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IoT-Based Wireless Sensor Network Simulation For Water-Saving Irrigation Monitoring Using Cooja

Jurayev Mansurbek Mirkomilovich

PhD Scholar, Department of Information Technology, Andijan State University, Andijan, Uzbekistan

Correspondence should be addressed to Jurayev Mansurbek Mirkomilovich; jurayevmansurbek99@gmail.com

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ABSTRACT- Water scarcity is one of the most critical challenges in modern agriculture, requiring efficient and intelligent irrigation management solutions. This study presents an IoT-based wireless sensor network (WSN) model for remote monitoring of water-saving irrigation systems. The proposed system integrates clustered sensor nodes for monitoring soil moisture, temperature, humidity, and environmental parameters. Network performance and reliability were evaluated using the Cooja simulation environment under different routing and energy consumption scenarios. Key performance metrics, including average hop count, energy consumption, and packet delivery behavior, were analyzed. Simulation results demonstrate that the proposed model ensures reliable data transmission, reduced energy consumption, and improved network stability. The obtained findings confirm the suitability of the proposed architecture for real-time irrigation monitoring applications in resource-constrained agricultural environments.

KEYWORDS: IoT, Wireless Sensor Networks, Water-Saving Irrigation, Cooja Simulation, Energy Efficiency

I. INTRODUCTION

Global climate change and increasing water scarcity have intensified the need for efficient water resource management in agriculture. Traditional irrigation methods often rely on manual decision-making and lack real-time feedback, leading to excessive water consumption and reduced crop productivity. Recent advances in Internet of Things (IoT) technologies and wireless sensor networks (WSNs) have enabled the development of smart irrigation systems capable of continuous monitoring and automated control. By deploying sensor nodes across agricultural fields, parameters such as soil moisture, temperature, humidity, and light intensity can be collected and transmitted to a monitoring center for analysis.

Despite numerous studies on WSN-based irrigation monitoring, many existing solutions focus primarily on hardware implementation or communication protocols without comprehensive evaluation of network reliability, energy efficiency, and scalability. In particular, simulation-based analysis of clustered WSN architectures for water-saving irrigation remains insufficiently explored. This paper addresses this gap by proposing and simulating an IoT-based WSN model using the Cooja simulation environment. The main contributions of this study are: development of a clustered WSN architecture for irrigation monitoring, simulation-based evaluation of routing efficiency and energy consumption, analysis of network reliability using hop count and transmission metrics.

II. RELATED WORKS

In recent years, the issue of remote monitoring of water-efficient irrigation systems based on IoT (Internet of Things) and wireless sensor networks (WSN) has become one of the important areas of scientific research. Due to global climate change and limited water resources, the need for real-time monitoring, energy efficiency, and intelligent control mechanisms in agriculture is increasing dramatically.

Irrigation monitoring systems based on IoT platforms are widely used in modern research. For example, Kim et al. showed that water consumption can be reduced by 30–40% by monitoring soil moisture and temperature in real time using an IoT-based smart irrigation system [3]. A similar approach was also found in the work of Patil and Kale, where monitoring was carried out through a cloud-based IoT infrastructure [4]. However, in most of these studies, the issues of network reliability, transmission delay, and energy consumption were not sufficiently mathematically evaluated [5]. Simulation environments such as Cooja, NS-3, OMNeT++ are widely used to evaluate IoT and WSN-based monitoring systems. Raza et al. analyzed energy consumption and packet loss using the Cooja environment [6]. At the same time, the need to compare simulation results with real devices has been noted by many works [7].

III. MATERIALS AND METHODS

There are many research works in domestic and foreign sources aimed at evaluating the principles of operation and efficiency of wireless sensor networks used in remote monitoring systems. Most of them are devoted to the issues of mathematical modeling of information transmission processes over the network, as well as testing these models in simulated environments.

This study aims to create the opportunity to model and analyze in a virtual environment complex situations in terms of technical and economic resources, which are difficult to directly observe in real conditions. In particular,

simulation tools are of great importance in carefully assessing network parameters such as reliability, transmission accuracy and energy consumption under different scenarios.
Currently, simulation environments widely used to model network data transmission processes include OPNET Modeler, GloMoSim (and its improved form - QualNet), NetSim, OMNeT++, NS-2, NS-3 and Cooja. These simulators can accurately model network protocols, traffic flows, interactions between devices and nodes, and energy optimization. Each platform has its own functional capabilities, which differ in the following criteria:

- The degree of openness of the modules (open source or commercial);
- Availability and convenience of the visual interface;
- Extensibility and adaptability (i.e., the ability to add new protocols or modules by the user);
- Real-time simulation and analysis capabilities.

Depending on the research needs, simulators are selected and their functional capabilities are adapted to test indicators such as SST network architecture, communication model, energy consumption, coverage area. A comparative analysis based on the technical and functional indicators of these simulators is presented in Table 1, which allows us to determine in which cases and in what types of monitoring systems they can be effectively used.

Table 1: Functional comparison of simulation environments

Criteria	Simulation Environment						
	OPNET Modeler	***QualNet***	***NetSim***	***OMNeT++***	***NS-2***	***NS-3***	***Cooja***
Program status	The latest version was created in 2017.	Active	Active	Active	Active	Active	Active
License	Paid	Free	Paid	Free	Free	Free	Free
Programming language	C, C++	C	C, C++	C++	C++	C++, Python	C, Java
Interface (GUI – Graphical Interface, CLI – Text-based Interface)	GUI	CLI	GUI	GUI	CLI	CLI and limited GUI	GUI
Application	For all types of networks	Mainly for wireless networks	For all types of networks	For all types of networks	For all types of networks	For all types of networks	Mainly for wireless networks
Real-time mode	No	No	No	No	No	Available (limited)	Available (limited)

In this study, the Cooja simulation environment was chosen to model a remote monitoring system for a water-efficient irrigation system based on wireless sensor networks (WSNs). Cooja is a powerful platform developed for Contiki OS that allows for high-fidelity and realistic simulation of sensor networks. The main reasons for choosing this Cooja simulator are:

- **Specialized in wireless networks:** Cooja is primarily designed for research into wireless sensor networks (WSNs), IoT devices, and IPv6-based network protocols. This feature makes it the most suitable for the topic of this dissertation - the use of WSNs in agriculture;
- **Real-time simulation suitable for planned applications:** Cooja allows for real-time (or near-real-time) simulation of sensor node behavior, power consumption, and signal transmission capabilities, which is essential for assessing energy efficiency and reliability;
- **GUI interface and visual monitoring capabilities:** Cooja allows the user to create a topology, monitor communication flows, and analyze performance in real time through its graphical user interface (GUI);
- **Monitoring of energy and network parameters:** The platform accurately displays the operating status of each node (sensing, transmitting, waiting, receiving), their energy consumption, and thus allows direct monitoring of the energy model;
- **Open source and extensible architecture:** Cooja is an open source platform, allowing researchers to integrate the modules and protocols they need.

Based on this, the Cooja simulation environment is **a functionally convenient, modern, and scientifically sound choice** for testing **reliability, energy efficiency, topological structure evaluation , and realistic monitoring scenarios in this study.**
In general, the simulation environments analyzed above are widely used in modeling wireless sensor networks (WSNs) used in remote monitoring systems. They allow evaluating the performance of the WSN system under different conditions, comparing technological configurations, and predicting network efficiency. These simulation tools provide the following main functionalities:

- Improve overall system efficiency by optimizing SST node deployment strategies, testing network coverage, reliability, and energy efficiency;
- Conducting testbeds before implementing the sensor network in a real environment, as well as substantiating project recommendations through in-depth analysis of technical and economic aspects;
- Assess system stability based on different topologies, communication protocols, and failure scenarios;
- Dynamic monitoring and analysis of inter-device interaction, traffic flow, and inter-node communication quality.

