Preprints are preliminary reports that have not undergone peer review. They should not be considered conclusive, used to inform clinical practice, or referenced by the media as validated information.

Distributed Region-Based Monitoring in Low-Power Listening Wireless Sensor Networks

Krita Pattamasiriwat
Kasetsart University
Chaiporn Jaikaeo (chaiporn.j@ku.ac.th)
Kasetsart University https://orcid.org/0000-0002-6400-1323

Research

Keywords: wireless sensor networks, network monitoring, distributed monitoring, region-based monitoring

Posted Date: September 8th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-65351/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

RESEARCH

Distributed Region-Based Monitoring in Low-Power Listening Wireless Sensor Networks

Krita Pattamasiriwat and Chaiporn Jaikaeo*

*Correspondence: chaiporn.j@ku.ac.th
Department of Computer Engineering, Faculty of Engineering, Kasetsart University, 50 Ngamwongwan Rd., Ladyao, Jatujak, 10900 Bangkok, Thailand
Full list of author information is available at the end of the article

Abstract

Advancement in IoT technology and the concept of Information-Centric Networking lead to less importance of node individuality since several nodes can work interchangeably. Multiple sensor nodes can be grouped into a *region* and monitored as one instance to guarantee sufficient coverage over the region. Therefore, a single node fault often does not need to be reported unless it is the last node in the region. In addition, there are occasions where a central monitor station cannot rely on continuous data delivery from nodes or regions to decide whether they are still alive, such as situations when nodes are deployed to detect rare events. Moreover, low-power listening MAC protocols, which significantly help reducing power consumption while nodes are mostly idle, put a lot more work on the transmission process. In such situations it is desirable to minimize status reports to the central monitor station. A distributed region-based monitoring scheme, or *DRMON*, is then proposed to facilitate this circumstance. This approach designates a representative to each region so that it can be used as an indicator of the region's status with a mechanism to re-elect a new representative until all nodes in the respective region are dead, implying region inactiveness. We evaluate the suitability of DRMON over various scenarios in two aspects: centralized vs. distributed monitoring schemes and individual-based vs. region-based monitoring schemes. Simulation results indicate that region-based schemes outperform the individual schemes in terms of power consumption and scalability when the number of regions is low. The distributed schemes also yield better efficiency in terms of message overhead and load distribution. In addition, detection accuracy of all schemes is not significantly different and fault detection delay is guaranteed. This outcome suggests that in the case where existence of individual node is out of concern, distributed region-based fault monitoring scheme could be employed to reduce energy usage and lower message overhead while retaining the detection accuracy.

Keywords: wireless sensor networks; network monitoring; distributed monitoring; region-based monitoring

Introduction

Wireless sensor networks (WSNs) consist of small-size, low-cost, low-power, multi-functional sensor nodes that collaborate with each other [1] to serve a variety of purposes. WSNs have recently been incorporated into the Internet of Things (IoT) to facilitate data acquisition and wireless communication. To guarantee the functionality of networks, nodes and communication links must be maintained in good condition. Therefore, network monitoring becomes a crucial part of the system, especially for safety-critical applications. Traditional monitoring methods such as human inspection or wired network monitoring protocols are not preferable or even applicable. Therefore, several monitoring and fault diagnosis mechanisms specifically designed for WSNs have been proposed to address this

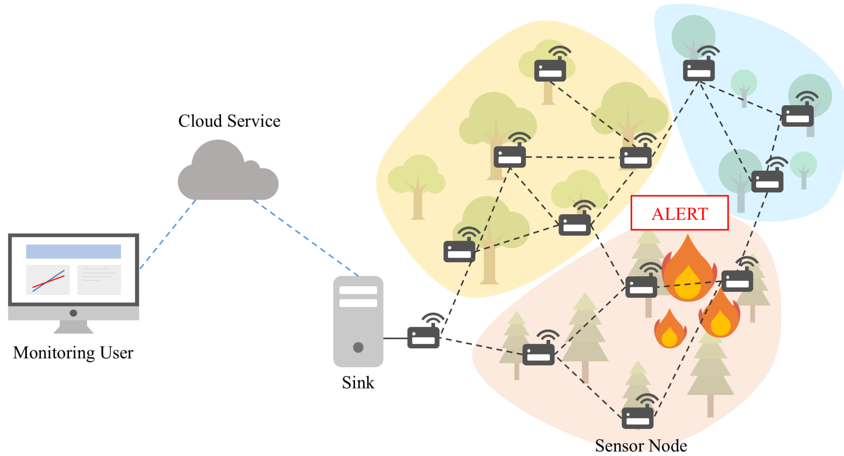


Figure 1: Forest fire detection scenario

problem. Network monitoring techniques can be classified into *centralized* and *distributed* approaches, depending on the location where the status of the nodes and links is determined. Advances in IoT technology is facilitating the large-scale deployment of WSNs. The concept of Information-Centric Networking (ICN) [2] has been widely adopted in this area. In this scenario, node individuality is irrelevant as several nodes are eligible to work interchangeably. Identical observations may be collected and reported by more than one node. As a result, the network is still able to operate correctly even if some nodes malfunction, thereby lowering repair cost. For example, in forest fire detection application, the monitored area is populated with sensor nodes that are randomly deployed using an aircraft. The coverage areas of nearby nodes likely overlap, as shown in Figure 1. The network then requires only one or a few nodes in the same region to detect an event. To minimize the cost of maintenance, the network administrator should be notified when all of the sensor nodes in a region are damaged or separated from the network.

Motivated by the concept of ICN, nodes could be grouped and monitored as one instance to guarantee the availability of specific content. To the best of our knowledge, existing monitoring approaches primarily focus on monitoring the individual node or link status. Although the awareness of the status of all nodes can be further processed to estimate the risk of network failure, redundant monitoring information is unnecessarily produced, resulting in the wasting of the nodes' energy and communication bandwidth. Moreover, modern WSN transceivers such as LoRa [3] rely on low-power listening mechanisms. Therefore, unnecessary transmissions are even more costly. Our proposed approach, the distributed region-based monitoring scheme (DRMON), monitors the network status in terms of *regions*, each of which is a predefined group of adjacent nodes. This scheme provides a framework for monitoring status of WSN used for rare event detection or non-continuous data collection, where periodic sensor reports are not always assured. The main objective of this method is to increase energy efficiency by reducing the traffic overhead generated in the monitoring process while maintaining effectiveness in both detection accuracy and latency aspects. This scheme can effectively support individual node monitoring by configuring each region to contain only one node if necessary.

To evaluate the efficacy of the DRMON scheme, four types of generic monitoring approaches, i.e., centralized individual scheme (CIMON), distributed individual scheme (DIMON), centralized region-based scheme (CRMON), and distributed region-based scheme (DRMON) were implemented. The evaluation was conducted using the Cooja simulator in the Contiki operating system [4].

Here we review previous work related on fault monitoring of wireless sensor networks.

Network Fault Monitoring

Faults in WSNs can be classified into *data faults* and *function faults* [5]. A data fault is a sensor data report that is inconsistent with the actual behavior of the phenomenon of interest [6]. Several fault detection schemes have been proposed to address this problem [7] [8]. Nevertheless, this type of faults is beyond the scope of this investigation. Function faults are defined as network operation abnormalities, such as node crashes, node energy depletion, link failures, and traffic congestion.

Data retrieval techniques used for network monitoring can be generally categorized into two categories: *active* and *passive*. Active monitoring [9] [10] results in the generation of extra probing packets or event report, in addition to the application of data traffic in the network. This method provides detailed information but usually results in high operation overhead if the probing frequency and monitoring parameters are not carefully selected.

Passive monitoring [11] relies on the utilization of existing information or piggybacking of data to infer fault occurrences without generating extra packets. This technique seems to be preferable because it has a minimal effect on network performance. However, in some cases such as non-periodic event-driven data applications, existing information or data traffic might be insufficient for the effective analysis of network status.

Network monitoring techniques could also be classified based on the location where the diagnosis process is performed. The traditional method where the node's status information is delivered to a powerful sink node for diagnosis is described as *centralized monitoring*. This method gives the complete status of the network and high accuracy rate but suffers from packet collisions and the energy sink-hole problem as the number of nodes in the network increases [12] [9] [11].

In large-scale networks, centralized approaches may encounter several problems, such as detection delay, packet loss, and the energy sink-hole problem. To achieve better energy efficiency and scalability, *distributed monitoring* techniques have been investigated [13] [10] [14] [15]. Using this scheme, any node in the network may assume the responsibility of monitoring and could implement countermeasures or report the status to the sink. Based on this concept, information is not relayed to the sink from the sensor nodes during normal operation and a report is made only when an anomaly is detected.

In addition, several investigations have been pursued that focus on the observation of the condition of communication links [16] [17]. However, all these schemes mainly focus on the monitoring of individual nodes. With the recent trend of ICN, individual nodes might be less relevant. To the best of our knowledge, an approach specifically designed to monitor an information-centric network has not been developed as yet.

Region-based Monitoring Technique

Conceptually, a region or a cluster is simply a set of nodes located in the same neighborhood to collectively perform specific tasks such as environmental observation, routing, and data aggregation. Regions can be dynamically formed using existing clustering methods such as *LEACH* [18] or *CHEF* [19]. Region members may also be predefined by an operator based on geographical location so that nodes in the same region can perform tasks on behalf of others.

In this case, we do not need to know the status of each individual node, but for each region instead. To the best of our knowledge, a monitoring scheme that monitors network status as predefined regions has not been proposed in the literature. The concept of regions may have been formerly used to describe the report generated by *eScan* [12], which is the integrated data of adjacent nodes that produce similar reported values. Nevertheless, the membership of nodes is not preserved in this method, which differs from the definition of the region in our scenario.

