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An Improved Asynchronous MAC Protocol (IA-MAC) For Optimization Of Energy & Latency Of Wireless Sensor Network For Continuous Surveillance Applications Having Infrequent Critical Data

***Abstract*—** Wireless Sensor Networks (WSNs) are integral to applications requiring long-term deployment and infrequent data transmission, such as environmental monitoring, structural health assessment, and disaster management. However, conventional Medium Access Control (MAC) protocols are not optimized for energy-efficiency and latency due to their reliance on periodic idle listening and frequent control message exchanges. This paper introduces a novel Wake-Up Receiver (WuRx)-based MAC protocol i.e. improved asynchronous MAC (IA-MAC) designed to optimize energy consumption, communication efficiency, collision rate, latency and idle listening in WSN application for 24x7 continuous monitoring with rare data transmission requirements. The proposed protocol leverages ultra-low-power wake-up receivers to eliminate the need for continuous listening with main transceiver, allowing sensor nodes to remain in sleep mode until explicitly triggered by an external event or data transmission request. Simulation and real-world deployment results demonstrate significant energy savings, extended network lifetime, and enhanced responsiveness to critical events. The protocol is particularly suited for low-duty-cycle applications such as forest fire detection, structural integrity monitoring, and remote wildlife tracking, where energy efficiency and prompt event-driven communication are paramount. This approach provides a scalable and robust solution for future energy-constrained WSN deployments. The use of high-range main transceivers combined with wake-up radio technology allows IA-MAC to achieve efficient data transmission with minimal energy consumption, even in high- density node deployments. The findings demonstrate that IA- MAC effectively mitigates issues like false wake-ups and unnecessary energy usage, which are prevalent in other protocols. Furthermore, the protocol ensures reliable multi-hop communication and supports emergency data transmission, making it highly suitable for critical applications such as environmental, structural health monitoring and disaster management.

Keywords: collision, critical surveillance application, duty cycle, energy, false wake-up, latency, multi-hop communications, wake-up receiver, wireless sensor networks.

I. INTRODUCTION

The proposed IA-MAC protocol demonstrates significant improvements in energy efficiency, latency reduction, and collision minimization for Wireless Sensor Networks (WSNs), making it a robust solution for low-duty- cycle and critical surveillance applications. By leveraging ultra-low-power wake-up receivers and a novel multi-hop communication strategy, IA-MAC addresses key challenges associated with traditional MAC protocols.

A. Background

Wireless Sensor Networks (WSNs) have emerged as a critical technology for a wide range of applications, including environmental monitoring, smart cities, industrial automation, and healthcare etc. These networks consist of small, low-cost sensor nodes that can sense, process, and communicate data wirelessly. However, WSNs face significant energy constraints due to the limited battery capacity of sensor nodes and the difficulty of replacing batteries in many deployment scenarios. The energy consumption in WSNs is dominated by wireless communication, which can account for up to 70% of a node's total energy usage. This constraint has led to the development of various energy-saving techniques, with a particular focus on efficient Medium Access Control (MAC) protocols. Traditional MAC protocols often suffer from energy waste due to idle listening, overhearing, and collisions making them unsuitable for long-term WSN deployments for continuous surveillance for critical and infrequent data collection. The problems can be alleviated by using a wake-up receiver (WuRx) based solution [1]. Figure 1 depicts architecture design of wakeup receiver based sensor node[2] which is equipped with a WuRx can power down its primary radio, along with any superfluous components, and remain in deep-sleep mode till it is prompted by a wake-up signal from another node or it desires to sample the sensor [3]. This promising technology has emerged to address the energy challenges in WSNs incurred due to idle listening by main transceiver. These are ultra-low-power receivers that continuously listen for wake- up signals while the main radio remains in sleep mode. When a wake-up signal is detected, the WuRx activates the main radio for data communication. Modern WuRx designs consume only nano watts of power, dramatically reducing idle listening energy consumption. Ultra low power WuRx enables the cancellation of the energy waste due to the rendezvous process and the periodic wake-ups as it consumes very less energy than main transceiver.