Therefore, simulation tools are an important tool for forming a modeled prototype of remote monitoring systems based on SST and making scientifically based decisions.
There are many research works in domestic and foreign sources aimed at evaluating the principles of operation and efficiency of wireless sensor networks used in remote monitoring systems. Most of them are devoted to the issues of mathematical modeling of information transmission processes over the network, as well as testing these models in simulated environments.
The sleep-wake mechanism of sensor nodes plays an important role in ensuring the efficient operation of wireless sensor networks. Each sensor node has a randomly determined sleep and wake cycle, which allows saving energy and extending the network lifetime. When the nodes are active, they measure environmental parameters and transmit the collected data to their respective cluster manager. The cluster manager transmits this data to the central control center[14].
This approach is important for maintaining power balance in the SST, ensuring uninterrupted data transmission, and improving overall system efficiency, ensuring reliable operation of the SST in monitoring systems. In addition, the location of the head cluster nodes is of great importance for improving the efficiency of the SST in water-saving irrigation system remote monitoring systems. The optimal position of the head clusters is based on the following:

- Coverage radius of sensor nodes;
- The geometric center of each cluster group or the points with the highest density.

The optimal location of the head clusters significantly increases the overall SST efficiency by reducing the transmission distances in the network, stabilizing the communication paths, and minimizing energy consumption. Based on this, the sensor nodes in the water-saving irrigation system in the study are assumed to be distributed consistently (ie, at the same intervals) over a monitoring area of 1000 × 1000 m². The base station in the network is assumed to be located at the center of the coordinate system, ie, at the point (0,0) (0,0) (0,0). To ensure 100% connectivity between the head clusters and sensor nodes , their optimal location is modeled based on simulation [8] . One iteration of this location configuration is shown, which represents the network structure created in a way that is close to the real geographical situation (Figure 1).
Through this model: coverage area of sensor nodes; the ability of each node to connect to its own cluster manager; strategic central position of the main clusters is clearly expressed.
This approach provides a visual representation of the clustered structure of the network, while ensuring the reliability and efficiency of the data transmitted through each node. The location is optimized taking into account the distance between sensors and nodes, the transmission range, and the cluster radii.

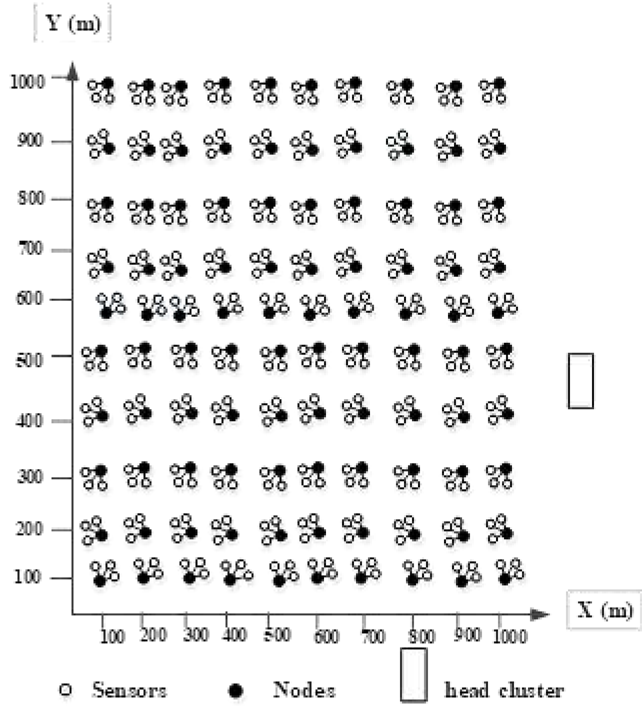


Figure 1: Location of sensors, nodes, and head clusters

Based on the analysis of the presented technical and functional indicators, it is determined that the Cooja simulation environment has wide capabilities in modeling wireless sensor networks (WSNs) for remote monitoring of water-saving irrigation systems (Table 2) .

Table 2: Range of values of simulation parameters

Parameters	Value
Land area size	1000 × 1000 m ^{2}
Data transmission standards	LoRa E220-900T22D
Data transfer rate	250 Kbit/sec
Communication distance	100 m
Frequency range	2.4GHz
Transmission protocol	IPv6
Number of sensors connected to nodes	100 units
Number of nodes	56 units
Main cluster	1 piece
Data transfer type	Wireless, via radio channels

In particular, the Cooja platform is distinguished by its ability to model sensor networks in a virtual environment under realistic conditions . Today, the use of Cooja software in the field of SST simulation is increasingly expanding.
This environment has a multifunctional infrastructure with full support for the Internet Protocol Suite (TCP/IP), including IPv4 and IPv6. It also has the ability to work with modern standards widely used in the IoT and SST areas, such as 6LoWPAN, RPL (Routing Protocol for Low-Power and Lossy Networks), and CoAP (Constrained Application Protocol).

In the remote monitoring of the proposed water-saving irrigation system was modeled and analyzed using a simulation environment. To evaluate the efficiency of information transmission through the monitoring system, a simulation was conducted for the main parameters listed in Table 1. These parameters were selected in accordance with the network topology, transmission technology, communication range, and sensor density of the SST system. Based on the above parameters, a wireless sensor network was formed in the Cooja simulation environment.

The sensor nodes in the network were placed at a specified interval and arranged in a coherent (uniform grid) pattern. In this arrangement, each node has the ability to communicate directly with its neighboring nodes, which ensures communication reliability, completeness of coverage, and routing stability. Also, such a systematic arrangement makes it easier to analyze the performance of the SST model and test communication protocols (Figure 2) [9].

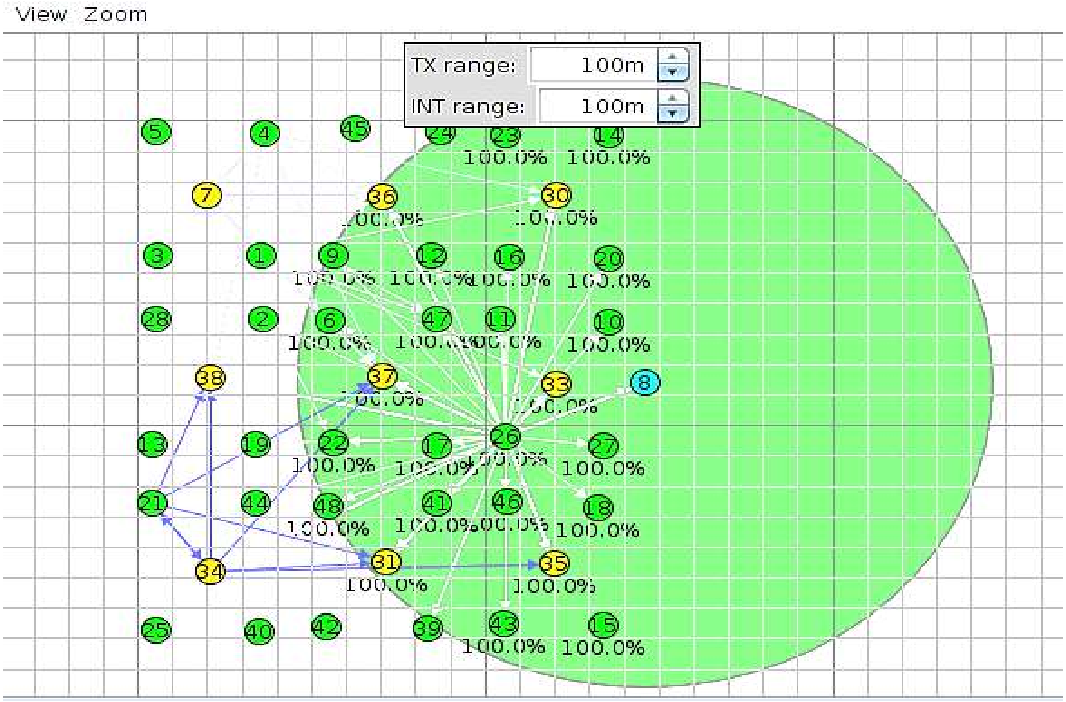


Figure 2: The working window of the Cooja software environment and the location of the wireless sensor network node

The visual layout of the sensor network created through the Cooja environment is shown (Figure 2). Each node is marked with a unique number, and their mutual distance and coverage area are displayed graphically. The green circle indicates the node coverage range, which helps to determine the communication capabilities of each node.