Impact of Low-Power Listening MAC Protocols on Network Monitoring

Low-Power Listening (LPL) is a well-known technique used for scheduling the wake-up periods of nodes. Nodes that adopt LPL periodically wake up to sample the medium and remain in an active state if there are available packets, otherwise they return to sleep mode until the next scheduled wake-up time. The power consumption rate of the network using LPL mechanism is thus drastically lower.

X-MAC [20] is an LPL-based MAC protocol that uses a series of short strobe packets with an embedded receiver ID to alleviate the overhearing problem and to increase scalability because non-target nodes return to the sleep mode as soon as they determine that there are no available packets for them. The communication duration is also decreased due to the gap between preamble packets, which allows the recipient to send an early acknowledgment packet back to the sender and to initiate data transmission. This protocol is widely adopted in WSN applications because it works efficiently in terms of reducing energy usage and has no limitations in terms of radio hardware choice. The procedure involved in data transmission using the X-MAC protocol is depicted in Figure 2. Unicast transmission is performed when the sender transmits probing packets until an acknowledgment is received from the intended receiver. The maximum duration of the packet repetition is the full wake-up interval, which guarantees packet reception of the receiver. In the case of broadcast transmission, the acknowledgment mechanism is not presented, thus, the sender must send the packet continuously throughout the full wake-up interval.

As LPL can inflict substantial energy consumption on transmitting nodes due to the use of multiple transmissions per packet, and also on overhearing nodes by waking them up, it is suitable for scenarios in which nodes rarely transmit, such as detecting rare events. Typical network monitoring requires nodes to report their status periodically, which worsens the performance of LPL, especially for nodes located around the central monitoring station in a centralized monitoring scheme. The evaluation of LPL-based MAC protocols on the performance of network monitoring was discussed in [21]. However, only individual-based monitoring schemes were evaluated in this previous work. In this paper, region-based monitoring approaches are also investigated.

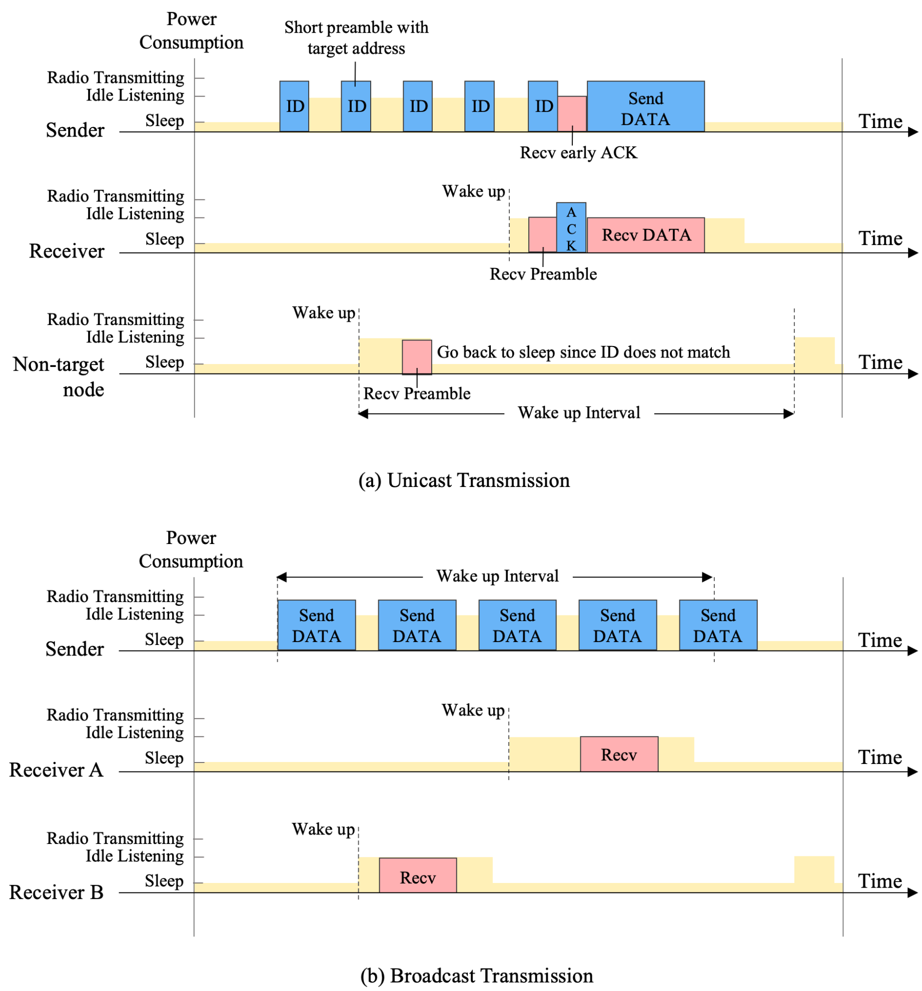


Figure 2: Duty-cycling mechanism of X-MAC protocol

Methods/Experimental

Our proposed monitoring mechanism, distributed region-based monitoring scheme (DR-MON), is a framework that could be flexibly configured to monitor individual nodes by considering each region to contain only one node. We assume that nodes are distributed in a 2-dimensional area without obstacles. All nodes have limited power resource and are not rechargeable, thus, radio duty cycle protocols could be utilized to prolong the network lifetime. There is exactly one powerful sink node located at the border of the network that can be easily accessed by the operator. Each node can communicate with the sink directly or indirectly via multi-hop communication.

A *region* is a group of adjacent nodes that can work interchangeably. It can be predefined by the operator or automatically arranged based on specific criteria. Faulty nodes in a region might result in lower performance but the region is still able to continue its operation if there is at least one functional node. A region is considered faulty if all its nodes fail or if there is no available path to the sink. Each sensor node must be aware of its region ID, which might be derived from a region information message propagated from the sink or a region map containing coordinate information.

Based on the definition of a region, only one node per region is required to be monitored at a time. These nodes are called region representatives, or *region reps* for short. To achieve energy efficiency and scalability, region reps are monitored by their one-hop neighbors. At the sink, the status of each region reported to the operator is assumed to be normal unless there is a fault notification from the monitoring nodes.

The DRMON mechanism consists of two phases, region representative election, and monitoring process. Each node participating in a region representative election generates *chance* based on related information readily available, such as hops to sink, remaining energy, and link quality, then broadcasts its chance to all nodes in the same region. The node with the highest chance is appointed as the region rep and its parent derived from the existing routing scheme will automatically become the monitoring node. In case the routing scheme has assigned multiple parents to a node, any one of the parents will be selected.

After region reps have been selected, the monitoring process begins. We use a simple monitoring method based on heartbeat messages. A region rep periodically broadcasts heartbeat messages embedded with its region ID every T_{hb} seconds to inform its monitoring node on the region status. The absence of heartbeat messages can be interpreted as a region failure. The monitoring node then notifies the sink of the region fault status. Monitoring timeout, T_{mon}, can be adjusted and needs to be carefully selected to balance the detection time and false alarm rate.

However, from the region fault definition, the death of a single node in a region does not always imply region failure. A mechanism to maintain the region-monitoring structure is required if it is possible. The substitute region's representative should be reelected within an appropriate time to reduce false alarm. To achieve this goal, the rest of neighbors of the region rep, except the monitoring node, assume the role of the *observers*. It's not necessary for observers to be in the same region as the region rep. An observer monitors heartbeat messages from a region rep and triggers a region representative election process by broadcasting a reelect message in the absence of heartbeats instead of reporting to the sink. When nodes in that particular region receive a reelect message, each of them will generate a new chance message and repeat all the election procedure. The parent node of the new region rep, derived from the existing routing information, will also become the next monitoring node for that region. The timeout of observer nodes, T_{obs}, should be shorter than T_{mon} to prevent false alarms at the sink since the report of absent previous representative node will be discarded.

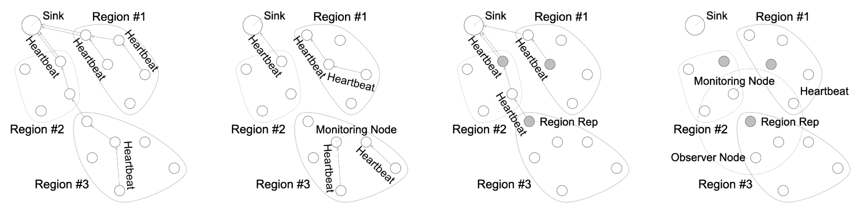
Finally, this monitoring framework reports two possibilities of region status, R_t, region *active* and *inactive* at time t, to the operator. The sink initially assumes that all regions are active until it receives region inactive reports from monitoring nodes and vice versa. However, region inactive reports are discarded once a new region active report is received for the same region.

To evaluate the performance of DRMON, four types of monitoring schemes that adopt different techniques for monitoring approaches and instances were implemented. Monitoring approaches are classified into centralized and distributed and monitoring instances are grouped as individual nodes and regions. All the implemented schemes are presented in Table 1.

In the CIMON approach, all nodes in the network directly send heartbeat messages to the sink every T_{hb} seconds. Figure 3(a) shows a snapshot of this mechanism. The sink is

Table 1: All types on monitoring approaches

	Centralized	**Distributed**
Individual	CIMON	DIMON
Region-based	CRMON	DRMON



(a) CIMON (b) DIMON (c) CRMON (d) DRMON

Figure 3: Heartbeat message snapshots of all the four network monitoring schemes

responsible for monitoring the status of all nodes. If heartbeat messages of any node are not presented within T_{mon} seconds, then that node is considered inactive.

