDN-WISE IoT networks.

**Keywords:** SDN-WISE, Fog Controller, Hybrid-Hop, Relay Node, Power consumption of Control Plane, IoT Networks.

## 1. Introduction

Wireless Sensor Networks (WSNs) are considered a fundamental pillar of the Internet of Things (IoT) concept and are used in many applications, including smart cities and industrial automation[1]. However, relying on battery-powered sensor nodes with limited capabilities turns energy conservation into a major bottleneck that cannot be easily overcome [2]. SDNs, have emerged as a practical solution to overcome such issues, including scalability limitation, inflexibility, or high energy costs, the control plane in SDNs abstracted from the data plane, enabling centralized management together with increased programmability. and dynamic configuration capabilities [3]. This principle has been adapted for wireless sensor networks WSNs through the implementation of SDN-WISE, which enables network operators to exercise stateful control, perform rule-based data manipulations, and achieve programmable network behavior [4], While SDN-WISE enhances the performance, intelligence, and flexibility of the Internet of Things (IoT), it also introduces a new energy challenge for the control plane. Control signaling, which includes reports, beacons, and configuration messages, takes place continuously between the nodes and the centralized controller and is energy-intensive, especially in dense and dynamic topologies [5]. Since all SDN controllers work in the cloud layer, extending signal distances and latency, this configuration increases the energy expenditure and reduces response time, especially where single-hop is employed for remote nodes, and the energy requirement is strongly influenced by multipath

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fading and long-distance transmission [6], [7]. To address this issue, fog computing has been introduced as a complementary method that seeks to position computation, control, and decision-making nearer to the sources of data. While signaling distance is drastically reduced in remote environments, owing to embedding control functionality inside the fog layer to reduce energy consumption and enhance real-time responsiveness [8], [9]. Besides, communication methods that incorporate multi-hop and relay assistance have been proven to decrease energy consumption during transmission and allow for the division of long-distance communication into shorter segments [10]. This hybrid-hop architecture can yield a favorable balance: between energy expenditure and communication speed. Consequently, this paper introduces an enhanced SDN-WISE Fog-Cloud model, which relocates the WISE-VISOR controller from the cloud layer to the fog layer while maintaining the cloud as a central hub for overarching coordination and prolonged data processing. The proposed model uses a hybrid-hop signaling approach which readapts the transition from direct signals to relay signals are generated based on the node distance and the required energy savings. Research in MATLAB considers power consumption pertaining to control-plane signaling across sensors, sink, fog and cloud layers. The results indicate an improvement of 18–20% in control-plane energy consumption compared to the traditional cloud-only SDN-WISE model. These findings illustrate how fog-assisted hybrid-hop control within IoT systems can achieve sustainable energy efficiency alongside reduced latency. Moreover, this improvement may form the basis for energy-conscious adaptive control features in future 5G/6G IoT deployments [5], [11].

### 1.1 Related Works

Energy efficiency in Wireless Sensor Networks (WSNs) and Internet of Things (IoT) systems represents a fundamental challenge for the widespread deployment of these technologies in modern applications. Since their inception, traditional WSN architectures, as documented by foundational research, have faced substantial obstacles stemming from limited battery capacity in nodes and the efficiency of communication protocols, leading to rapid energy depletion and significantly reduced network operational lifetime [12]. With the emergence and evolution of the IoT paradigm, the scope of these challenges expanded, highlighting the need for scalable frameworks capable of supporting high connectivity and reliability among vast numbers of devices [13]. As these complexities escalated, Software-Defined Networking (SDN) emerged as a revolutionary methodology that reshaped network architecture. This model, as outlined by comprehensive survey studies [3], centers on the decoupling of the control and data planes, enabling flexible centralized management and dynamic network programmability. Various academic efforts have attempted to fit these benefits into wireless contexts that are usually constrained in several resources. A prominent attempt among these was the proposal of the SDN-WISE architecture [4], which provided a complete solution offering stateful control and programmable behavior for sensor networks. However, this centralization imposed a new overhead: the control-plane and Signaling (due to the continuous exchange of control packets—such as Beacons, Reports, and Configuration messages) between distributed nodes and the central controller. Contemporary research indicates that the challenge of energy consumption, particularly in the control plane, persists even in advanced network architectures such as O-RAN and integrated 5G systems [14]. In an effort to mitigate the communication latency in response to latency, scalability, and energy consumption associated with the centralized cloud-based model in SDN, Fog Computing emerged. As the critical intermediate layer, its core concept is to bring control logic and processing resources closer to data sources at the network edge. Foundational work in this field has highlighted the role of fog computing as a key enabling factor for time-sensitive IoT applications [15], [16], [17]. Very recent (2024) research reviews emphasize that distributed and intelligent control models within the Fog-Cloud continuum are essential for the success of next-generation IoT applications [18], [19]. Subsequent research has focused on designing energy-efficient fog-SDN architectures, showing promising results in reducing response time and improving local processing efficiency [8]. However, it is noted that most current research efforts in this context primarily focus on computational offloading strategies and data-plane routing optimization, while accurate analytical modeling of energy consumption in the control-signaling path itself within these hierarchical architectures remains incomplete, creating a gap in the comprehensive assessment of their true energy efficiency. Parallel to architectural shifts, data transmission strategies have evolved to optimize energy utilization. Multi-hop Routing stands as one of the most established strategies, working to enhance network resilience by breaking a long-range communication link (where energy loss scales with  $d^4$ ) into several shorter, more efficient hops (where loss scales with  $d^2$ ) [7]. Contemporary protocols continue to explore dynamic relay selection mechanisms and energy-aware routing to achieve scalability in IoT environments [20]. However, when attempting to integrate these strategies within the SDN-WISE framework, prevalent models often impose rigid assumptions. Some hybrid SDN methodologies focus on improving reliability under unstable