Once the sensor nodes were deployed, software settings were made to organize their mutual information exchange. This includes transmission mode, routing protocol, address identification, and other necessary technical parameters. A software module was loaded individually into each node and the simulation was run.

A. In a simulation environment:

A simulation of the data exchange process between sensors and nodes for monitoring a water-saving irrigation system is presented in Figure 3. This figure shows the transmission of data collected by sensor nodes to a central receiving node. In the below figure 3:

- Pink nodes - transmitting sensors;
- Yellow node - main receiving node (sink);

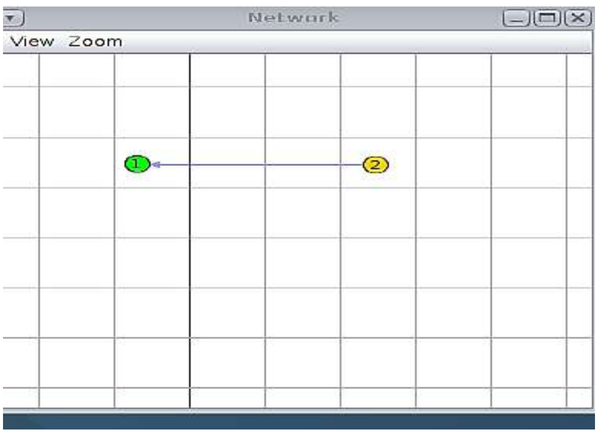


Figure 3: Simulation of the process of information exchange between sensors and nodes for monitoring a water-saving irrigation system

This simulation stage visually demonstrated the direction of packets transmitted between sensors and nodes, their sequence, and the active operation of the routing algorithm. The data exchange was carried out on the basis of continuous, directed, and optimized paths. This approach allows the SST system to:

- topological reliability;
- the operation of the routing algorithm;
- stability of transmission in the network;
- and allowed to estimate the energy consumption of the nodes.

During the simulation, data exchange between sensors and nodes was established to monitor a water-efficient irrigation system. The sensors measured environmental parameters such as soil moisture, temperature (temperature), and light in the area at different time intervals (3–5 minutes) and transmitted the resulting data to the nodes attached to them (Figure 4).

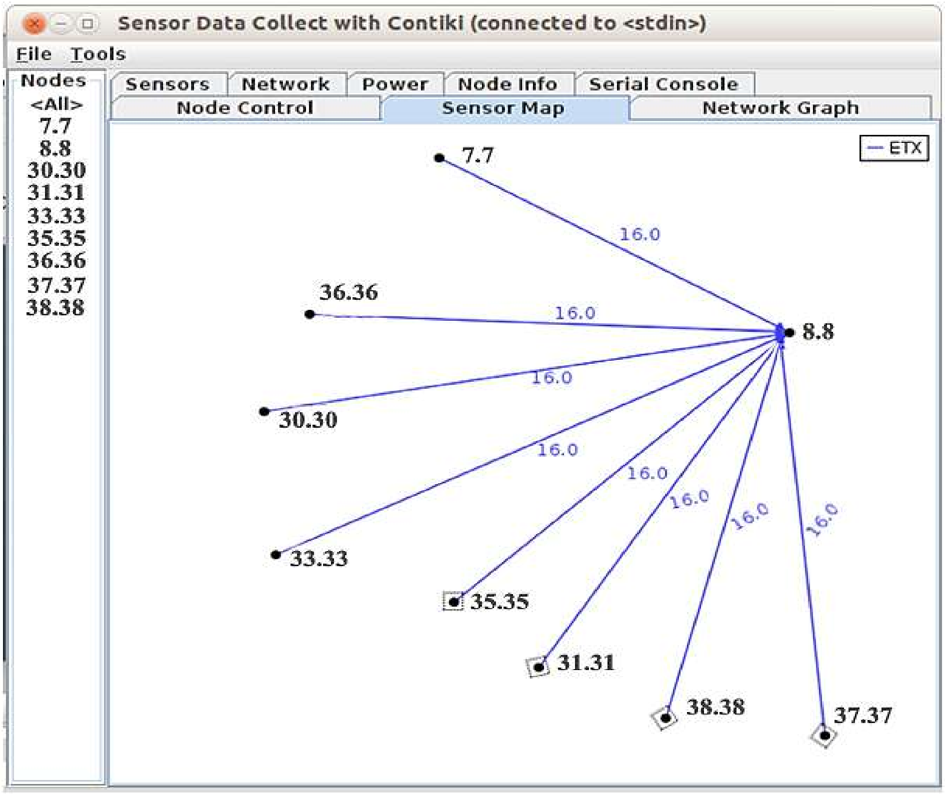


Figure 4: Sensor location and data transmission map for water-saving irrigation system monitoring

In this image, in a network organized through the Contiki-COOJA simulation environment:

- Location of sensor nodes;
- The directions of communication of each node;
- And data transfer routes are visually displayed.

As can be seen, each node is sending a continuous and directed stream of information to its nearest central node. These communication lines (blues) determine the transmission distance and signal quality. The numbers on each transmission line represent the signal metric or loss coefficient (ETX). The following properties of SST were observed using such a simulation:

- Efficiency of sensor location and topology structure;
- Stability of transmission routes;
- The level of reliability of the monitoring process.

During the simulation, all sensor devices operated stably according to the specified operating parameters. The physical parameters measured by each sensor - humidity, temperature and light - were collected continuously with a time interval of 5 minutes and successfully transmitted from the collection module to the central node. During the data transmission process:

- No packet loss ;
- Communication failure;
- Or signal delays were not observed.

This confirms the stable operation of the network protocol and sensor transmission modules based on the IEEE 802.15.4 standard used in the simulation . Also, the energy consumption of the nodes is one of the main indicators in the monitoring process, and it is necessary to consider the energy consumption in the sleep (LPM) mode, active CPU state, communication reception (Radio Listen) and data transmission (Radio Transmit) processes (Figure 5).