In the case of DIMON, parent nodes, derived from existing routing information, assume the responsibility of monitoring their child nodes, as seen in Figure 3(b). Heartbeat messages are no longer forwarded to the sink and a delay longer than T_{mon} seconds causes the parent node to send an inactive message for this node to the sink. Node status information for both CIMON and DIMON will be further interpreted into region status to compare the results with region-based approaches.

The mechanism of CRMON is similar to that of DRMON. It uses the same region representative election process, but after region reps emerge, only heartbeat messages from region reps are sent to the sink. The sink monitors the status of every region. The region status will become inactive if a heartbeat message from that region does not arrive within T_{mon} seconds. To avoid false reports, the sink broadcasts a region status confirmation message to every node in the network after it detects an inactive region. This message will trigger the region representative election process in that region. If a new region rep can be mediated, a heartbeat message sent by the new region rep will resume the active status of that region. Figures 3(c) and (d) illustrate snapshots of CRMON and DRMON, respectively.

The performance of all network monitoring schemes was evaluated using Contiki's Cooja simulation platform. The hardware used in this simulation includes Tmote Sky, a sensor node with an MSP430 processor and a CC2420 transceiver. This platform has 10 kB of RAM and 48 kB of flash memory.

The network consists of several homogeneous sensor nodes and a powerful sink. Nodes are deployed in a two-dimensional area with uniform random placement. Heartbeat messages are transmitted every 20 seconds with random delays to avoid collisions and the monitoring interval is set to $3T_{hb}$. As the topology could change in real situations, all nodes are configured to operate in both TX and RX modes, even if they are leaf nodes. For DRMON, the observing interval used by observers in the region to trigger the region rep reelection process is set to $2T_{hb}$. The simulation was executed for 1 hour. Table 2 summarizes the parameters used in this simulation, where TX and interference ranges are typical values for Tmote Sky nodes, and time-related parameters reflect time-critical applications such as landslide monitoring.

Table 2: Simulation parameters

Parameters	Values
Number of seeds	10
Simulation time	3600 seconds
Number of sinks	1
TX range (R_{TX})	50 meters
Interference range (R_{Int})	100 meters
Heartbeat Interval (T_{hb})	20 seconds
Observing Interval (T_{obs})	40 seconds
Monitoring Interval (T_{mon})	60 seconds

Table 3: Varied simulation parameters

Parameters	Values
Number of region	3, 5, 9, 25
Number of node	16, 25, 49

We assumed that each node is aware of its route to the sink if there are available routes. Each node selects the nearest node with the smallest number of hops to the sink as its parent node. The re-routing mechanism is triggered immediately after the occurrence of a node fault. We did not choose to enable a dynamic routing protocol to avoid the effect of routing overhead, which would dominate the comparison results. The application data was omitted for the same reason.

We evaluated the Cooja-based simulation for the scenario in which a random region failure was generated at a fixed point in time. Node faults in the defective region occur sequentially every 5 minutes. All faults are permanent, which indicates that nodes are completely destroyed and cannot recover.

Results and Discussion

We first compared the results between XMAC, which represents LPL-based, energy-efficient MAC protocols, and the typical IEEE802.15.4 with no LPL (nullMAC). NullMAC in the Contiki platform denotes the standard CSMA/CA protocol without the duty cycling mechanism. In other words, the RX duty cycle is set to 100%. The numbers of regions and nodes were varied to observe the flexibility and scalability of the monitoring schemes. The parameters used for the evaluation are described in Table 3.

We evaluated the monitoring schemes for both efficiency and effectiveness. The efficiency evaluation metrics include the average power consumption per node and message complexity. In the case of effectiveness, we examined the fault detection accuracy with precision and recall the results and detection delay. All results are shown with error bars representing 95% confidence intervals. In addition, the sink node has the LPL mechanism disabled and is excluded from the results because it is generally attached to an external power source.

Power Consumption

Low power consumption is crucial for WSN applications to prolong the network's lifetime. The average power consumption can be calculated from the ratio of the CPU ticks for each state of the sensor node within a sampled time interval. The CPU ticks can be retrieved from the Energest module in the Contiki OS. The node's operating states consist of transmitting (TX), receiving (RX), CPU idle, and sleep mode. In sleep or Low Power Mode (LPM), a node consumes considerably less energy compared to other states. Tmote Sky which operates at 3V has different current consumption rates for different modes of operation, as shown in Table 4.

Table 4: Current consumption of different operating states

Operating States	Tmote Sky	LoRa Feather
Transmission (Radio TX)	17.7 mA	120.5 mA
Receiving (Radio RX)	20 mA	11.3 mA
CPU Idle	1.8 mA	9.2 mA
Low Power Mode (LPM)	0.0545 mA	0.8 mA

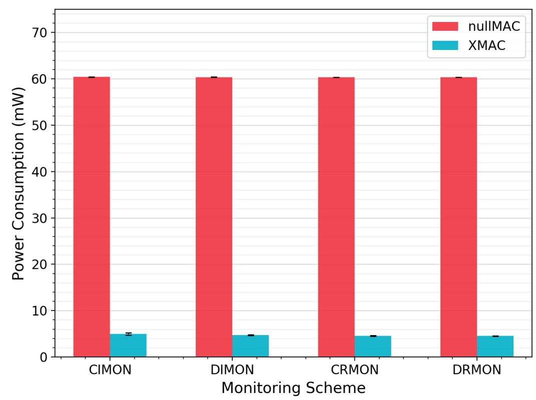


Figure 4: Average power consumption per node using different MAC protocols and network monitoring schemes

The comparison of average power consumption per node in a network using different MAC protocols is shown in Figure 4. By adopting the energy-efficient MAC protocol, the network monitoring process using XMAC clearly outperforms the nullMAC process. Nodes using nullMAC generally waste most of their energy in the idle state. However, the power consumption of all schemes using XMAC is approximately the same because the power used for TX activities is relatively small compared to the total power consumption used during periodic wake-ups. The difference in energy usage between nodes that use XMAC and nullMAC favors the use of XMAC to extend the network's lifetime. Therefore, the remainder of the results will be based on XMAC because of its superior suitability for deployment in real-world applications.

We studied the scalability of each monitoring scheme by varying the number of nodes in the network. The result presented in Figure 5 shows that CIMON is the most affected by the increase in network size. As CIMON requires participation of all nodes in the monitoring process and all of the heartbeat messages need to be sent to the sink, the growth of the network size leads to higher power consumption. However, the distributed or region-based schemes consume approximately the same amount of energy regardless of network size, which implies that these schemes are scalable.

To further compare energy usage of all schemes in recent radio hardware, we additionally calculated the average power consumption of the nodes using current consumption profiles measured from an Adafruit Feather M0 RFM95 LoRa Radio module [22] with identical network topologies. Current consumption rates of LoRa-enabled nodes are shown in Table 4. Figure 6 shows that the CIMON scheme consumes the most energy, followed by DIMON, whereas CRMON and DRMON consume the least energy for both platforms. It is also

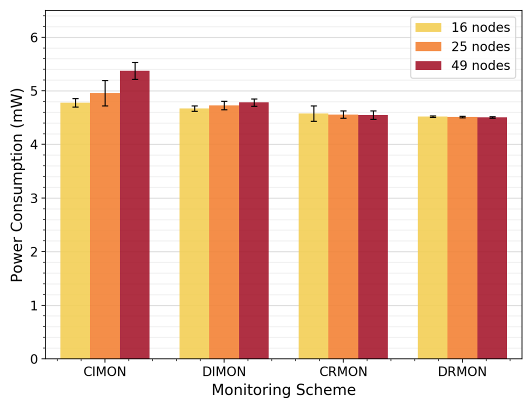


Figure 5: Average power consumption per node using different network sizes and network monitoring schemes

evidenced that by using LoRa technology, the differences in the power consumption of all the schemes become larger.

In conclusion, with respect to power consumption, CIMON used the most energy in the monitoring process. DRMON consumed the least and was marginally affected by the increase of the network size.

Message Overhead

Message overhead can be evaluated by recording the number of packets and frames used during the initialization and the monitoring processes. The number of messages is indicative of the magnitude of the network's traffic, which might have an impact on the data transmission of the application. Thus, it is desirable to use a low number of messages for monitoring.

Figure 7 illustrates the message transmission and reception overhead for the four monitoring schemes for various network sizes. The addition of nodes clearly increases the number of messages generated in individual-based monitoring schemes. In contrast, region-based mechanisms attempt to minimize the participation of nodes in the monitoring process, thus, the number of messages is not obviously related to the network size if the number of regions is the same.

We also investigated the case where every node in the network has to be monitored. In this case, region-based monitoring schemes, namely CRMON and DRMON, consider each single node as a separate region. The result displayed in Figure 8 indicates that individual monitoring schemes perform better than the region-based ones. The message overhead of CRMON and DRMON drastically increase when the number of regions changes from 5 to 25. This implies that the performance of region-based schemes tends to deteriorate if the number of regions increases due to the overhead of the region representation election process during the initializing state.

In summary, the region-based monitoring schemes outperform the individual monitoring schemes in situations where the number of regions is low. The distributed schemes also yield better results compared to those based on centralized schemes.