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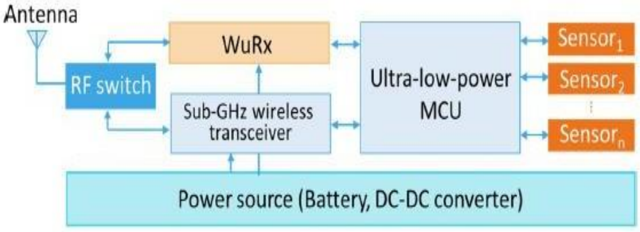

Figure 1 Architecture Design of Wakeup Radio [2]

B. Motivation

The motivation for wake up receiver based MAC protocols with optimized energy and latency for wsn applications performing 24x7 continuous monitoring with rare data transmission requirements is given below:-

- The existing MAC protocols don’t address the rapid and recent advancement in micro and nano technology suitable for sensor node architecture and may become obsolete very soon.
- Duty cycle based MAC protocols activate main radio interface periodically after sleep state and transceiver is switched on/off based on proactive scheduling which is advantageous due to lesser energy consumption than MAC protocols with always ON radio but idle listening and overhearing of data intended to others during duty cycle incurs a significant amount of energy waste. Besides, these protocols suffer by high latencies due to waiting for schedule.
- Wakeup receiver (WuRx) based schemes uses either range based wakeup or direct wakeup but hybrid approach can be utilized according to remaining energy of sensor node or to exploit low and high power radio signals.
- To find out a suitable protocol for low-duty-cycle and critical applications like environmental, structural health monitoring, disaster management and wildlife tracking etc.
- No MAC protocol addressed such schemes in which Wakeup receiver (WuRx) based transceiver can exploit temporally correlated data for the lifelong surveillance applications which need to send bulky data like photograph, multiple sensor values etc.
- Wakeup receiver based sensor nodes may be a game changer in continuous surveillance application, IoT applications, smart man less vehicle applications and smart city applications and many more for monitoring borders of battle field, agriculture, health, structural health, habitat, traffic, environment, vehicular network etc.

C. Organization of the paper

This paper aims to address the energy efficiency, latency, idle listening and collision rate related challenges in WSNs by leveraging wake-up radios. The literature review is provided in part II with key findings. Part III will explain design of IA-MAC which incorporates cross-layer interactions between the MAC and routing layers to jointly optimize energy efficiency and network performance. It includes formats of wakeup, control, data frames at MAC layer with routing supportive parameters for network discovery and data transmission phases. The energy model is explained in part IV. The simulation setup is explained in part V and simulation results are discussed in part VI. The whole research work is concluded in part VII with future directions.

II. RELATED WORK

Talking about low-energy WSNs the energy effectiveness for the conservative MAC protocols currently follow duty cycling, where a short active period is followed by a long sleep period, is used to conserve energy. These low duty-cycle protocols are separated into two classes depending upon the harmonization of data exchanges and these classes are named as synchronized and unsynchronized. We will discuss them briefly in the next section with their disadvantages and to overcome those disadvantages an ultra low power wakeup radio device or wakeup receiver (WuRx) based protocols will also be discussed. Such devices permit a wakeup receiver (WuRx) furnished with the foremost transceiver can be taken for the use of uninterruptedly monitor the channel to decrease the power ingesting of the high-power main transceiver in idle listening. It empowers the node to be triggered for inward communications permitting for decently asynchronous actions.

A. Synchronous Vs Asynchronous MAC Protocols

Traditional MAC protocols for WSNs can be broadly categorized into synchronous and asynchronous approaches. Synchronous protocols such as S-MAC [4] and T-MAC [5], coordinate sleep/wake cycles among nodes to reduce idle listening. However, they suffer from synchronization overhead and are less adaptable to dynamic network conditions. Asynchronous protocols like B-MAC [6] and X- MAC [7] use preamble sampling to achieve low-power communication without synchronization. While more flexible, they can still incur significant energy costs due to extended preambles or frequent channel checking. Hybrid protocols: Z-MAC [8] combines the strengths of TDMA and CSMA approaches, adapting to varying levels of contention. However, it still faces challenges in highly dynamic environments. The synchronous MAC protocol [4] that employs a duty cycle which alternates between the active and sleep mode. The essential operation of synchronous MAC protocol is to synchronize the wakeup time throughout during all over wakeup/sleep period. In contrast to the synchronous MAC protocol that requires a distinct synchronization frame, the asynchronous MAC protocol lets each node to repeat the wakeup/sleep cycle rendering to their timetable without the usage of a distinct synchronization frame. LPL (low power listening) [9] is exploited by spreading and getting nodes to communicate while adhering to the duty cycle. Scheduled operations are utilized by synchronized low duty-cycle MAC protocols to ensure that both transmitters and receivers have a defined, short as well as active period denoted as T_{active} to exchange one or more frames with neighboring nodes. Asynchronous/Unsynchronized MAC protocols depend on a Low Power Listening (LPL) mechanism, where nodes intermittently poll the channel to identify potential traffic.