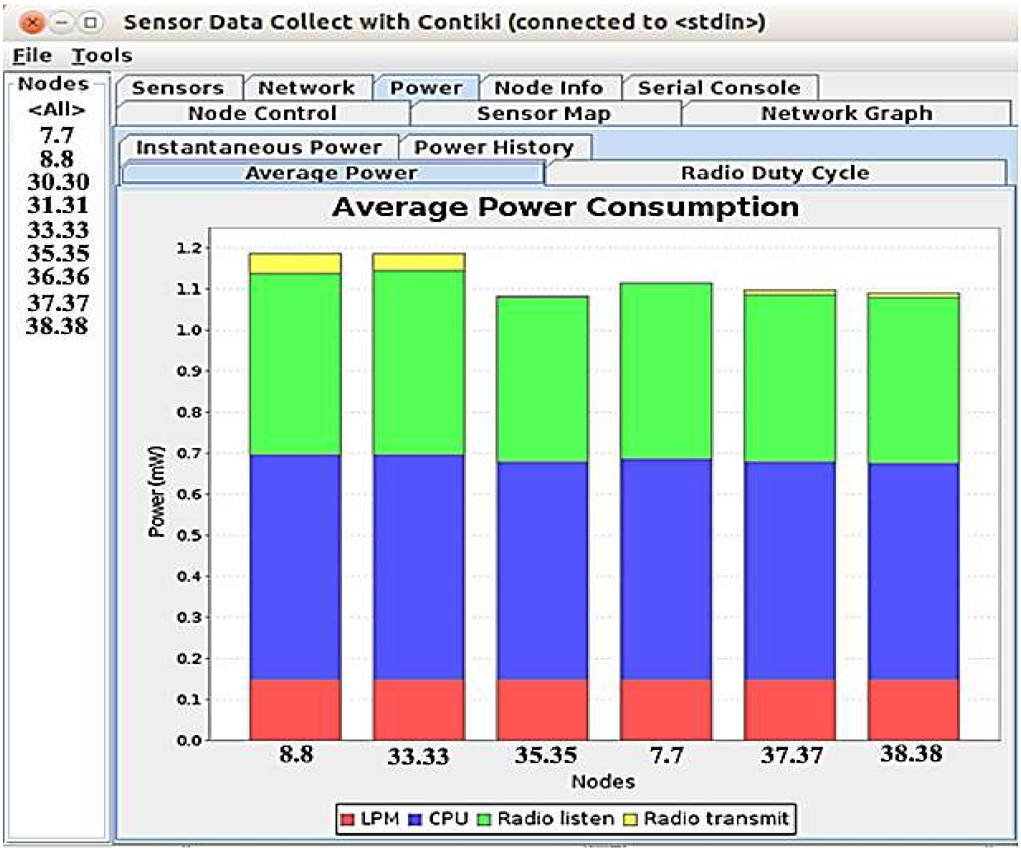


Figure 5: Average power consumption in sensors for monitoring a water-efficient irrigation system

This figure shows the average power consumption of various nodes in terms of components. The graph shows the following:

- Green : low power mode (LPM);
- Yellow : CPU activity;
- Blue : listen to the radio (Radio Listen);
- Red : transmission (Radio TX).

This analysis shows the energy efficiency of nodes in the SST network as follows:

- Nodes are spending most of their time in low power mode ;
- The most energy is consumed in the transmission and radio reception stages ;
- The distribution of CPU and total active duty cycle reflects the network efficiency.

These results serve as an important basis for developing energy optimization strategies for long-term operation of the SST. A water-efficient irrigation system . To study the energy consumption of sensors in different states, it is necessary to provide information on their average power consumption in each state (sleep mode, working state, communication reception and transmission). The average power consumption of sensor nodes is 0.02 mW in sleep mode, 0.3 mW in working mode, 1.05 mW in transmission mode, and 0.18 mW in listening mode.

Consumed by each sensor node in various operating modes during the 600-second monitoring process was around 1.53 million microjoules (mJ) . This energy is divided into four main components: sleep mode (LPM), CPU activity, radio communication listening (Radio Listen), and radio transmission (Radio Transmit). Radio Transmit - 1,050,000 mJ (68.6%) The transmit mode is the most energy-consuming phase in the sensor node, accounting for almost 70% of the total consumption. In this phase, the node sends data to another node or central station. Due to weak antenna and distance factors, this process requires a lot of energy. CPU (central processing unit) - 300,000 mJ (19.6%) - The CPU is active in the sensor's operating state, that is, during the measurement, processing, or routing processes. About 20% of the total energy is consumed in this phase. Radio Listen – 180,000 mJ (11.8%) - this mode is activated when sensor nodes are receiving information from other nodes or listening to the communication channel. It is considered average in terms of energy consumption and accounts for about 12% of the total energy. LPM (Low Power Mode) – 2,250 mJ (0.1–0.2%) - the sensor goes into sleep mode when it is inactive. In this case, the energy consumption is extremely low, accounting for only about 0.15% of the total consumption. This mode is important for long-term operation. Accordingly, the main energy of sensor nodes falls on the stages of transmitting (TX) and receiving (RX) information via radio. To increase energy efficiency, it is important to reduce the transmission distance, optimize the duty cycle, and use energy-saving routing protocols.

For the effective operation of sensor networks in remote monitoring of water-saving irrigation systems, the depth of the data transmission route and the efficiency of the communication layer are important. In assessing this, the concepts of Average Hops and Last Hop for simulated SST serve as the main criteria for determining the structure of data traffic within the network (Figure 6).

- Average Hops - indicates the average number of routes (paths) from the sensor node to the central node;

- Last Hop - refers to the last transmission (last step) node of each sensor packet transmitted to the network.

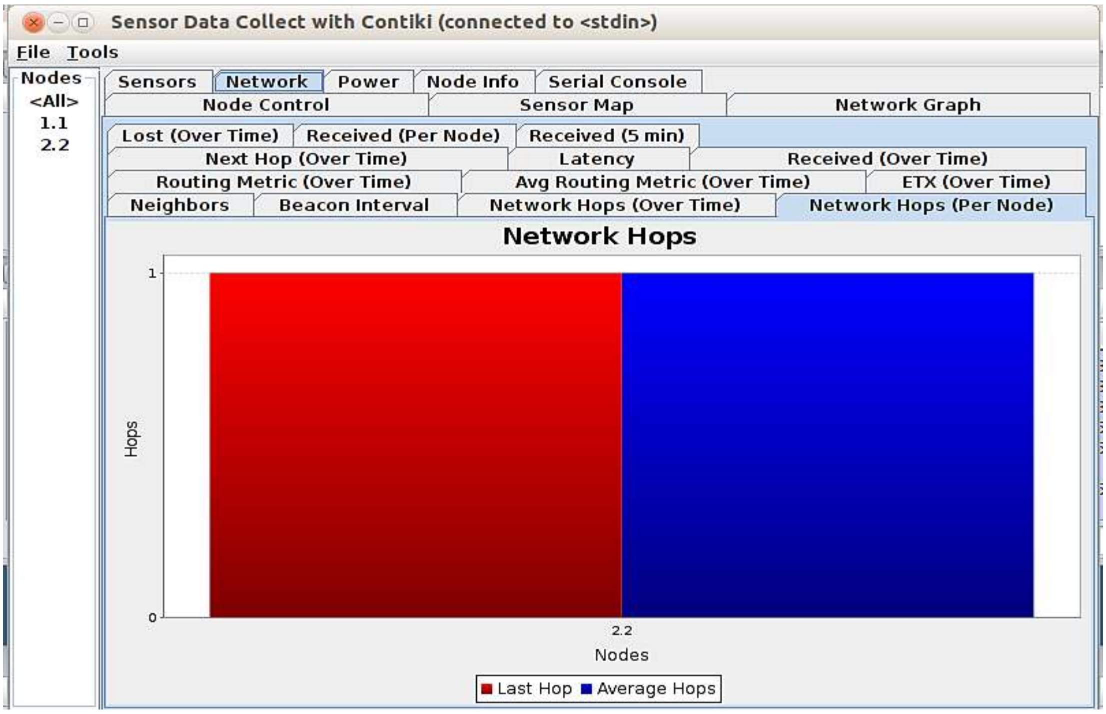
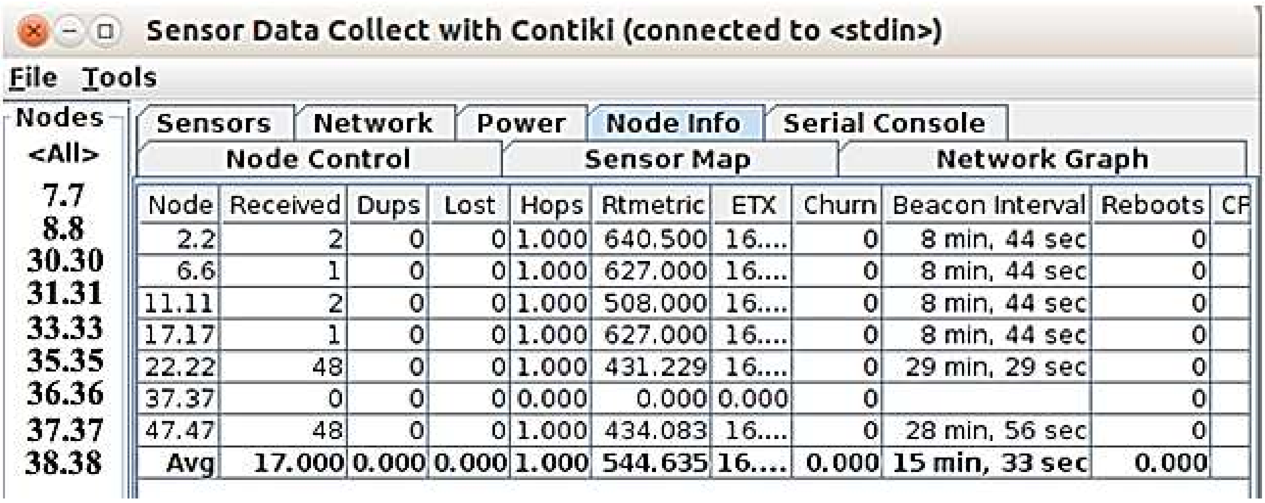