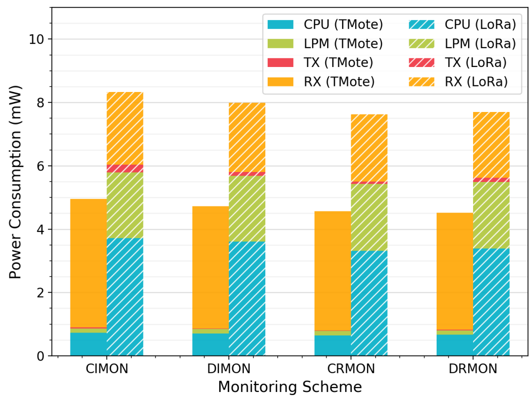
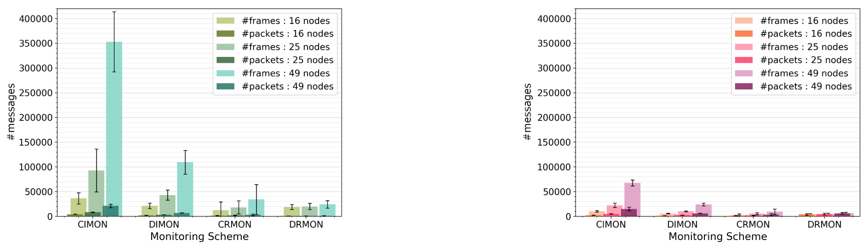


Figure 6: Average power consumption per node using different node models and network monitoring schemes



(a) TX

(b) RX

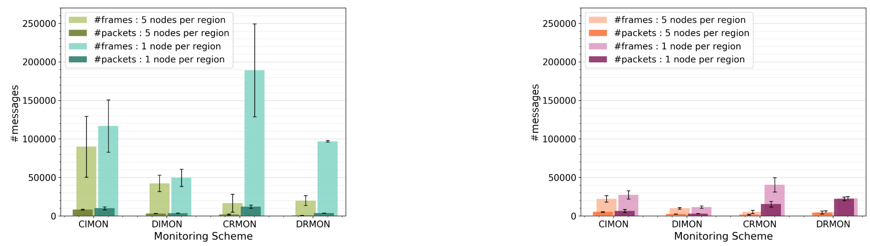
Figure 7: Message overhead using different network sizes

Fault Detection Accuracy

To evaluate the effectiveness of network monitoring schemes, the ground truth of the status of the nodes is needed. Ground truth, $G_{r,t}$, is the actual state of a region r at time t, which is 1 if region r is active and has at least one route to the sink at time t; otherwise, it is 0. The result of network monitoring is represented in the form of reports. The status of a region r at time t as reported by the sink is denoted as $R_{r,t}$. It is 1 if the sink reports that region r is currently active to the operator, or 0, otherwise.

In this work, we use *precision* and *recall* as the metrics to indicate the fault detection accuracy. Instead of measuring the accuracy in terms of quantity by counting the number of correct faults reported, we decided to include the time-dimension in the evaluation. Precision is defined as the ratio of the length of the time for which the system correctly identifies faults to the total time of fault occurrences. Faults are correctly detected when $G_{r,t}$ and $R_{r,t}$ are both equal to 0 for identical r and t. Given a set of discrete points in time T, the precision is then defined as follows:

$$Precision = \frac{|\{t \in T \ : \ G_{r,t} = 1 \wedge R_{r,t} = 1\}|}{|\{t \in T \ : \ G_{r,t} = 0\}|} \tag{1}$$



(a) TX (b) RX

Figure 8: Message overhead using different numbers of regions

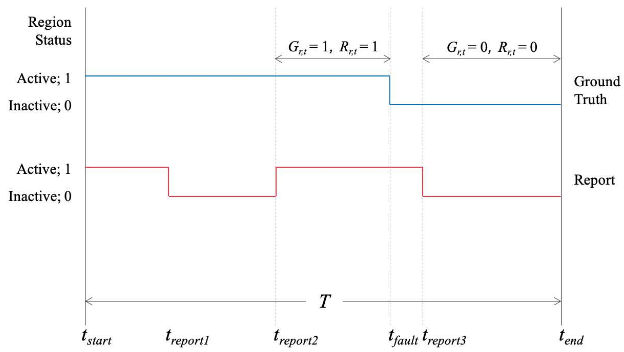


Figure 9: Diagram of ground truth ($G_{r,t}$) and fault report ($R_{r,t}$)'s status

Recall is the ratio of the length of time for which the system accurately reports region status, both active and inactive, per total time of all reports. It is defined as follows:

$$Recall = \frac{|\{t \in T : G_{r,t} = R_{r,t}\}|}{|T|} \tag{2}$$

Figure 9 illustrates the status of ground truth and fault reports. The fault detection accuracy result shown in Table 5 indicates that all schemes perform fairly well in terms of both precision and recall. The detection delays are also guaranteed within $T_{hb} + T_{mon}$, which is 80 seconds. These results suggest that all schemes can be used interchangeably to monitor faults in WSNs.

Conclusions

Low-power listening MAC protocols significantly assist in reducing power consumption of WSNs by preventing idle listening and lowering transmission process loads. Traditional network monitoring, which requires periodic updates of the node status, can cause an increase in transmission, which greatly reduces network lifetime. In this work, we propose *DRMON*,

Table 5: Detection accuracy using different monitoring approaches

	CIMON	DIMON	CRMON	DRMON
Precision	97.01%	86.98%	86.79%	91.61%
Recall	99.44%	88.84%	98.54%	97.74%
Delay	13.41 s	29.39 s	35.51 s	39.78 s

a distributed region-based monitoring scheme that can be used to monitor wireless sensor nodes that are physically divided into groups, called regions. This approach increases energy efficiency and reduces the message overhead generated during the monitoring process while maintaining comparable detection accuracy. If necessary, the scheme supports individual node monitoring by configuring each region to contain only one node.

Evaluations of centralized, distributed, individual and region-based monitoring schemes were conducted to compare their performance. The simulation results show that region-based schemes outperform the individual monitoring schemes in terms of power consumption and message overhead in cases where the network has a low number of regions. However, if the number of regions is high, individual monitoring approaches are recommended as there is no message overhead for electing and maintaining the region's representatives (i.e., region reps).

In future work, region reps rotation process should be implemented to further improve the performance of DRMON. Further evaluation of these monitoring schemes could be facilitated by the investigation of additional parameters such as heartbeat and monitoring intervals, as well as other energy-efficient MAC protocols.

List of Abbreviations

CHEF	cluster head election mechanism using fuzzy logic
CIMON	centralized individual monitoring scheme
CRMON	centralized region-base monitoring scheme
CSMA/CA	carrier sense multiple access with collision avoidance
DIMON	distributed individual monitoring scheme
DRMON	distributed region-base monitoring scheme
ICN	information-centric networking
LEACH	low-energy adaptive clustering hierarchy
LPL	low-power listening
LPM	low-power mode
MAC	medium access control
RX	reception
TX	transmission
WSN	wireless sensor networks

Declarations

Availability of Data and Materials
Not applicable

Competing Interests
The authors declare that they have no competing interests.

Funding
This research was supported in part by the master's degree scholarship from the Faculty of Engineering, Kasetsart University. It was also supported partially by the Japan Science and Technology Agency/Japan International Cooperation Agency, and the Science the Technology Research Partnership for Sustainable Development (JST/JICA, SATREPS).

Authors Contribution
KP designed, conducted experiments, and analyzed the results, as well as drafted the manuscript. CJ proofread and substantially revised the manuscript. All authors read and approved the final manuscript.