B. Wake-up radio based MAC protocols

The addition of Wake up Receiver (WuRx) technology to Wireless Sensor Networks (WSNs) is a huge leap forward in the effort to reduce energy and increase network performance. That's because as evidenced by a wide variety of studies that show how these technologies can be used up and down the layers of network design, they can facilitate power conservation as well as improved operational lifetimes. The integration of wake-up radios has led to a new generation of energy-efficient MAC protocols. STEM (Sparse Topology and Energy Management) [10] was one of the first protocols to propose a separate wake-up radio channel, though it used a higher-power radio than modern WuRx. WUR-MAC [11] introduced a duty-cycled wake-up radio approach, reducing energy consumption compared to always-on WuRx designs. OPWUM (Opportunistic MAC leveraging Wake-Up receivers in WSNs) [12] combined wake-up radios with opportunistic forwarding, demonstrating significant energy savings over traditional approaches. ALBA-WUR [13] extended the ALBA-R cross- layer protocol to exploit wake-up radio features, showing improvements in both energy efficiency and packet delivery ratio. Energy consumption of sensor nodes at the MAC layer is minimized focusing on removing idle listening and transmission times. In 2002, a MAC protocol [14] was introduced that conserves energy, scheduling sleep periods of network nodes to drastically cut idle listening durations and extend the lifespan of the network .Following from this, Lebreton et al designed a system [15] which combines duty cycling with wake up radio (WuR) technology to deal with overhearing problems whilst dramatically improving network energy efficiency by only activating nodes when necessary. In order to deal with the in-band interference, they have continued their research to address interference effects as well as withhold in WSNs [16]. With significantly reduced energy use and response times over traditional duty cycling, Gu and Stankovic [17] innovated with a radio triggered wake up and show that this is more than sufficient for real time applications in WSNs. In [18] Demirkol, Ersoy and Onur put forward the advantages and difficulties of installing WuRx to WSNs mentioning the possible savings of a great quantity of power whilst there are challenges associated to system complexity and deployment costs and range extension mechanism is explained in [19].In addition, Djiroun and Djenouri [20] explored various MAC protocols with WuRx technologies and found that such systems improved both network lifetime and reduced low idle listening compared to conventional ones. Ntshabele, Isong and Abu-Mahfouz [21] proposed an energy efficient scheduling mechanism done by applying the clustering technique, K means, in conjunction with the Sensor- Medium Access Control protocol (S-MAC) to reduce network complexity and interference. Duty cycles associated with these two functions are optimized in order to achieve higher energy efficiency and a more responsive network. DelPrete et al [22] also created a dual band wake up radio that enables nodes to operate on two different frequency bands which effectively expedites energy use as dictated by the network demand and extends the network capacity to utilize energy more efficiently.

Ye and Au [23] studied how sleep/ wake up scheduling strategies with varying adaptive strategies based on network conditions can improve energy efficiency while maintaining the responsiveness of the network. These technologies, as incorporated into MAC protocols by Agarwal, Jain and Goswami [24], have been shown to significantly increase network lifetime and efficiency as such to play a large role in expanding the capabilities of WSNs. The further contributions include Magno et al. [25] who review power minimization techniques for Wakeup receivers, as a means to reduce WuRx power consumption for the sake of WSN sustainability. WuR has been introduced by Bdiri and Derbel [26], as a wake up receiver for real time constrained WSNs, showing how WuRx integration meets the stringent power requirements of time sensitive applications. Building on this, hutu et al. [27] proposed a new architectural design for WuRx to address deployment challenges and expand the application of WSN technology.

The performance gains afforded by WuRx based data forwarding techniques in green wireless networks have been empirically evaluated by Basagni, Koutsandria and Petrioli [28]. Le-Huy and Roy [28] studied low power WuRx technology for WSNs: tradeoffs between power consumption and system responsiveness and WuRx potential in mobile network applications.