control channels without addressing energy-efficient transmission mode switching [11]. Meanwhile, other models strictly adhere to either direct single-hop communication or a fixed multi-hop routing network for all control traffic, lacking an intelligent adaptive mechanism capable of dynamically selecting the optimal transmission mode based on real-time energy and distance criteria for each individual control message. Synthesizing this analysis, Furthermore, mathematical modeling has been essential for WSN optimization. Energy-constrained modulation models [21], node placement optimization [22], in-network aggregation techniques [23], and routing optimization frameworks [24] provide the mathematical foundations for our integrated energy modeling approach. a clear research gap emerges in the holistic modeling and optimization of control-plane energy performance for architectures that integrally combine:

1. Hierarchical Fog-Cloud Control to shorten the propagation path of control signals.
2. Adaptive Hybrid Communication to optimize the transmission energy per control packet according to the node's instantaneous distance Previous works have largely addressed these components in isolation. The SDN-WISE architecture [4] provided the programmable framework but at the cost of high signaling overhead. Fog-SDN solutions[15], [16], [17], [8] reduced latency without optimizing the underlying wireless transmission strategy for control packets. On the other hand, multi-hop routing protocols [7], [20] focused on conserving data-plane energy without organic integration with SDN's centralized control logic. Therefore, this research paper proposes a new architecture named Fog-Based Hybrid-Hop SDN-WISE. The key contribution in this work is an integrated analytical framework that incorporates the advantages of fog-layer control with a hybrid transmission system that is versatile. The proposed model relies on an analytically derived distance threshold  $R_{th}$  for dynamic switching between direct (single-hop) and relay-assisted (multi-hop) communication modes when handling control packets. This aims to achieve near-optimal energy efficiency for control-plane signaling in large-scale, energy-constrained IoT deployments, thereby seeking to bridge the identified research gap.

## 1.2 Contributions

This work addresses the critical problem of excessive power consumption in the WSDN control plane using an integrated analytical methodology. First, we provide a comprehensive mathematical model (To the best of our knowledge and based on the reviewed literature, no prior study has addressed the analytical integration between fog-based SDN-WISE and a hybrid transmission mechanism. This mechanism relies on dynamic switching between single-hop and multi-hop communication to minimize power consumption within the control plane) that uniquely and quantitatively assesses the energy impact resulting from the combined integration of the hierarchical Cloud-Fog architecture and an adaptive hybrid-hop signaling mechanism. We introduce an innovative adaptive switching algorithm that allows nodes to determine the most effective communication mode either single-hop or multi-hop through real-time analysis of energy and distance trade-offs. Simulation data demonstrates that this integrated methodology achieves significant and demonstrable power savings in the control plane, thus outperforming static cloud-based approaches, confirming the efficacy of this combined strategy as a decisive solution for control plane optimality in sustainable IoT networks.

Table 1. Compiling a Summary of Symbols and Parameters.

Symbols	Definition	Symbols	Definition
$SN$	Sensor Node	$PC_{SN}$	Power Consumption in SN
$SNK$	Sink Node	$PC_{SNK}$	Power Consumption in SNK
$RN$	Relay Node	$PC_{RN}$	Power Consumption in Relay Node
$FS$	Fog Node	$PC_{NOS}$	Power Consumption in NOS
$CTR$	Control Plane Signaling	$PC_{TM}$	Power Consumption in Topology Management
$d$	Distance between nodes	$PC_{Adapt}$	Power Consumption in Adaptation Processing
$R_{th}$	Relay Threshold Distance	$PC_{FS}$	Power Consumption in FS
$PC_{cloud}$	Power Consumption in Cloud		

## 2. System Model and Problem Formulation

### 2.1. Network Architecture

The proposed Software-Defined Wireless Sensor Network (SDN-WISE) architecture adopts a hierarchical multi-layer model supported by fog computing, aimed at minimizing control-plane energy consumption while ensuring scalability and low-latency responsiveness. The proposed framework integrates distributed sensor nodes with aggregator nodes, as well as fog and cloud layers, to strike a balance between latency and energy efficiency.