Acknowledgements
Not applicable

References

1. Akyildiz, I.F., Su, W., Sankarasubramaniam, Y., Cayirci, E.: Wireless sensor networks: a survey. Computer Networks **38**(4), 393–422 (2002). doi:10.1016/S1389-1286(01)00302-4
2. Ahlgren, B., Dannewitz, C., Imbrenda, C., Kutscher, D., Ohlman, B.: A survey of information-centric networking. IEEE Communications Magazine **50**(7), 26–36 (2012). doi:10.1109/MCOM.2012.6231276
3. Semtech: What is LoRa? https://www.semtech.com/lora. [Online; accessed 25-December-2018] (2018)
4. Dunkels, A., Gronvall, B., Voigt, T.: Contiki - a lightweight and flexible operating system for tiny networked sensors. In: Proceedings of the 29th Annual IEEE International Conference on Local Computer Networks. LCN '04, pp. 455–462. IEEE Computer Society, Washington, DC, USA (2004). doi:10.1109/LCN.2004.38. https://doi.org/10.1109/LCN.2004.38
5. Guo, S., Zhong, Z., He, T.: Find: Faulty node detection for wireless sensor networks. In: Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems. SenSys '09, pp. 253–266. ACM, New York, NY, USA (2009). doi:10.1145/1644038.1644064. http://doi.acm.org/10.1145/1644038.1644064
6. Ni, K., Ramanathan, N., Chehade, M.N.H., Balzano, L., Nair, S., Zahedi, S., Kohler, E., Pottie, G., Hansen, M., Srivastava, M.: Sensor network data fault types. ACM Trans. Sen. Netw. **5**(3), 25–12529 (2009). doi:10.1145/1525856.1525863
7. Chen, J., Kher, S., Somani, A.: Distributed fault detection of wireless sensor networks. In: Proceedings of the 2006 Workshop on Dependability Issues in Wireless Ad Hoc Networks and Sensor Networks. DIWANS '06, pp. 65–72. ACM, New York, NY, USA (2006). doi:10.1145/1160972.1160985. http://doi.acm.org/10.1145/1160972.1160985
8. Zhang, Y., Yuan, X.: Fault diagnosis in clustering wsn based on neighbor cooperation. In: 2016 Chinese Control and Decision Conference (CCDC), pp. 1803–1807 (2016). doi:10.1109/CCDC.2016.7531274
9. Ramanathan, N., Chang, K., Kapur, R., Girod, L., Kohler, E., Estrin, D.: Sympathy for the sensor network debugger. In: Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems. SenSys '05, pp. 255–267. ACM, New York, NY, USA (2005). doi:10.1145/1098918.1098946. http://doi.acm.org/10.1145/1098918.1098946
10. Meier, A., Motani, M., Siquan, H., Künzli, S.: Dimo: Distributed node monitoring in wireless sensor networks. In: Proceedings of the 11th International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems. MSWiM '08, pp. 117–121. ACM, New York, NY, USA (2008). doi:10.1145/1454503.1454526. http://doi.acm.org/10.1145/1454503.1454526
11. Liu, Y., Liu, K., Li, M.: Passive diagnosis for wireless sensor networks. Networking, IEEE/ACM Transactions on **18**(4), 1132–1144 (2010). doi:10.1109/TNET.2009.2037497
12. Zhao, Y.J., Govindan, R., Estrin, D.: Residual energy scan for monitoring sensor networks. In: Wireless Communications and Networking Conference, 2002. WCNC2002. 2002 IEEE, vol. 1, pp. 356–362 (2002). IEEE
13. Hsin, C.-f., Liu, M.: A distributed monitoring mechanism for wireless sensor networks. In: Proceedings of the 1st ACM Workshop on Wireless Security. WiSE '02, pp. 57–66. ACM, New York, NY, USA (2002). doi:10.1145/570681.570688. http://doi.acm.org/10.1145/570681.570688
14. Liu, K., Ma, Q., Zhao, X., Liu, Y.: Self-diagnosis for large scale wireless sensor networks. In: INFOCOM, 2011 Proceedings IEEE, pp. 1539–1547 (2011). doi:10.1109/INFCOM.2011.5934944
15. Ma, Q., Liu, K., Miao, X., Liu, Y.: Sherlock is around: Detecting network failures with local evidence fusion. In: INFOCOM, 2012 Proceedings IEEE, pp. 792–800 (2012). doi:10.1109/INFCOM.2012.6195826
16. Ma, Q., Liu, K., Xiao, X., Cao, Z., Liu, Y.: Link scanner: Faulty link detection for wireless sensor networks. In: INFOCOM, 2013 Proceedings IEEE, pp. 2688–2696 (2013). doi:10.1109/INFCOM.2013.6567077
17. Dong, D., Liao, X., Liu, Y., Shen, C., Wang, X.: Edge self-monitoring for wireless sensor networks. Parallel and Distributed Systems, IEEE Transactions on **22**(3), 514–527 (2011). doi:10.1109/TPDS.2010.72
18. Heinzelman, W.R., Chandrakasan, A., Balakrishnan, H.: Energy-efficient communication protocol for wireless microsensor networks. In: System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference On, pp. 10–2 (2000)
19. Kim, J.-M., Park, S.-H., Han, Y.-J., Chung, T.-M.: Chef: Cluster head election mechanism using fuzzy logic in wireless sensor networks. In: Advanced Communication Technology, 2008. ICACT 2008. 10th International Conference On, vol. 1, pp. 654–659 (2008). doi:10.1109/ICACT.2008.4493846
20. Buettner, M., Yee, G.V., Anderson, E., Han, R.: X-mac: A short preamble mac protocol for duty-cycled wireless sensor networks. In: Proceedings of the 4th International Conference on Embedded Networked Sensor Systems. SenSys '06, pp. 307–320. ACM, New York, NY, USA (2006). doi:10.1145/1182807.1182838. http://doi.acm.org/10.1145/1182807.1182838
21. Pattamasiriwat, K., Jaikaeo, C.: Evaluation of low power listening mac protocol on network monitoring in wireless sensor networks. In: 2017 9th International Conference on Knowledge and Smart Technology (KST), pp. 260–265 (2017). doi:10.1109/KST.2017.7886117
22. Adafruit: Adafruit Feather M0 Radio with LoRa Radio Module. https://learn.adafruit.com/adafruit-feather-m0-radio-with-lora-radio-module. [Online; accessed 5-December-2019]

Figure Title and Legend

Figure	Title	Legend
1	Forest fire detection scenario	In forest fire detection application, the monitored area is populated with sensor nodes that are randomly deployed using an aircraft. The coverage areas of nearby nodes likely overlap. The network then requires only one or a few nodes in the same region to detect an event.
2	Duty-cycling mechanism of X-MAC protocol	(a) for a unicast transmission, the sender transmits probing packets until an acknowledgment is received from the intended receiver, and (b) for a broadcast transmission, the sender must send the packet continuously throughout the full wake-up interval because an acknowledgment is not used.
3	Heartbeat message snapshots of all the four network monitoring schemes	(a) in CIMON, each individual node periodically sends heartbeats to the sink, i.e., the centralized monitor station, (b) in DIMON, parent nodes assume the responsibility of monitoring their child nodes and do not forwarded heartbeats to the sink, (c) in CRMON, only the representative of each region (i.e., region rep) is responsible for sending heartbeats to the sink, and (d) for DRMON, each region rep's heartbeats are monitored by one of its one-hop neighbor, where the rest of them become observers that will immediately trigger a region representative process in case the current region rep fails.
4	Average power consumption per node using different MAC protocols and network monitoring schemes	Nodes using nullMAC generally waste most of their energy in the idle state. However, the power consumption of all schemes using XMAC is approximately the same because the power used for TX activities is relatively small compared to the total power consumption used during periodic wake-ups.
5	Average power consumption per node using different network sizes and network monitoring schemes	As CIMON requires participation of all nodes in the monitoring process and all of the heartbeat messages need to be sent to the sink, the growth of the network size leads to higher power consumption. However, the distributed or region-based schemes consume approximately the same amount of energy regardless of network size, which implies that these schemes are scalable.
6	Average power consumption per node using different node models and network monitoring schemes	CIMON consumes the most energy, followed by DIMON, whereas CRMON and DRMON consume the least energy for both platforms. It is also evidenced that by using LoRa technology, the differences in the power consumption of all the schemes become larger.
7	Message overhead using different network sizes	The addition of nodes clearly increases the number of messages generated in individual-based monitoring schemes. In contrast, region-based mechanisms attempt to minimize the participation of nodes in the monitoring process, thus, the number of messages is not obviously related to the network size if the number of regions is the same.
8	Message overhead using different numbers of regions	When every node in the network has to be monitored, i.e., each region consists of only one node, individual monitoring schemes are shown perform better than the region-based ones. The message overhead of CRMON and DRMON drastically increase when the number of regions changes from 5 to 25. This implies that the performance of region-based schemes tends to deteriorate if the number of regions increases due to the overhead of the region representation election process during the initializing state.
9	Diagram of ground truth ($G_{r,t}$) and fault report ($R_{r,t}$)'s status	Precision is defined as the ratio of the length of the time for which the system correctly identifies faults to the total time of fault occurrences. Faults are correctly detected when $G_{r,t}$ and $R_{r,t}$ are both equal to 0 for identical region, r, and time, t. Recall is the ratio of the length of time for which the system accurately reports region status, both active and inactive, per total time of all reports.

Figures

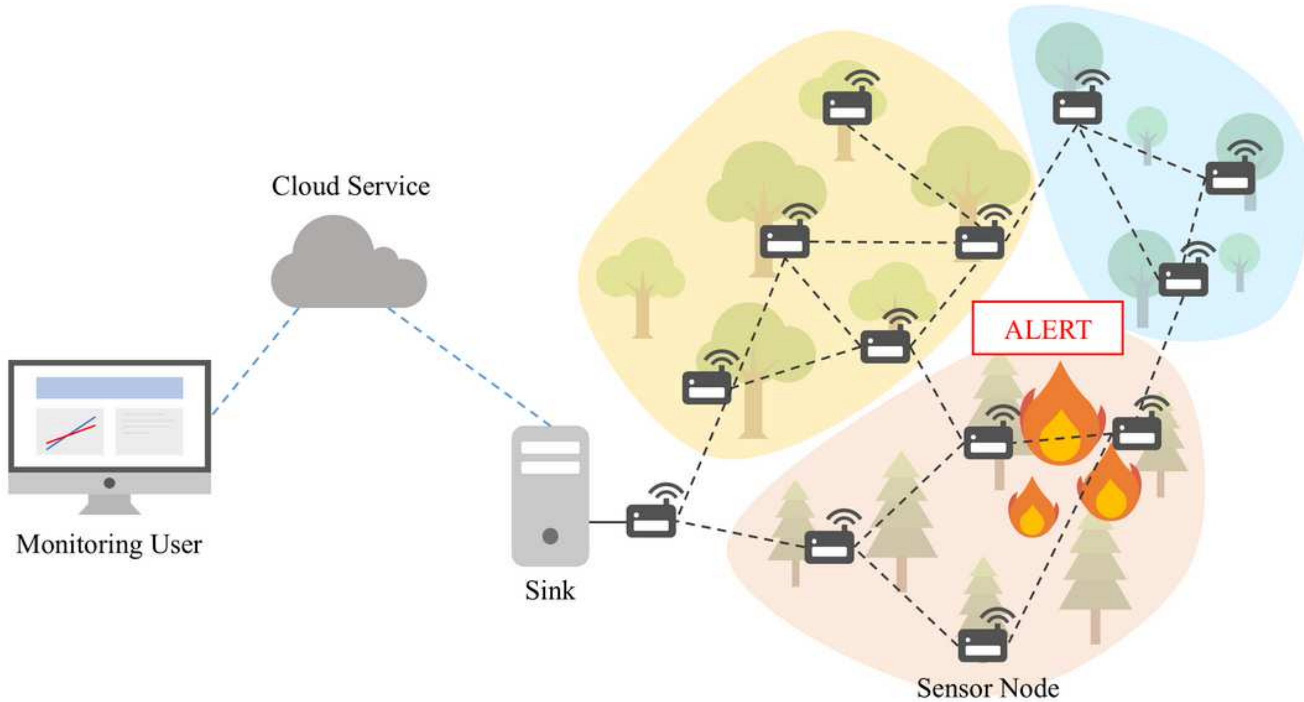


Figure 1

Forest fire detection scenario. In forest fire detection application, the monitored area is populated with sensor nodes that are randomly deployed using an aircraft. The coverage areas of nearby nodes likely overlap. The network then requires only one or a few nodes in the same region to detect an event.