Despite being still under active research, Wake up Receiver (WuRx) technologies are pushing towards being integrated into Wireless Sensor Networks (WSNs) to enable new advancements in network energy efficiency and performance. In this progress advanced routing techniques have had a great bearing. Chukwuka and Arshad [30] showed that WuRx technologies can be employed to improve energy savings in WSNs. Conversely, Ghadimi, Landsiedel, Soldati, and Johansson [31] developed an opportunistic routing metric applied on duty cycled WSNs to derive new techniques in improving performance of duty cycled WSNs by applying strategically the WuRx techniques for selecting routing to improve network efficiency. On top of WuRx applications, Blobel ([32] - [35]) extends the scope of wake up receiver based low power wsn to find utility in wildlife tracking, IoT networks, and industrial communications. WuRx can support low energy consumption and low delays without loss of communication performance, thereby making them adaptable and compatible with present state of the art network technologies, according to his research. This is complemented by the work of Whichi et al. [37] that uses MATLAB and OMNeT++ to perform a comprehensive simulation-based analysis of WuRx technologies. Finally, their results show that WuRx based systems outperform traditional MAC protocols like X-MAC and B-MAC in terms of energy efficiency and reliability and continue to afford the viability of WuRx found in modern digital communications environment.

Ding [38-40] introduces efficient signaling methods that minimize the energy used during the wake-up process. These techniques include the use of low-power wake-up signals and protocols that determine the optimal timing and frequency of these signals to reduce the overall network energy consumption while ensuring timely data transmission. The wake-up radio is engineered to be highly sensitive, requiring minimal energy to activate but robust enough to avoid false wake-ups caused by ambient radio frequencies.

In addressing the challenge of energy holes for multi-hop WSNs, Odedokun et al.[41] proposed an algorithm exploiting ultra low power WuRx and novel energy scheduling strategies. By optimizing energy distribution amongst sensor nodes, more particularly sensor nodes close to sink nodes suffering heavy transmission load, their study extends network lifetime by a large factor and brings up the throughput considerably.

Promising implementation of WuR-MAC protocols has also been achieved. In OMNeT++ simulations for indoor WSNs, Baazaoui et al. [42] demonstrated that WuR-MAC protocols significantly lower energy consumption while maintaining data integrity. Furthermore, the energy efficiency and enhanced performance of WuRx is compared to traditional duty cycled MAC protocols in confined environments. Like Sailaja and Benakop [43], tested different MAC protocols combined with the WuRx through NS2 simulations. They showed that a significant amount of these problematic issues like idle-listening and overhearing could be mitigated, to the benefit of network energy efficiency, delay, and node lifetime respectively.

Taken as a whole, these studies highlight the way in which WuRx technologies can collectively optimize energy efficiency and overall operational effectiveness in WSNs. These advancements directly address issues like interference, energy holes and idle listening which are critical for sustainable and high performance digital ecosystems, which in turn address issues of protocol development and system optimization. The evolution of energy efficient WSNs and joining larger IoT and industrial applications has been substantiated by this growing body of literature. In [44], FAWR-MAC Integrates dual-radio systems for multi-hop wake-up schemes. A centralized base station controls network operations, such as neighbor discovery and data requests. It provides high flexibility with support for diverse network topologies without requiring predefined routes. FAWR-MAC reduces collisions and latency via centralized coordination and dual data rates. The authors in [45] presents W2M-MAC (Wake-up Radio-based Multi-hop Multi-channel), an asynchronous MAC protocol for Wireless Sensor Networks (WSNs) leveraging wake-up radio (WuRx) technology. W2M achieves ultra-low power consumption and low latency by using WuRx for signaling and multi-channel communication for data exchange.W2M was compared to the Time Synchronized Channel Hopping (TSCH) protocol using simulations on the Contiki-NG platform. In low-traffic scenarios, W2M reduced energy consumption by at least 68% compared to TSCH. W2M also exhibited lower and more stable end-to-end delays, outperforming TSCH in terms of responsiveness.