**1- Sensor Nodes (SNs):** are dispersed terminal equipment which detects data and performs basic control services. Each SN executes SDN-WISE protocol stack which includes [4]:

- A Forwarding Layer (FWD)
- An In-Network Packet Processing (INPP) Layer
- A Topology Discovery (TD) Layer
- IEEE 802.15.4 Medium Access Control (MAC) and Physical (PHY) layers for low-power wireless communication [25] .

**2- Relay Nodes (RNs):** These are intermediary nodes placed at key positions between remote Sensor Nodes (SNs) and Sink Nodes. Each cluster of 125 SNs contains three RNs installed on a path with a radius of 80 meters that are center on the Sink Node. Every RN performs three operations, according to a control packet: it gets the data of a remote SN and uses it through the SDN-WISE layers and sends it to the Sink Node [26], [27] The relay node distribution strategy is based on a clustering model, where each WSN cluster of 125 sensor nodes incorporates three relay nodes distributed radially around the sink node. Selecting three relay nodes creates a practical trade-off between minimizing the transmission distances and handling the processing overhead of the relay nodes while ensuring adequate reliability. Using more relay nodes would decrease hop distance at the cost of an increased cumulative processing cost and otherwise would, in turn, significantly raise path loss with fewer relays. Therefore, this specific distribution was adopted as a balanced operating point for the system.

**3- Sink Nodes (SNKs):** These are centralized aggregation nodes in each cluster, and they have two interfaces

- A local wireless IEEE 802.15.4 interface to SNs and RNs.
- A wired Ethernet (802.3) interface to be connected to the Fog Controller. They consist of Adaptation and TCP/IP layers to enable the translation of protocols [28], [29] .

**4- Fog Controller:** acts as the intelligence of the network placed in strategic position in the Fog Layer to ensure latency and significantly reduce the use of control-plane signaling energy by reducing the distance of communication [30], [31] . Operationally the Controller. Processes control signals, Sink Nodes (SNKs) manages routing, scheduling and resource allocation processes and maintains a global view of the network state [32] . It is designed on Cloud-Fog management strategy where the Controller is able to implement effective localized control [9]. It also makes use of devices (such as FSMs) to improve sensor nodes and make them less dependent, on the central controller [4] .

**5- Cloud Layer:** Although the Fog Controller is responsible of the principal control work, the Cloud Layer still remains a top-level controller, in the hierarchical framework [9], [8]. The Cloud provides the necessary storage, capabilities, global network management and robust computing resources needed to run applications that Big Data analytics and machine learning involved [15]. The Fog cloud continuum has a balance: Fog decreases the latency and the energy use on the edge whereas the Cloud offers the flexibility, reliability and large scale coordination, in distributed IoT contexts [33].

**6- Network Operating System (NOS):** The NOS is the software component residing at Fog Controller which has the essential functions of SDN. Its most important tasks relate to managing Flow Tables and monitoring the network states and implementing control policies. The execution of these functions by the NOS enables the Fog Controller to effectively handle the input of control and translate it into decisions that control the operation of the network. Moreover, the NOS is interoperable with the Cloud Layer through standard protocols, which allows the exchange of data and uses large-scale computational capabilities as needed [5] .

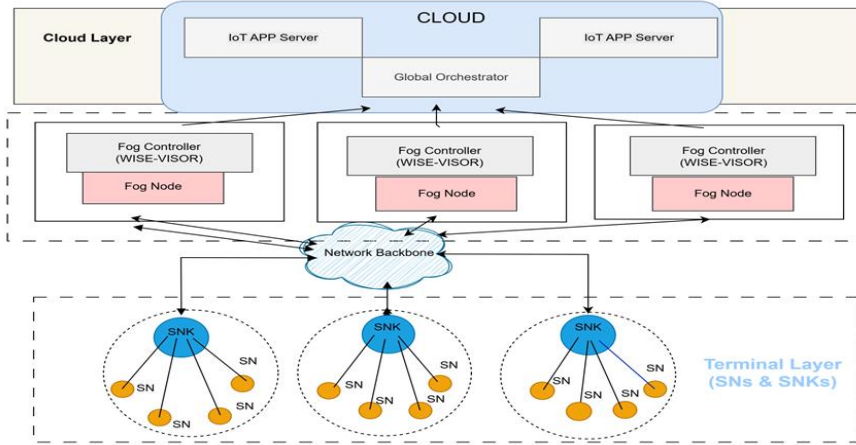


Figure 1. Proposed Fog-Based Hybrid-Hop SDN-WISE Architecture.