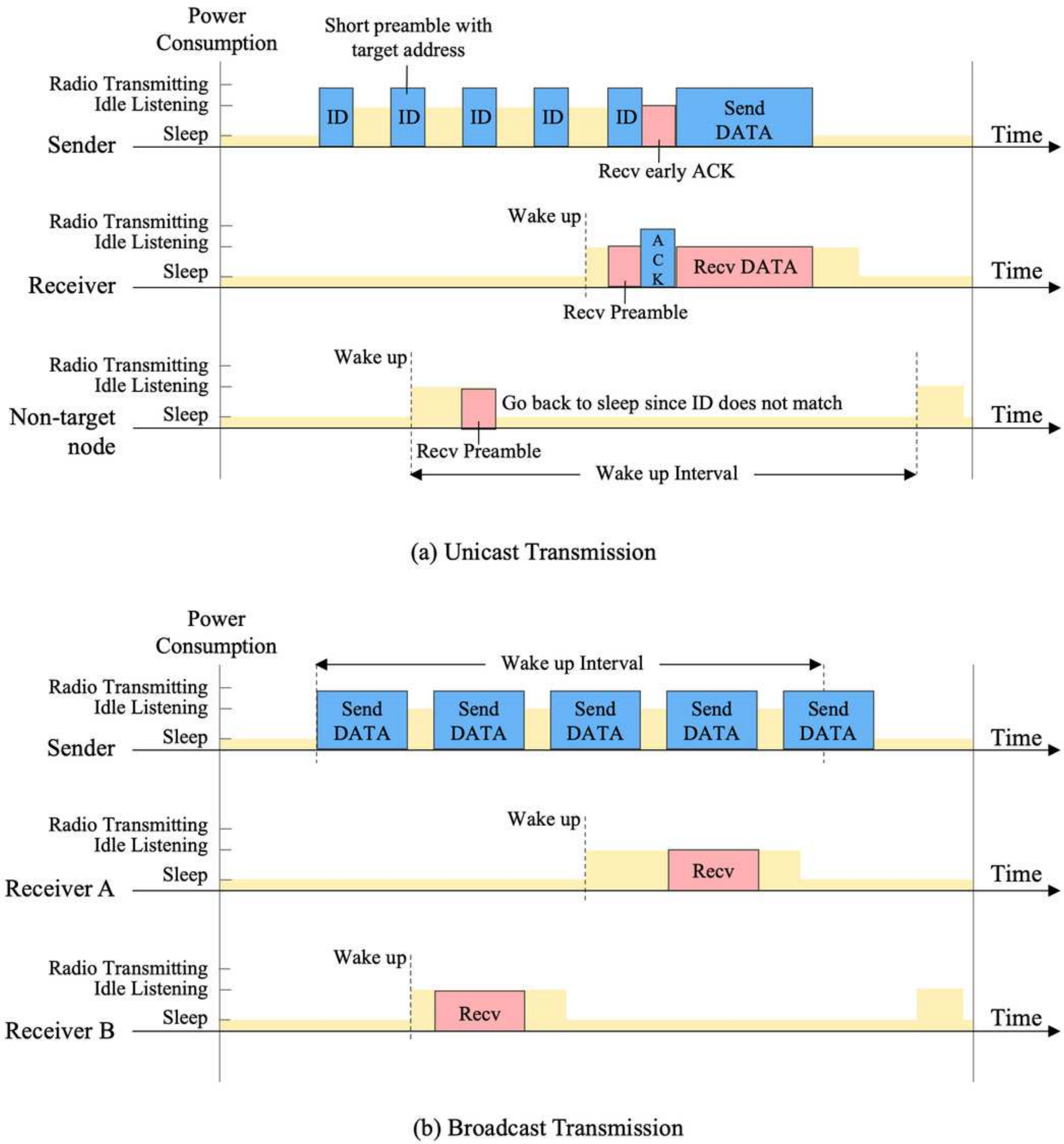
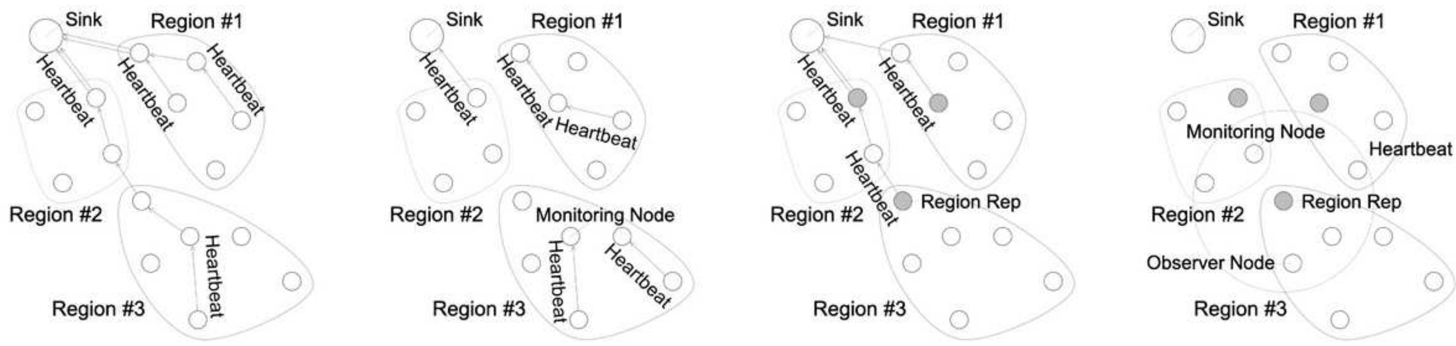


Figure 2

Duty-cycling mechanism of X-MAC protocol. (a) for a unicast transmission, the sender transmits probing packets until an acknowledgment is received from the intended receiver, and (b) for a broadcast transmission, the sender must send the packet continuously throughout the full wake-up interval because an acknowledgment is not used.



(a) CIMON (b) DIMON (c) CRMON (d) DRMON

Figure 3

Heartbeat message snapshots of all the four network monitoring schemes. (a) in CIMON, each individual node periodically sends heartbeats to the sink, i.e., the centralized monitor station, (b) in DIMON, parent nodes assume the responsibility of monitoring their child nodes and do not forwarded heartbeats to the sink, (c) in CRMON, only the representative of each region (i.e., region rep) is responsible for sending heartbeats to the sink, and (d) for DRMON, each region rep's heartbeats are monitored by one of its one-hop neighbor, where the rest of them become observers that will immediately trigger a region representative process in case the current region rep fails.