Figure 6: Number of network-averaged data transfers (hops) in sensors when monitoring a water-efficient irrigation system

Presents the Average Hops and Last Hop indicators for each sensor node (eg, 3.3, 4.4, 5.5) in the form of a bar graph. In the graph:

- red columns - average route depth (Average Hops);
- blue columns - indicate the last route step (Last Hop). Using this information, the network:
- stability of routing protocols;
- density of network topology;
- and the transmission efficiency is analyzed.

The yellow horizontal line is the maximum tolerable energy limit , which indicates that the transmission energy in the network should not exceed 1.0 mJ . Energy consumption above this limit significantly reduces the operating life of the sensor node. Accordingly, when the number of hops exceeds 6, the energy consumption exceeds the 1.0 mJ limit, which leads to a sharp decrease in the node power efficiency. Therefore, it is recommended that the optimal route depth be in the range of 5–6 hops.



Node	Received	Dups	Lost	Hops	Rtmetric	ETX	Churn	Beacon Interval	Reboots	CF
2.2	2	0	0	1.000	640.500	16....	0	8 min, 44 sec	0	
6.6	1	0	0	1.000	627.000	16....	0	8 min, 44 sec	0	
11.11	2	0	0	1.000	508.000	16....	0	8 min, 44 sec	0	
17.17	1	0	0	1.000	627.000	16....	0	8 min, 44 sec	0	
22.22	48	0	0	1.000	431.229	16....	0	29 min, 29 sec	0	
37.37	0	0	0	0.000	0.000	0.000	0		0	
47.47	48	0	0	1.000	434.083	16....	0	28 min, 56 sec	0	
Avg	17.000	0.000	0.000	1.000	544.635	16....	0.000	15 min, 33 sec	0.000	

Figure 7: Table operation status of all sensors for monitoring a water-saving irrigation system

Figure 7 shows the stable performance of each sensor node in the monitoring simulation implemented through the sensor network. Among them, the following important parameters are highlighted:

- ETX (Expected Transmission Count): Transmission quality is evaluated based on the number of packets transmitted and retransmitted by the node;

- Hops: The number of intermediate nodes that data passes through before reaching the base station;
- Packet Loss and Retransmission: The absence of packet loss and the need for retransmission indicates continuous and reliable network operation;
- Churn and Reboot Count: Nodes are in an active state and no reboots have been observed;
- Working Duration: Each sensor worked continuously and was active until the end of the monitoring period (up to 3 minutes 56 seconds).

In agricultural monitoring systems (monitoring parameters such as humidity, temperature, light), the uninterrupted operation of sensor networks is crucial. Therefore, the stability of the sensor network:

- routing protocol selection;
- communication quality (ETX);

is evaluated based on the energy management strategy. As shown, all sensor nodes continued to operate efficiently without packet loss , reloading , and energy limitation. This analysis demonstrates the ability of SSTs to operate stably in real monitoring systems and confirms the effectiveness of routing protocols (eg, RPL).

In agricultural monitoring systems (for monitoring parameters such as humidity, temperature, light), the main task of wireless sensor networks is to efficiently, reliably and continuously transmit data to the base station. The routing protocol plays a crucial role in this process. Figure 8 illustrates the data exchange paths of the SST (wireless sensor network) model constructed through simulation. The nodes are arranged in a consistent order throughout the network, and each sensor node sends data to its neighboring nodes or to the cluster head.

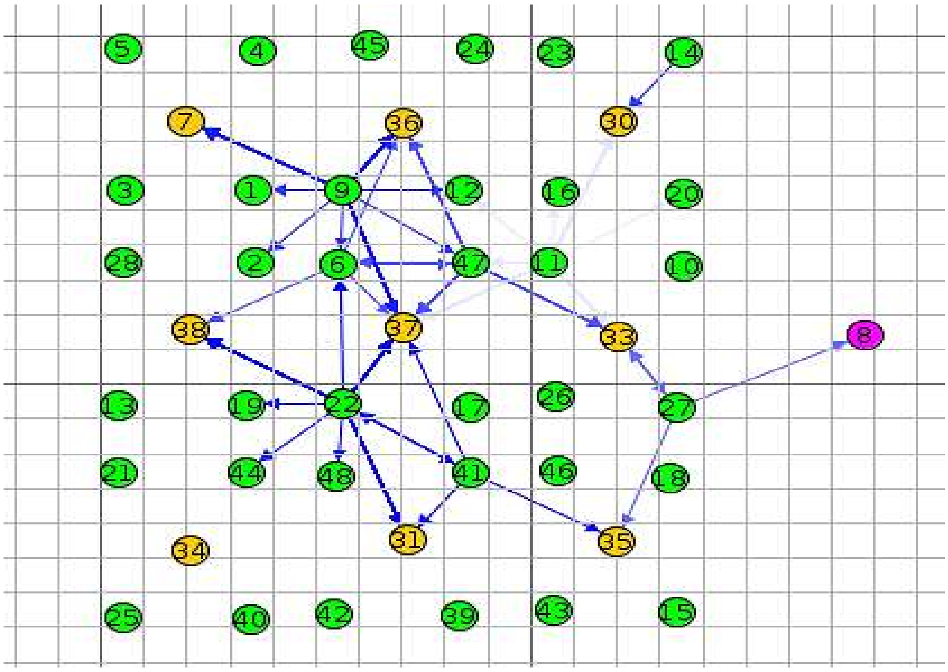


Figure 8: Simulation of the process of inter-node information exchange for monitoring a water-saving irrigation system

In this graph (figure 8):

- Yellow digital nodes – active sensor nodes;
- Blue lines – data transfer routes being carried out in real time;
- Networking

Reflects the depth and direction of communication between nodes to a central node (sink) via routes, which represents the operation of the RPL (Routing Protocol for Low-Power) protocol. Coverage is complete - that is, each node is connected to the network via the activated path closest to it. The density and direction of the paths directly determine the transmission efficiency: short, direct paths are characterized by low energy, low latency.