## 2.2. Mathematical Model for Control Plane Power Consumption

The total power consumption (PC) of the control plane in the proposed architecture is modeled as the sum of contributions from all active components the term energy consumption in this research refers to the energy required to process or transmit a single control packet, whereas power consumption is derived by dividing the total consumed energy by the Transmission Time Interval (TTI). Accordingly, all power results presented in the results section are directly dependent on energy modeling and the control of the transmission timing:

$$PC_{model} = PC_{SDN-WISE(CTR)} \quad \dots (1)$$

$$PC_{SDN-WISE(CTR)} = \sum_{Net=1}^M \left( \sum_{SN=1}^{K_{Net}} PC_{SN(CTR)} + \sum_{SNK=1}^{J_{Net}} PC_{SNK(CTR)} \right) + \sum_{Fog=1}^{N_{Net}} PC_{Fog(CTR)} + PC_{Cloud} + NOS \quad \dots (2)$$

where M denotes the total count of terminal WSN clusters, represented by [Net = 1, ..., M]. The variables  $K_{Net}$  and  $J_{Net}$  indicate the respective quantities of SNs and SNKs within each network node.

### 2.2.1. Power Consumption in Sensor Nodes (SNs)

The control plane power consumption of an SN is defined as [7], [31], [21]

$$PC_{SN(CTR)} = PC_{SN(CTR)(Tx)} + PC_{SN(CTR)(Rx)} + PC_{SN(Proc)} \quad \dots (3)$$

Here, Transmission includes : (Report , Request, Beacon) and reception includes: (OpenPath, Configuration, Beacon and Response)

Beacon messages are periodic, whereas Report, Request, and Response are event-driven. Configuration and Open messages are generated on demand by the controller.

### 2.2.2. Transmission and Reception Energy Model

The energy consumed to transmit a control packet of length  $L_{PHY}$  bits over a distance d is given by:

$$E_{Tx}(L_{PHY802.15.4}, d) = \begin{cases} L_{PHY802.15.4} \times E_{elect} + L_{PHY802.15.4} \times \epsilon_{fs} \times d^2, & d \leq d_0 \\ L_{PHY802.15.4} \times E_{elect} + L_{PHY802.15.4} \times \epsilon_{mp} \times d^4, & d > d_0 \end{cases}$$

Reception energy:

$$E_{Rx}(L_{PHY802.15.4}, d) = L_{PHY802.15.4} * E_{elect} \quad \dots (6)$$

where:

$E_{elec}$  Energy consumed by electronic circuitry per bit (50 nJ/bit).

$\epsilon_{fs}, \epsilon_{mp}$  Amplifier energy parameters for free-space and multi-path fading models, respectively.

$d_o = \sqrt{\epsilon_{fs}/\epsilon_{mp}}$  : The critical distance threshold for switching between propagation models.

### 2.2.3. Hybrid Hop Mechanism and Relay Threshold

The hybrid communication strategy builds upon mathematical optimization principles for relay placement [22] and energy-efficient routing [24]. To optimize energy efficiency, a hybrid communication strategy is employed to simplify the analysis and derive the distance threshold, this paper assumes that multi-hop communication follows a pattern based on two equal-distance hops ( $d_1 = d_2$ ). This scenario is considered an ideal case, providing a benchmark for minimum energy consumption using the path loss model, as dividing the distance into two equal parts minimizes the total transmission of energy. Although unequal hops have been used for various applications based on node distribution, the proposed mathematical model remains scalable to include such cases. Nonetheless, this research relies on equal hops for the sake of simplicity and as a standardized approach that can be extended for comparative analysis with the final simulation results:

Direct Single-Hop (SH): Used for SNs located within a threshold distance  $R_{th}$  from the SNK.

Relay-assisted Multi-Hop (MH): Used for SNs beyond  $R_{th}$ , where packets are forwarded via a Relay Node.