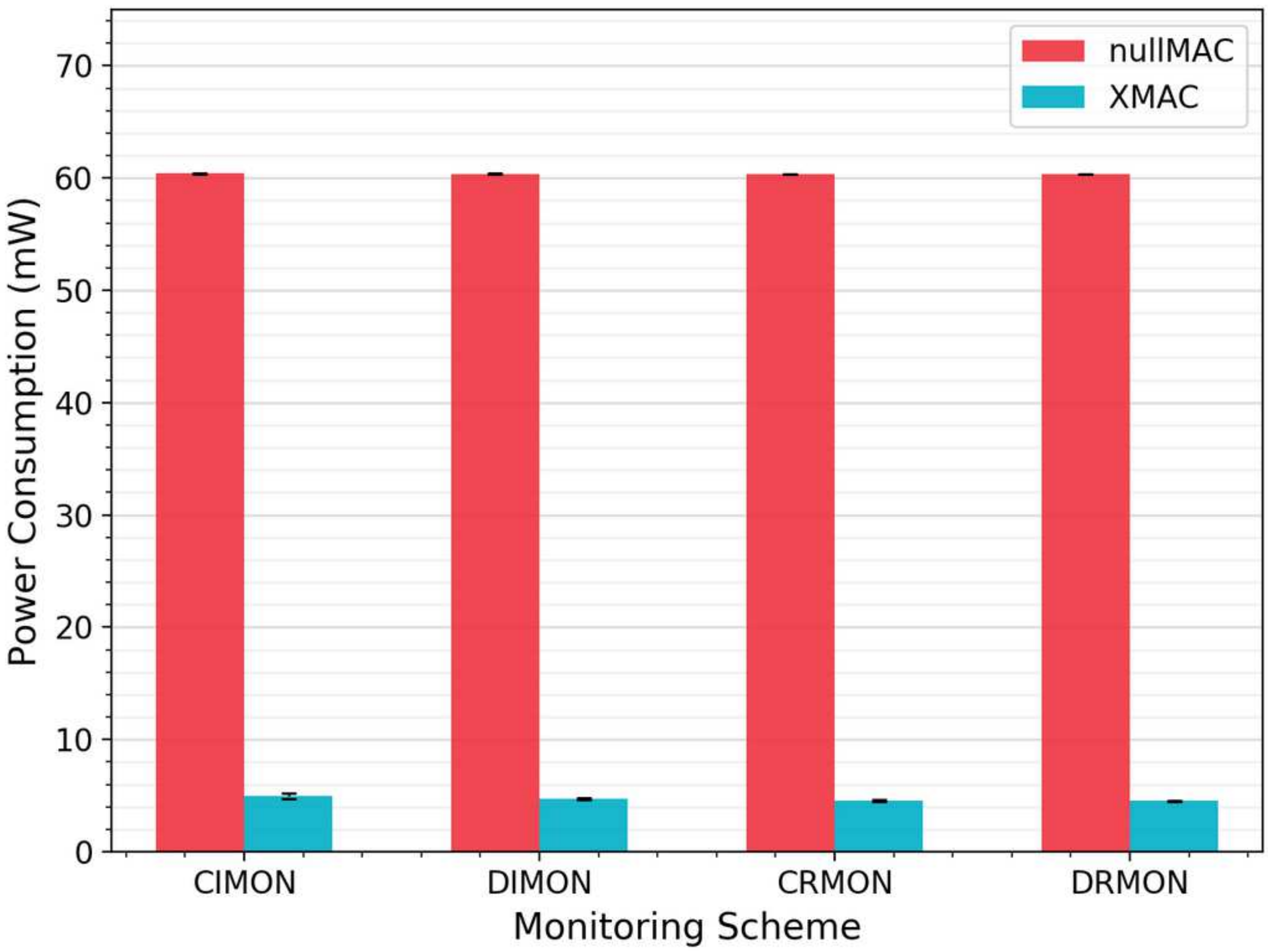


Figure 4

Average power consumption per node using different MAC protocols and network monitoring schemes. Nodes using nullMAC generally waste most of their energy in the idle state. However, the power consumption of all schemes using XMAC is approximately the same because the power used for TX activities is relatively small compared to the total power consumption used during periodic wake-ups.

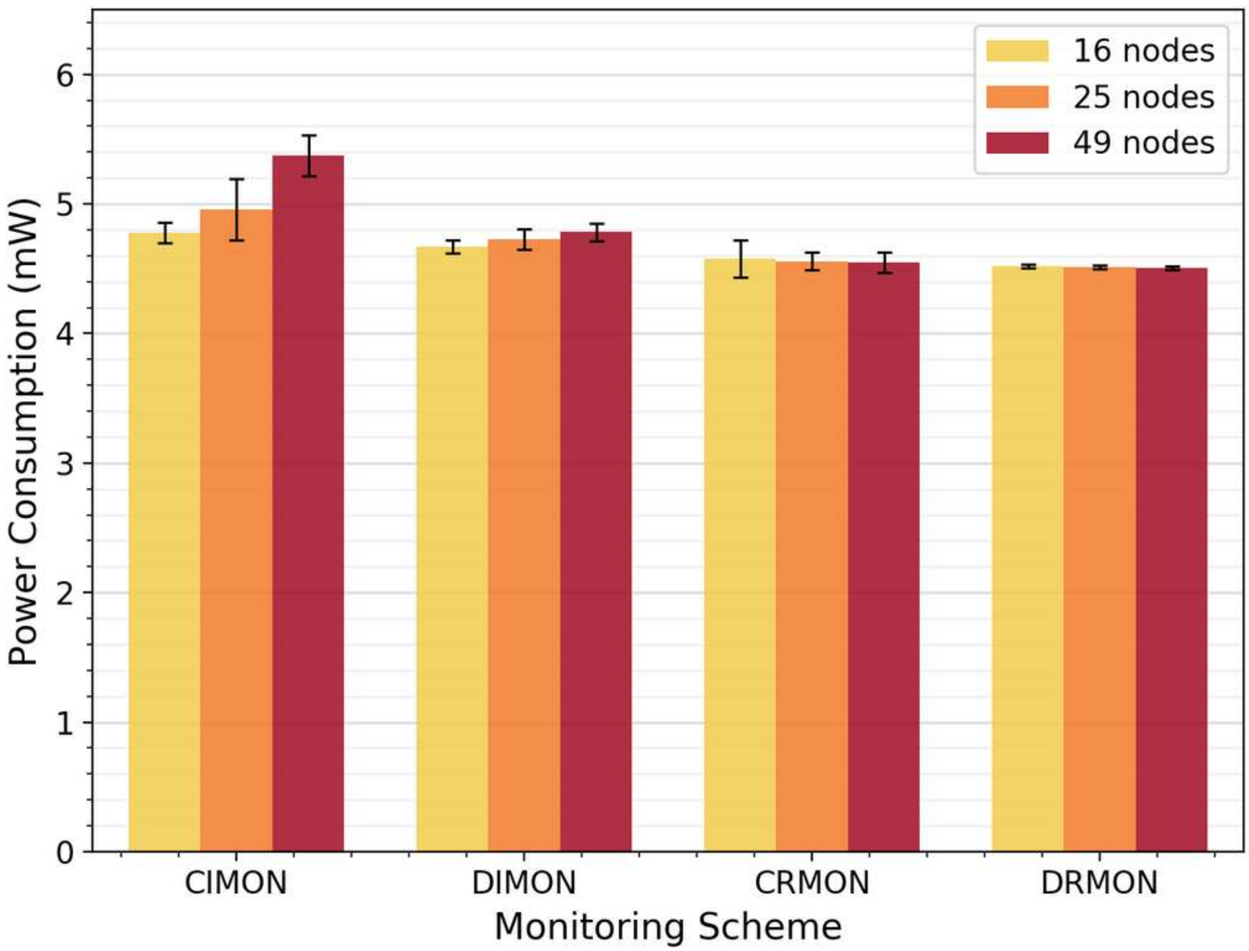


Figure 5

Average power consumption per node using different network sizes and network monitoring schemes. As CIMON requires participation of all nodes in the monitoring process and all of the heartbeat messages need to be sent to the sink, the growth of the network size leads to higher power consumption. However, the distributed or region-based schemes consume approximately the same amount of energy regardless of network size, which implies that these schemes are scalable.

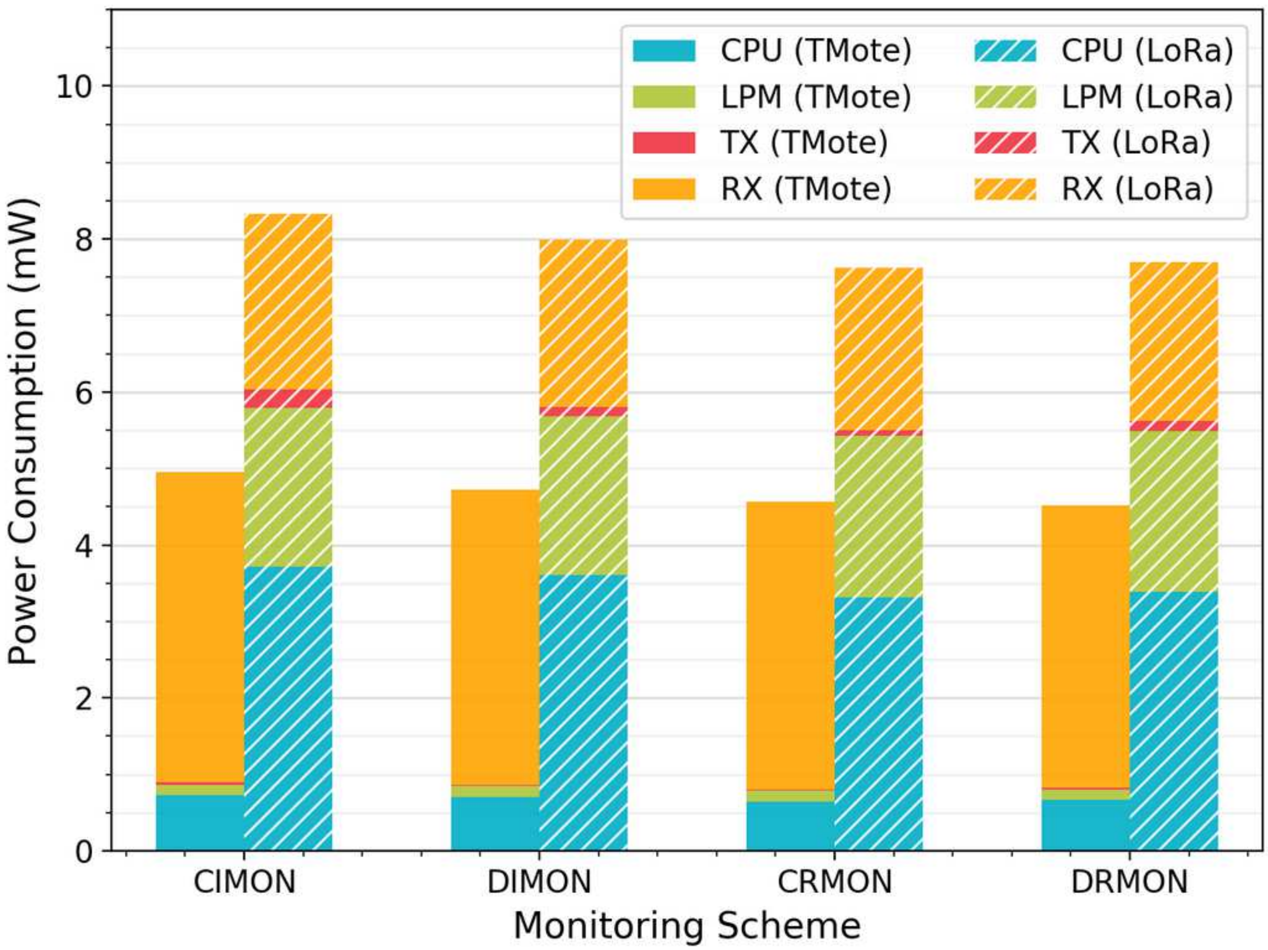
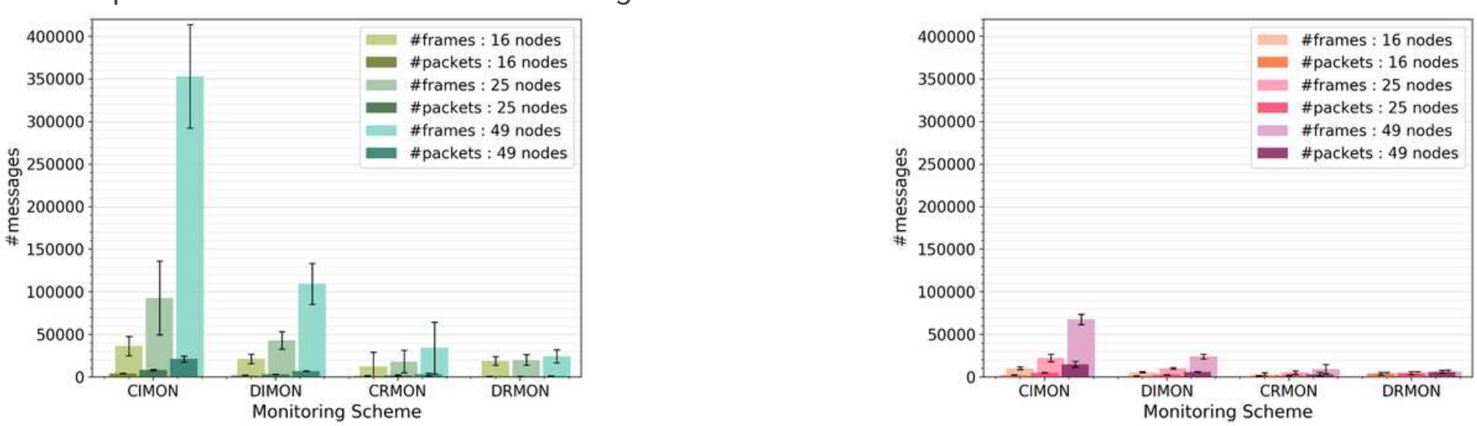