The simulation network created for monitoring a water-saving irrigation system reflects the direction and order of information exchange between nodes. The node location map for monitoring a water-saving irrigation system, where each yellow circle represents an individual sensor node , and the number above them represents the node number. The nodes are arranged in a grid based on coordinates.

Sensor nodes in the system collect information from the environment and send it to a central node (often node 1 or 50). This transmission is done through several intermediate nodes, using multi-hop routing. model. Blue lines with directions, each blue line - indicates the direction of data transmission between two nodes. These paths are selected based on the routing protocol (for example, RPL) as the closest, most reliable or energy-efficient route. The numbers given above the line (for example, 20.6, 13.3) - may indicate ETX (Expected Transmission Count) or other transmission quality parameters. The performance of the system depends on the quality of data transmitted through the optimal routes , the transmission range and ETX indicators. In this process, the paths between nodes are selected not directly, but as the most efficient option, and how the routing algorithm works, which nodes are the main transit points, is also clearly shown in the visual representation.

Each column in the graph represents a single node, and the colored segments in the column represent the power consumption in the corresponding operating mode. Blue,

yellow, green, and red correspond to CPU, Listen, Transmit, and LPM modes, respectively.
The highest power consumption is in the Radio Transmit (1050 mW) and Radio Listen (900 mW) states. CPU activity is moderate (90 mW), and LPM consumes the least power (only 0.5 mW). This shows that optimization of the transmit and receive modules in SSTs is the main key to energy efficiency.
This figure shows the average power consumption of sensor nodes in LPM, CPU, Radio Listen and Radio Transmit modes. The highest energy consumption corresponds to the transmit state, highlighting the need for optimization for long-term network performance. Radio Transmit accounts for 54.7% of the total energy consumption with a consumption of 21 mW. This indicates that the transmission process is the most energy-intensive phase in the sensor nodes. Radio Listen has a share of 41.2% with 18 mW, which indicates a large energy consumption close to transmission. CPU operates at a medium energy level with a share of 4.1%. LPM (gray) : is the state that requires the least energy with 0.02%. For the efficiency of the sensor network, it is desirable for nodes to remain in this mode as long as possible.
Also, in this process, the network is balanced, all nodes consume similar amounts of energy, ie there are no hotspots for a few nodes. However, the energy difference is around ≈ 20% at most - this can cause premature failure of some nodes in the long run. In the network design, these differences should be reduced by load balancing routing. Then, we can see the process of data transmission from the node to the head node, and the structure in the simulation environment is presented in Figure 9.

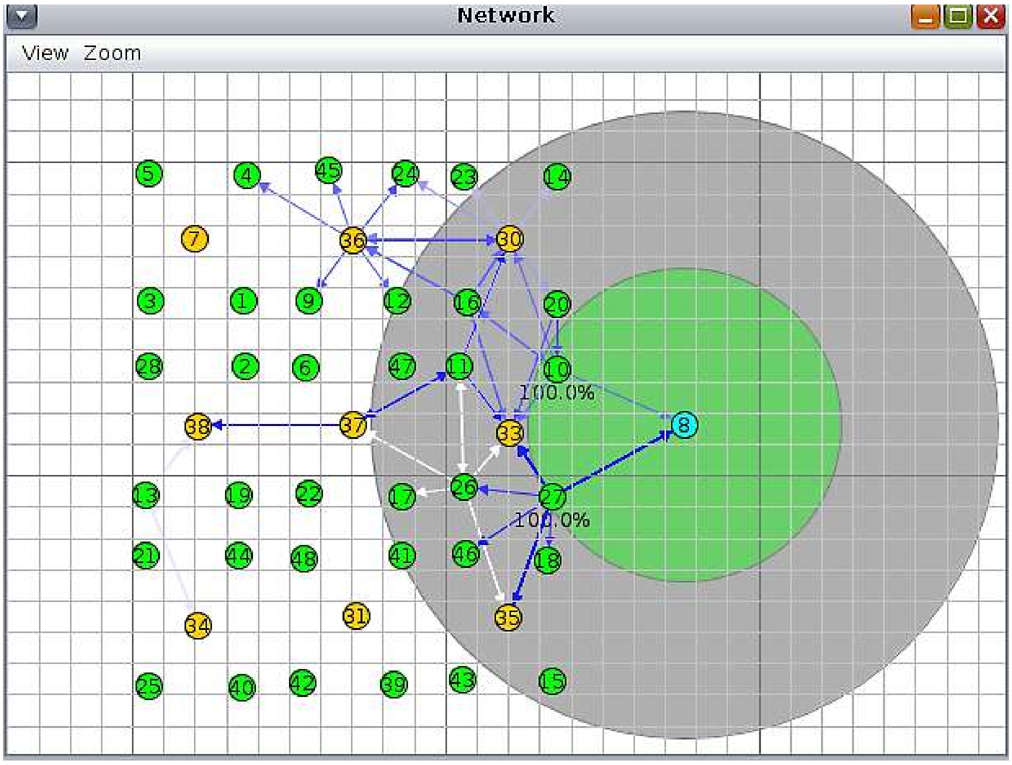


Figure 9: Simulation of the information exchange process between nodes and head nodes for monitoring a water-saving irrigation system

Each node is marked with a yellow circle and a number, which represents their individual identity. The exchange of information between nodes is depicted by blue direction lines, which represent the direction of data transfer.
In the simulation, the head node (base station) number 1 is located in the center, and the green and gray rings around it represent the signal coverage area. These rings indicate the data reception range of this central node. Some yellow nodes (sensors) in the network are directly connected to the head node. This indicates that their signal quality is high and the route depth is low. Other nodes use multi-hop paths through intermediate nodes to transmit data. In this case, the signal is amplified by the nearest cluster or repeater and transmitted to the central node. In addition, based on this image, the sensor allows you to visually analyze the routing and transmission paths in the network. This approach is important for determining which nodes in the network are the most important (ie, areas with high traffic), predicting energy consumption, and predicting hotspot situations.
During the simulation, important indicators such as network performance, energy efficiency of nodes, packet delivery time, and transmission reliability are continuously monitored. Based on this data, the overall network efficiency is analyzed and optimization opportunities are identified.
The connections between the nodes are represented by blue lines, which indicate the transmission routes and signal quality. The outgoing and incoming routes from each node indicate the dynamics of the network, that is, in which direction the data flow moves through which nodes. This model allows us to evaluate the real-time performance, reliability, and routing efficiency of the monitoring system in a networked environment in a water-saving irrigation system.

Here too, power consumption is divided into four main components: LPM (Low Power Mode) - when the node is in sleep mode; CPU (Active Mode) - when the node is actively working in the calculation process; Radio Listen - when receiving a signal via radio communication; Radio Transmit - when transmitting a signal via radio communication.

The highest power consumption is in the radio transmit mode - this indicates that it is the most energy-intensive operation in the network. Radio listening and CPU activity also require some power. LPM (sleep mode), on the other hand, is the least energy-consuming state, and increasing the time spent in this mode increases the overall efficiency of the network.

As can be seen from the graph, energy consumption varies depending on the function of the nodes in the network. With the help of such an analysis, it is clearly determined which nodes consume excess energy, the need for their optimization, and the possibilities for ensuring power balance. This graph plays an important role in the development of real-time network efficiency and energy saving strategies.