The optimal relay threshold distance  $R_{th}$  is determined by equating the total energy cost of both modes for a control packet of length L:

$$E_{SH(d_{th})} = E_{MH} \quad \dots (7)$$

The Single -Hop energy for distance  $d_{th}$  is:

$$E_{SH(d_{th})} = \underbrace{(L * E_{elect} + L * \epsilon_{mp} * d_{th}^4)}_{\text{SN Transmission Energy}} + \underbrace{(L * E_{elect} + E_{proc\_SNK}) + E_{Proc\_SN}}_{\text{SNK Reception and Processing Energy}} \quad \dots (8)$$

The Multi -Hop energy (assuming two equal hops,  $d_1 = d_2 = d_{th}/2$ ) is:

$$E_{MH} = \underbrace{(L * E_{elect} + L * \epsilon_{fs} * \left(\frac{d_{th}}{2}\right)^2)}_{\text{SN to RN (Hop 1)}} + \underbrace{(2L * E_{elect} + L * \epsilon_{fs} * \left(\frac{d_{th}}{2}\right)^2)}_{\text{RN Cost(Rx,Tx,Processing)}} + \underbrace{2 * E_{Proc\_RN}}_{\text{RN Processing}} + \underbrace{L * E_{elect}}_{\text{SNK Reception}} + E_{Proc\_SN} \quad \dots (9)$$

Calculating  $R_{th}$  By setting  $E_{SH(d_{th})} = E_{MH}$  and solving for  $d_{th}$ , we determine the optimal relay threshold distance. Assuming a simplified two-hop configuration where  $d_1 \approx d_2 = \frac{d}{2}$ , the equation is solved primarily by balancing the  $d^4$  transmission cost against the cumulative  $d^2$  transmission and relay processing costs

Energy Balance Equation:

$$(2L * E_{elec} + L * \epsilon_{mp} * d_{th}^4 + E_{Proc\_SNK} + E_{Proc\_SN}) = \left(4L * E_{elec} + L * \epsilon_{fs} * \left(\frac{d_{th}^2}{2}\right) + 2 * E_{Proc_{RN}} + E_{Proc_{SN}}\right) \quad \dots (10)$$

**Simplifying ( $E_{Proc\_SN}$  Cancels from both sides):**

$$(2L * E_{elec} + L * \epsilon_{mp} * d_{th}^4 + E_{Proc\_SNK}) = \left(4L * E_{elec} + L * \epsilon_{fs} * \left(\frac{d_{th}^2}{2}\right) + 2 * E_{Proc_{RN}}\right) \quad \dots (11)$$

**Rearrange to standard Quadratic Form:**

$$L * \epsilon_{mp} * d_{th}^4 - \left(L * \frac{\epsilon_{fs}}{2}\right) * d_{th}^2 - 2L * E_{elec} - 2 * E_{Proc_{RN}} + E_{Proc_{SNK}} = 0 \quad \dots (12)$$

Let  $x = d_{th}^2$

$$L * \epsilon_{mp} * x^2 - \left(L * \frac{\epsilon_{fs}}{2}\right) * x - (2L * E_{elec} + 2 * E_{Proc_{RN}} - E_{Proc_{SNK}}) = 0 \quad \dots (13)$$

**Divided by L**

$$\epsilon_{mp} * x^2 - \left(\frac{\epsilon_{fs}}{2}\right) * x - (2E_{elec} + (2 * E_{ProcRN} - E_{ProcSNK})/L) = 0 \quad \dots (14)$$

The optimal relay threshold distance ( $R_{th}$ ) is therefore calculated as:

$$R_{th} = d_{th} = \sqrt{\frac{\epsilon_{fs}}{4\epsilon_{mp}} + \sqrt{\left(\frac{\epsilon_{fs}}{4\epsilon_{mp}}\right)^2 + \frac{2E_{elec}}{\epsilon_{mp}} + \frac{2 * E_{ProcRN} - E_{ProcSNK}}{L * \epsilon_{mp}}} \quad \dots (15)$$

This equation demonstrates the theoretical justification for selecting  $R_{th}$ (approximately 100 meters in the simulation setup), as it represents the point where the quadratic energy savings from splitting the hop length outweigh the linear increase in energy processing costs introduced by the relay [34].

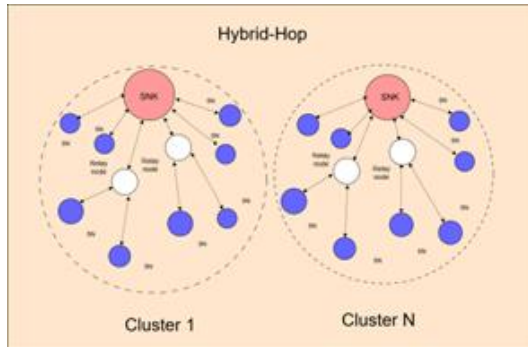


Figure 2. Two-Hop Relay-Assisted Communication Model Between SN and SNK.