Figure 6

Average power consumption per node using different node models and network monitoring schemes. CIMON consumes the most energy, followed by DIMON, whereas CRMON and DRMON consume the least energy for both platforms. It is also evidenced that by using LoRa technology, the differences in the power consumption of all the schemes become larger.

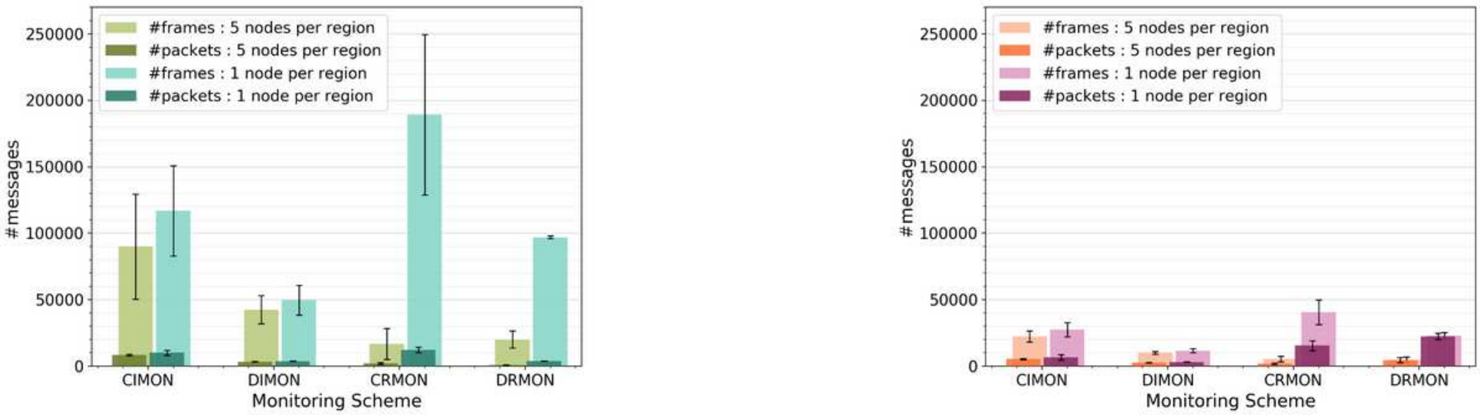


(a) TX

(b) RX

Figure 7

Message overhead using different network sizes. The addition of nodes clearly increases the number of messages generated in individual-based monitoring schemes. In contrast, region-based mechanisms attempt to minimize the participation of nodes in the monitoring process, thus, the number of messages is not obviously related to the network size if the number of regions is the same.



(a) TX (b) RX

Figure 8

Message overhead using different numbers of regions. When every node in the network has to be monitored, i.e., each region consists of only one node, individual monitoring schemes are shown perform better than the region-based ones. The message overhead of CRMON and DRMON drastically increase when the number of regions changes from 5 to 25. This implies that the performance of region-based schemes tends to deteriorate if the number of regions increases due to the overhead of the region representation election process during the initializing state.

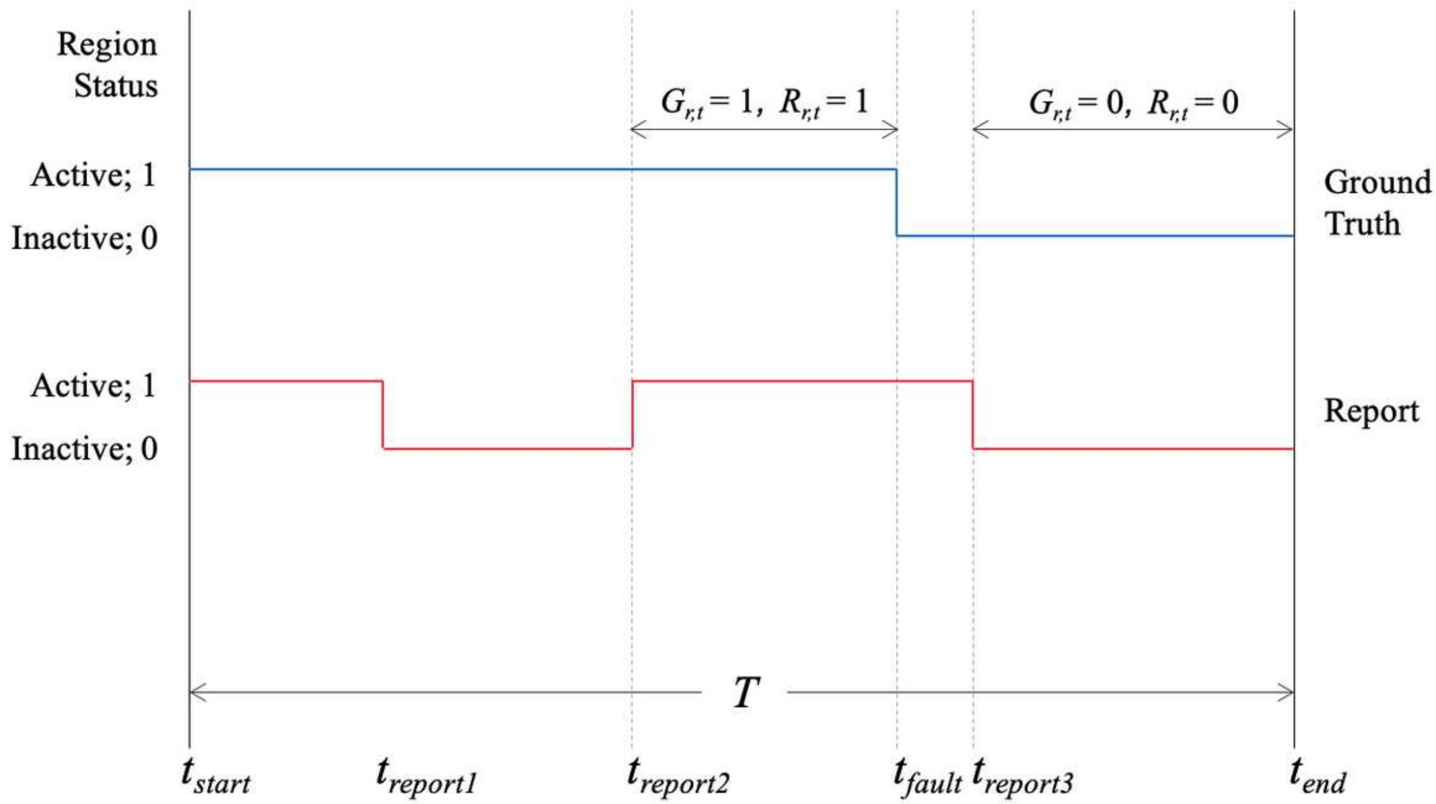


Figure 9

Diagram of ground truth (Gr,t) and fault report (Rr,t)'s status. Precision is defined as the ratio of the length of the time for which the system correctly identifies faults to the total time of fault occurrences. Faults are correctly detected when Gr,t and Rr,t are both equal to 0 for identical region, r, and time, t. Recall is the ratio of the length of time for which the system accurately reports region status, both active and inactive, per total time of all reports.