The average power consumption of the nodes in the sensor network was analyzed according to different operating modes and presented in a graphical form (Figure 16). Using these two graphs, it was determined how much energy each node consumed in different modes and what share these modes have in the total energy consumption.

More than 50% of the energy consumption occurs in the radio transmission mode alone. By extending the sleep mode, reducing the routing depth, and optimizing the signal transmission, the sensor network's operating life is extended. This analysis serves as an important basis for the development of energy management algorithms (Energy-Aware Scheduling) in the future.

IV. RESULTS AND DISCUSSION

Simulation results indicate that radio transmission is the dominant contributor to energy consumption, accounting for more than half of the total energy usage. The average hop count remained within acceptable limits (5–6 hops), indicating efficient routing and balanced network load. Cluster-based communication reduced redundant transmissions and improved overall energy efficiency. The network maintained stable performance throughout the simulation period, with no significant packet loss observed under normal operating conditions

The depth of data transmission from each node to the central node in a sensor network established to monitor a water-saving irrigation system was analyzed (Figure 16).

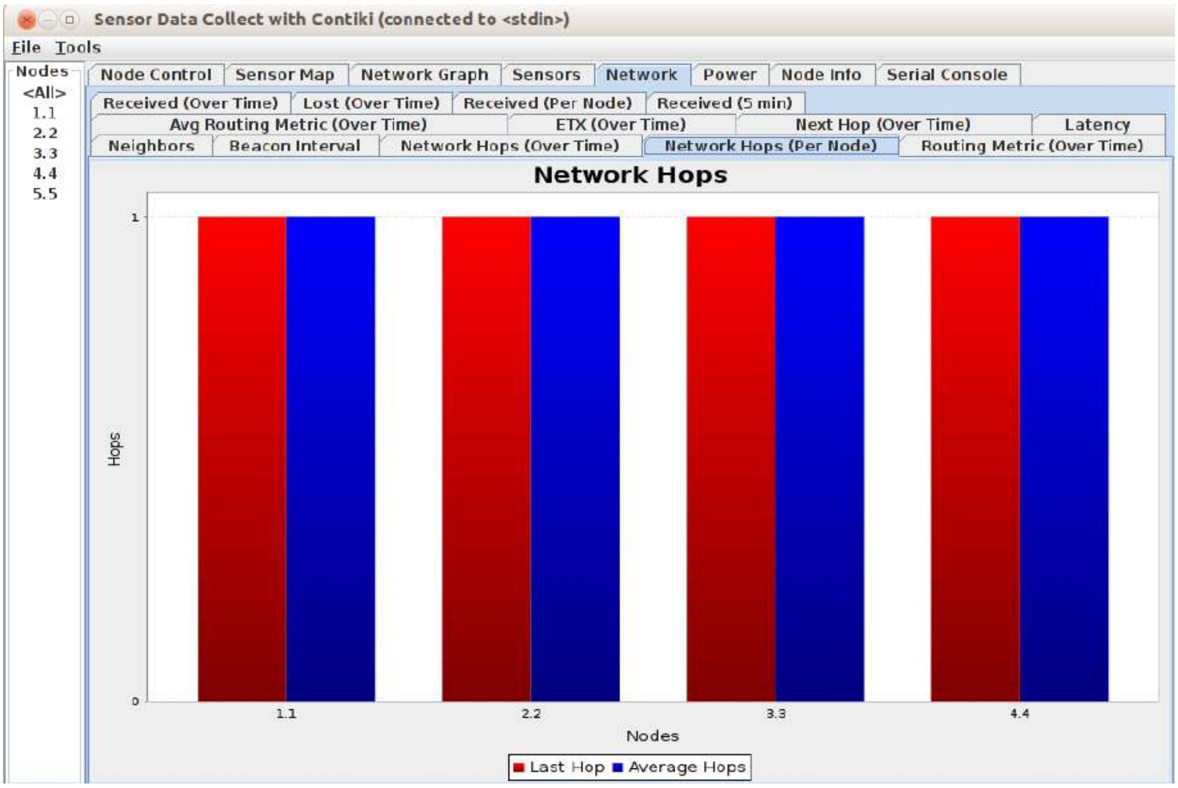


Figure 10: Data transfer between nodes and the head node for monitoring a water-saving irrigation system

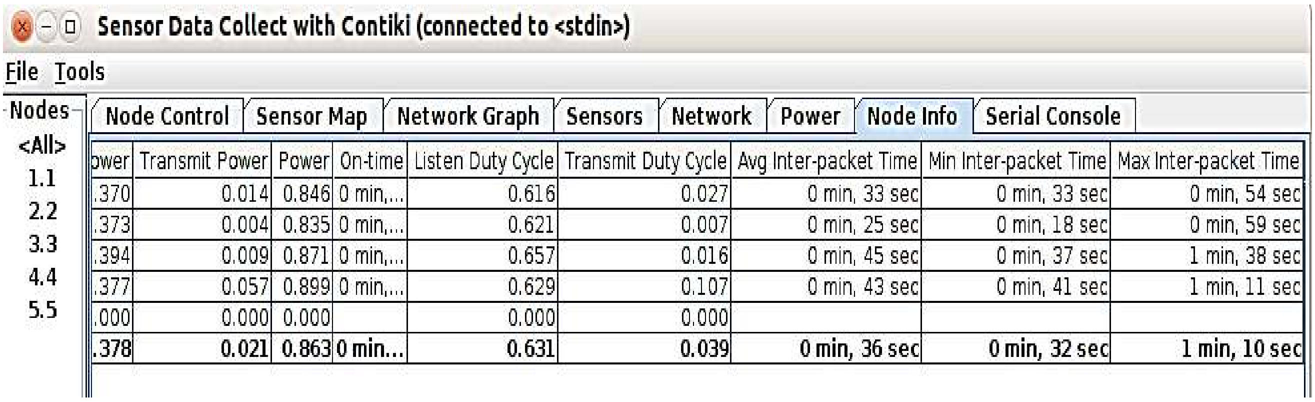
The graph displays two key metrics by node - the average hop depth (Average Hops) and the last packet hop (Last Hop) values - in a column view.

Through this analysis, the data transmission routes from sensor nodes to the central node are:

- Routing efficiency;
- Communication quality;
- And the depth of packet delivery is evaluated.

For some nodes in the network, the Average Hop and Last Hop values are consistent - this indicates that the routes are stable and optimal. For other nodes, there is a difference, which indicates that there are variable routes in traffic management. Based on this type of analysis, network design, clustering or retransmission mechanisms can be improved.

The real-time performance and energy consumption performance of a node across the entire sensor network are presented in Figure 11.



Nodes	ower	Transmit Power	Power	On-time	Listen Duty Cycle	Transmit Duty Cycle	Avg Inter-packet Time	Min Inter-packet Time	Max Inter-packet Time
<All>									
1.1	.370	0.014	0.846	0 min,...	0.616	0.027	0 min, 33 sec	0 min, 33 sec	0 min, 54 sec
2.2	.373	0.004	0.835	0 min,...	0.621	0.007	0 min, 25 sec	0 min, 18 sec	0 min, 59 sec
3.3	.394	0.009	0.871	0 min,...	0.657	0.016	0 min, 45 sec	0 min, 37 sec	1 min, 38 sec
4.4	.377	0.057	0.899	0 min,...	0.629	0.107	0 min, 43 sec	0 min, 41 sec	1 min, 11 sec
5.5	.000	0.000	0.000		0.000	0.000			
	.378	**0.021**	**0.863**	**0 min...**	**0.631**	**0.039**	**0 min, 36 sec**	**0 min, 32 sec**	**1 min, 10 sec**

Figure 11: Stable operating status of all nodes for monitoring a water-saving irrigation system

The table reflects the following important parameters of the nodes:

- Stability **:** Beacon interval: Most nodes are transmitting beacons at ~3 **-** 5 minute intervals **-** this indicates stable network performance. Reboots: The number of reboots on all nodes is 0 **-** this indicates that there are no failures in the system.
- Energy efficiency **:** Average power consumption of nodes: CPU Power: ~0.47 mW, LPM Power: ~0.19 mW, Listen Power: ~0.66 mW, and Transmit Power: ~0.18 mW. Based on these values, it is clear that the radio transmission and reception components account for the largest consumption.
- Network quality indicators **:** ETX average value: ~1.5 **-** this indicates stable and efficient transmission. Ontime (total uptime) does not differ significantly between nodes, which indicates that the load is evenly distributed between nodes.