#### 2.2.4. Power Consumption in Other Network Components

**Relay Nodes (RNs):**

$$PC_{RN(CTR)} = PC_{RN(CTR)(Tx)} + PC_{RN(CTR)(Rx)} \quad \dots (16)$$

**Sink Nodes (SNKs):**

$$PC_{SNK(CTR)} = PC_{SNK(CTR)(Tx)} + PC_{SNK(CTR)(Rx)} + PC_{SNK(Eth-Port-Config)} \quad \dots (17)$$

**Fog Controller:**

$$PC_{Fog(CTR)} = PC_{WISE-VISOR} + PC_{NOS} \quad (18)$$

Where:

$$PC_{WISE-VISOR} = PC_{CTR} + PC_{TM} + PC_{Adapt} \quad \dots (19)$$

**Cloud Layer:**

$$PC_{Cloud} = PC_{NOS-Cloud} \quad \dots (20)$$

Modeled as a constant or negligible overhead.

### 3. Numerical Analysis

The simulation environment was implemented in MATLAB to evaluate the control-plane signaling power under the three considered communication configurations. The key parameters used in the simulation are summarized in Table 1 and 2. This section analyzes the impact of the distances between SNs and SNKs on the total PC of the control plane. To isolate the effect of distance as the primary independent variable the transmission Time Interval (TTI) is fixed at 10 seconds throughout the analysis. The three communication scenarios introduced in section 2 - single-hop, multi-hop, and proposed hybrid-hop strategy are evaluated under increasing SN-SNK separation distances. All configurations follow the system architecture and the analytical model defined in Section 2, therefore structural or modeling details are not repeated here. The results are presented in terms of

instantaneous power, in watts, versus distance, whereby a comparison is made that underlines the relative efficiencies of the proposed fog-assisted architecture compared with the baseline cloud-only model. The percentage improvements are included to show the benefits of adaptive communication strategies in minimizing control-plane signaling energy.

Table 2. System Parameters Employed in the Simulation.

Parameter	Setting
Energy consumption of electronic circuit (E <sub>elect</sub> )	50nJ/bit
Channel Parameter of free space model ( $\epsilon_{fs}$ )	10 pJ/bit/m <sup>2</sup>
Channel Parameter of Multipath Amplifier ( $\epsilon_{mp}$ )	0.0013pJ/bit/m <sup>2</sup>
Energy consumption for (INPP, FWD, TD)	5 (nJ/bit)/packet processing[35]
The propagation setting	
PC (Fog Controller [PC] _ (WISE-VISOR)	0.3909 W
Energy Consumption for Adaptation process	197.208nJ/packet processing)
Network Size (N*N)	350m×350m
Distance between SN and Gateway SNK )	20 To 200 M
Number of SNs	2000 SNs
Number of SNKs	16 SNKs
Number of Terminal WSNs	16 WSNs
Number of SNs per Terminal WSN	125 SNs
Number of Fog FS	16 FS
Number of RN	48 RN
Processing Energy (Relay/Fog)	7 n J/bit
Threshold Relay Distance	100 m
TTI	10s

Table 3. Control Message Parameters

Message Type	Size (Bytes)	Transmission Rate	Nature
Beacon	2	Every TTI	Periodic

Report	18	Event-based	Aperiodic
Request	92	Event-based	Aperiodic
Response	6	Event-based	Aperiodic
Configuration	3	On-demand	Controller-triggered
OpenPath	11	On-demand	Controller-triggered
Registry Proxy	28	On-demand	Controller-triggered

The control plane signaling energy is determined by the message size and the transmission frequency. Some control plane messages are transmitted at fixed intervals, i.e., at the TTI, while others, i.e., the event-driven messages, are triggered by events and include the Report, Request, and Response messages, as well as the Configuration and OpenPath messages, which are triggered by the controller. To model the event-driven nature of these messages, they are modeled as a Poisson process with arrival rates 0.1 and 0.01 per TTI, respectively, as in [5], [11].

#### 4. Results and Discussion (Analysis of Control-Plane Power Consumption)

This section provides a comprehensive evaluation of the control plane power consumption within an SDN-WISE-based architecture, implemented on a hierarchical multi-layer model supported by hybrid-hop fog computing. In this model, Sensor Nodes (SNs) located within a threshold distance of 100 meters connect directly to aggregation nodes, which in turn connect to the controller at the Fog layer. However, for nodes beyond this distance, control messages are relayed by Relay Nodes (RNs). The purpose of this analysis is to examine the relationship between signal power and the distance of communication, type of message, and Transmission Time Interval (TTI). Figure 4 illustrates the characteristics of the basic control messages, namely Beacon (BEC), Report (REP), and Configuration (CFG). At distances below 100 meters, all curves exhibit relatively low and stable power levels, reflecting the efficiency and stability of single-hop communication. However, a significant increase in signal power is noticed once the threshold distance is crossed. This sudden change is justified by the activation of the transmission through the relay nodes, which adds extra energy consumption for the reception, retransmission, and processing of the signal at the relay nodes. After this sudden change, the energy consumption gradually increases because of the increased transmission distances.

A similar two-region behavior is observed in Figure 5 for Request (REQ) and Response messages. The results show a gradual increase within the single-hop range, followed by a sharp jump near the threshold distance, and subsequently, a smoother ascending increase within the multi-hop communication range. This confirms that while the hybrid architecture imposes additional signaling overhead when relaying is activated, it concurrently curbs the excessive growth of transmission power over extended distances.

In contrast, Figure 6 presents an additional analysis for Register Proxy (REG) and Open Path messages. These signals demonstrate a higher sensitivity to distance variations, attributed to their larger data payloads and the additional processing requirements imposed on the relay node.

Figure 7 depicts the total control plane power consumption for all message types. A clear point of inflection, or knee, is noticed in the graph exactly at the threshold distance, thus justifying the handover distance specified in Section 2. In addition, Figure 8 shows the joint effect of distance and TTI through a three-dimensional surface graph, where both distance and TTI were varied to study their effect on power consumption. The outcome of the experiment shows that an increase in the value of TTI significantly reduces the control signal power. On the other hand, an increase in the communication distance always results in an increase in the transmission power because of the signal attenuation.

Finally, Figure 8 compares the proposed hybrid fog-based architecture with the traditional cloud-based architecture within the SDN-WISE framework. For all distances considered in the experiment, the cloud-based architecture was simulated using the same settings as the fog-based architecture. The proposed model consistently demonstrated lower total control plane power consumption. At larger distances, such as 200 meters, the average improvement per node reached 18-20%. This enhancement is attributed to the reduced communication distance between the aggregator node and the fog controller, coupled with the replacement of direct, high-loss transmission (proportional to  $d^4$ ) over long distances with more energy-efficient multi-hop transmission (proportional to  $d^2$ ). These results confirm the effectiveness of hybrid control leveraging a fog layer in energy-constrained Internet of Things (IoT) environments. The relay density significantly influences the threshold distance  $R_{th}$ . A higher density of relays reduces the optimal switching distance by making multi-

hop transmission more efficient over shorter ranges. Conversely, a lower density increases  $R_{th}$ . Further quantitative analysis of relay placement is a subject for future research.

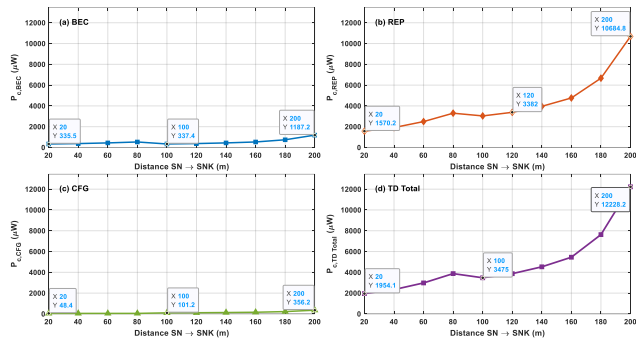


Figure 3. Control-Plane Power Consumption for TD Messages: Beacon, Report, Configuration, and Total TD under Hybrid Scheme (TTI = 10 s,  $d_t$  = 100 m).

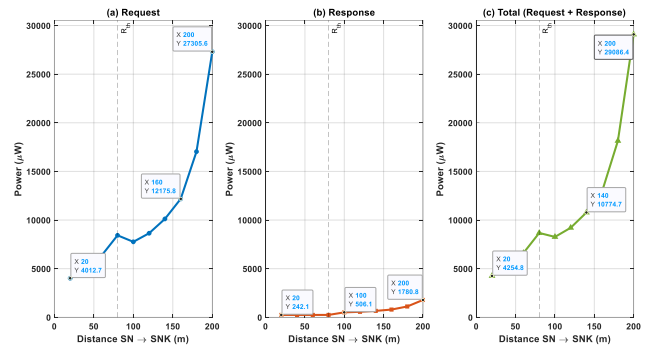


Figure 4. Control-Plane Power Consumption for Event-Driven Messages: Request, Response, and Total Request-Response under Hybrid Scheme.