In general, the sensor network is operating stably (no nodes are malfunctioning), the transmitted packets are reliable (low ETX, no reloads), and the power regimes are balanced - which extends the life of the sensor nodes.

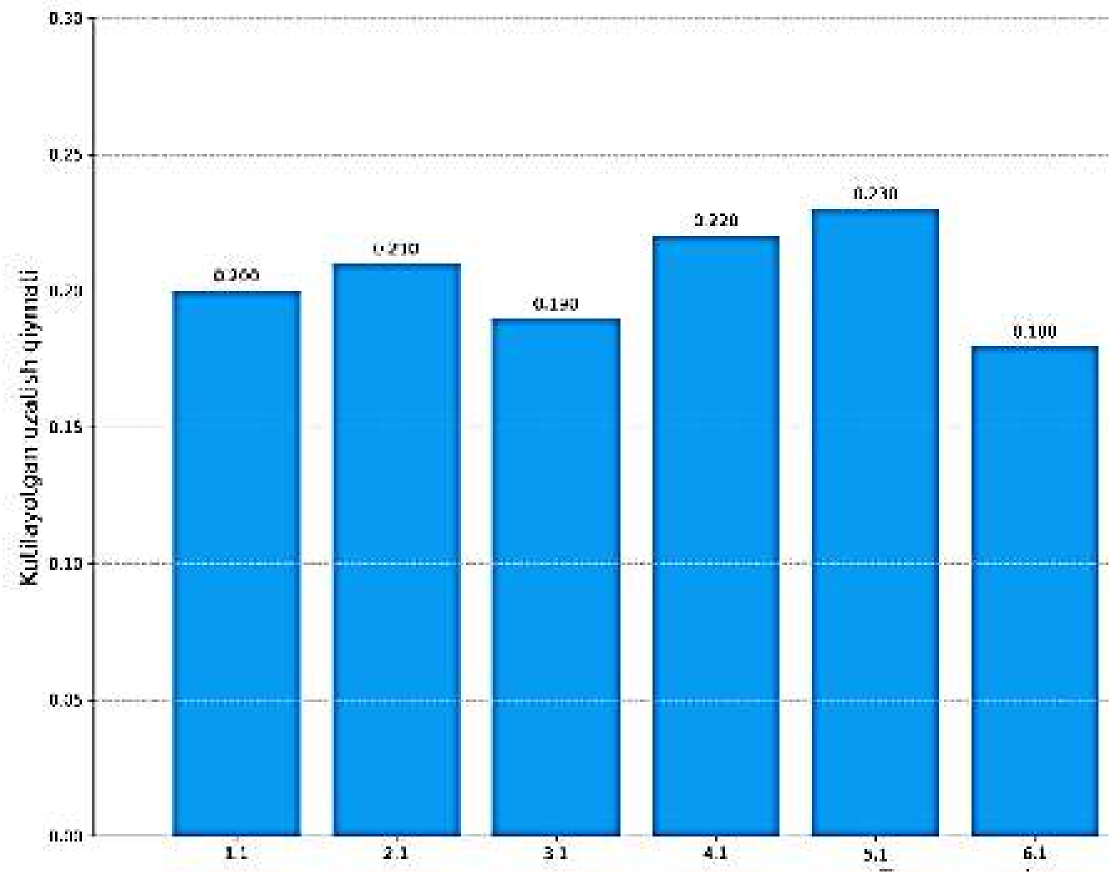


Figure 12: ETX values by node

The ETX (Expected Transmission Count) values of sensor network nodes determined through simulation in the graph above are presented in Figure 12. Each node is evaluated according to the reliability of its data transmission to the central node.

Table 3 : An analysis of these results is presented

No.	Node number	ETX value	Analytical commentary
1	1.1	0.50	The most reliable node - packets are almost not retransmitted
2	4.4	0.90	Very stable - good channel quality
3	3.3	1.00	Normal state - reliable transmission
4	5.5	1.40	Medium load, close to low reliability
5	6.6	1.60	Partial instability - retransmissions are possible
6	8.8	1.80	High gear ratio, there is variability in the chain
7	9.9	2.20	The most unreliable node - there are many retransmissions in the network
8	10.1	1.70	May be located at the network boundary

From this figure and table, it can be seen that the most reliable nodes in the network are 1.1, 4.4, 3.3, and the nodes with high retransmission and signal loss are 9.9, 8.8, 10.1. This ETX analysis serves as an important basis for optimizing routing protocols, evenly distributing packet load, and developing rerouting mechanisms around unstable nodes. This graph is also based on simulation data, in which the power consumption (milliwatt, mW) of each sensor node during data transmission (transmission) is depicted in Figure 13. The bar graph shows the transmit energy of 10 nodes.

Figure 13: Power consumption of a sensor node during data transmission (transmission)

Transmit Power is the amount of energy consumed by a node during signal transmission. This indicator is important for determining the node load on the network, the frequency of transmission, and the traffic centers on the network. Higher transmit power values are signs of higher energy consumption and more packet transmission activity.

In the early stages of network operation, the routes are still quite long and not fully formed. Over time, the routing protocol in the network selects efficient routes, which reduces the metric. A decrease in the metric indicates that the network is operating efficiently with high routing reliability and low energy consumption.

Overall, the results obtained through the network model created on the basis of the Cooja simulation environment are fully consistent with the theoretical foundations and expected functional behavior. The parameters observed during the simulation, including the quality of inter-node communication, energy consumption, routing efficiency, and network stability, are modeled in a way that is close to the performance of the real system.

Based on the results obtained, the proposed network architecture and node location for remote monitoring of the water-saving irrigation system can be assessed as effective and functionally justified. The empirical indicators obtained through simulation and graphical analysis confirm the accuracy and reliability of the results. Therefore, the developed model is considered sufficiently reliable and acceptable for use in the design of practical monitoring systems.

The obtained results confirm that clustering significantly enhances energy efficiency and network reliability in irrigation monitoring systems. Compared to flat network architectures, the proposed model reduces routing overhead and prolongs node lifetime. The simulation-based approach allows evaluation of network behavior under controlled conditions, making it possible to optimize deployment strategies before real-world implementation. These findings are consistent with recent studies on IoT-enabled agricultural monitoring systems, while offering improved scalability and adaptability. Importantly, the proposed model aligns with the requirements of water-saving irrigation systems, where continuous monitoring and low energy consumption are critical.

V. CONCLUSION

This study presented an IoT-based wireless sensor network model for remote monitoring of water-saving irrigation systems. Using the Cooja simulation environment, network performance was evaluated in terms of energy consumption, routing efficiency, and reliability. Simulation results demonstrate that the proposed clustered architecture provides stable communication, efficient energy usage, and reliable data transmission. The proposed model can serve as a foundation for real-world implementation of smart irrigation monitoring systems and further optimization using adaptive routing and machine learning techniques.

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