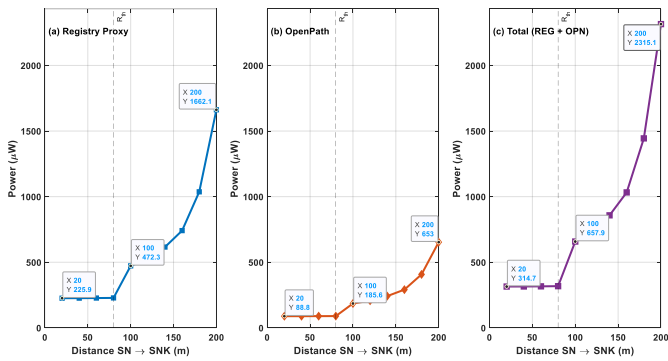


Figure 5. Control-Plane Power Consumption for Controller-Triggered Messages: Registry Proxy, OpenPath, and Total under Hybrid Scheme.

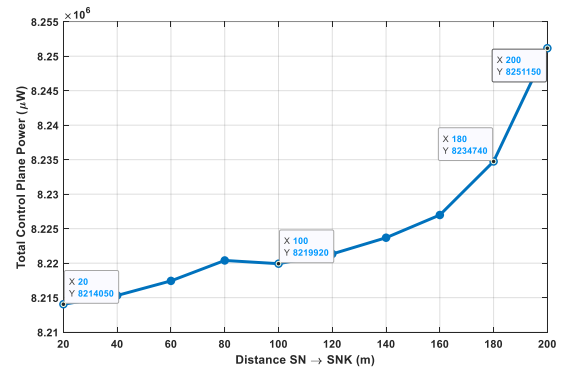


Figure 6. Total Control-Plane Signaling Power Versus Distance under Hybrid-Hop Scheme (TTI = 10 s,  $d_t$  = 100 m).

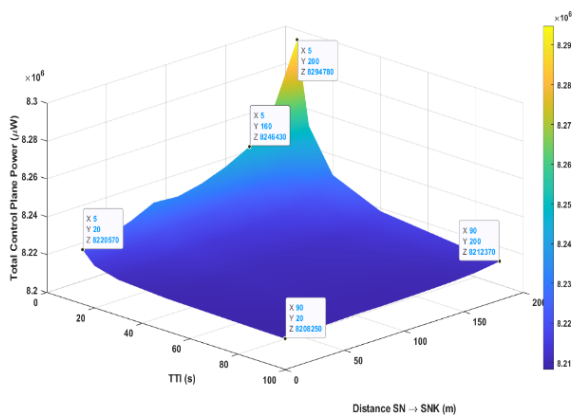


Figure 7. Normalized Control-Plane Power Consumption as a Function of Distance and TTI under Hybrid Scheme.

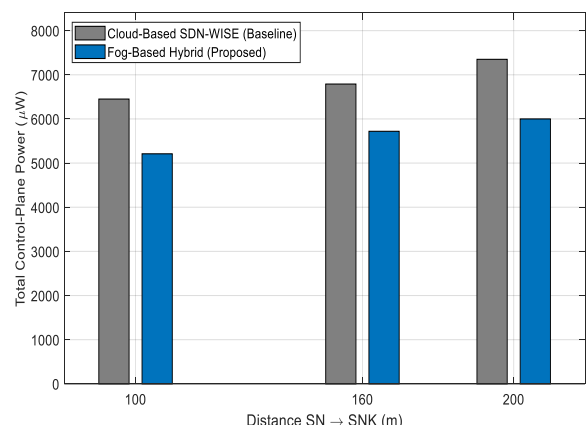


Figure 8. Comparison of Total Control-Plane Power Between Proposed Hybrid Fog-Based Architecture and Baseline Cloud-Based SDN-WISE Model.

#### 4. Conclusions

This work presented a Fog-based Hybrid-Hop SDN-WISE architecture to address energy inefficiency in IoT network control planes. By relocating the controller from the cloud to the fog layer and implementing an adaptive hybrid-hop transmission mechanism, the proposed model achieves significant energy savings. Key results show an 18-20% saving in total control-plane energy consumption compared to traditional cloud-based SDN-WISE designs, while maintaining QoS requirements. The analytical model effectively quantifies both the dynamic processing costs and static hardware overheads at the fog layer, thus being more Realistic energy assessment for future work, we will explore intelligent dynamic controller placement, energy-aware routing algorithms, and predictive power management to further optimize control-plane performance in emerging 5G/6G IoT networks.

#### Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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#### Author Contributions

All authors proposed the research problem. Ismail H. supervised the overall research framework and provided scientific guidance. Hassan K. contributed to the development of mathematical model and analysis methodology. Khalaf B. supported the modeling of control-plane signaling and reviewed the technical aspects of the study. Emad B. M. reviewed the manuscript and provided critical comments to improve the quality of the work. Duaa A. K. developed the methodology, performed the simulations and analysis, and wrote the manuscript. All authors read and approved the final

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