III. IMPROVED ASYNCHRONOUS MAC (IA-MAC) PROTOCOL

We have proposed an improved pure asynchronous medium access control protocol for multi-hop wireless sensor networks using wake- up receiver which is best suitable for applications requiring long-term deployment and infrequent data transmission, such as environmental monitoring, structural health assessment, and disaster management. However, conventional Medium Access Control (MAC) protocols are often energy-inefficient due to their reliance on periodic idle listening and frequent control message exchanges. This paper introduces a novel Wake-Up Receiver (WuRx)-based MAC protocol designed to minimize energy consumption and optimize communication efficiency in WSNs with rare data transmission requirements. The proposed protocol leverages ultra-low-power wake-up receivers to eliminate the need for continuous listening, allowing sensor nodes to remain in sleep mode until explicitly triggered by an external event or data transmission request. Simulation and real-world deployment results demonstrate significant energy savings, extended network lifetime, and enhanced responsiveness to critical events. The protocol is particularly suited for low-duty-cycle applications such as forest fire detection, structural integrity monitoring, and remote wildlife tracking, where energy efficiency and prompt event-driven communication are paramount. This approach provides a scalable and robust solution for future energy- constrained WSN deployments.

The two main phases of IA-MAC are network discovery and data transmission phases which are used to manage asynchronous communication and energy efficiency in wireless sensor networks (WSNs) with wake-up receiver without any synchronization.

A. Network Discovery Phase

Network Discovery phase uses DiscoveryW Wakeup frame to maintain the topology of network. These are used to identify new nodes in the range of a sensor node according to wakeup receiver and maintain its forwarding table with node id, its parent node, hop distance from sink, battery percentage and flag bit which is 0 if two consecutive transmissions are unsuccessful otherwise 1. The sink broadcast a discovery wake-up frame to find nearby sensor nodes, upon receiving it nodes wake up, determine their position in the network (e.g., how many "hops" they are from the sink), and decide their "parent" node based on proximity or energy efficiency. This process helps to create a chain or pathway for communications from sink to SN through multiple nodes using forwarding table.

The wakeup frame format of 5 byte (Table I) and forwarding Decision table (Table II) are given below:-

Table I :-Wakeup Frame Format

8 bit	8 bit	8 bit	4 bit	4 bit	7 bit	1 bit
H/W Preamble	Destination address (for DiscoveryW) /Sender's Address (for ReplyW)	Parent's Address for ReplyW frame	hop distance from sink	Type of wakeup frame - DiscoveryW, ReplyW, DataReqW, UD_Req, UD_Rep, UD_Wup, UD_Wup_Rep	Battery Percent % (BP)	Flag (set to 0 if two consecutive transmissions are unsuccessful else 1

Table II :-Forwarding Decision Table

At Sink	Parent address	Hop distance	Battery %	Flag
node 1	2	2	100	1
node 2	0	1	100	1
node 3	0	1	100	1
node 4	3	2	100	1
node 5	2	2	100	1
node 6	0	1	100	1
node 7	0	1	100	1
node 8	0	1	100	1
node 9	3	2	100	1
node 10	6	2	100	1
node 11	6	2	100	1
node 12	7	2	100	1
node 13	8	2	100	1
node 14	8	2	100	1
node 15	10	3	100	1
node 16	11	3	100	1
node 17	12	3	100	1
node 18	13	3	100	1
node 19	14	3	100	1

The complete procedure is explained in fig. 1 to fig. 3 as follows:- Initially Sink broadcast DiscoveryW Frame (size 5 B=40 bit) to find out 1-hop neighbors. The sink will broadcast DiscoveryW frame to find out its 1-hop nodes by settling destination address and parent's address to itself i.e. 0x00 & hop distance =0, after receiving it, all 1-hop neighbors will set sink as their parent and update hop distance from 'null' to '1' and prepare ReplyW frame by adding sender's address to itself and parent's address to 0x00 (I.e. sink) and sets random back off timer to send it via main transceiver after doing CCA. Now sink has all its 1-hop neighbors.

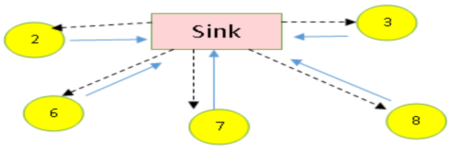

Fig.1. Network discovery at 1-hop of sink using transmission & reception of DiscoveryW and ReplyW wake-up frame received by WuRx at low data rate. Dotted Arrow represents transmission of DiscoveryW wake-up Frame, Solid Arrow represents parent selection by transmission of ReplyW wake-up Frame.

Then node 2. 3. 6, 7, 8 make sink as parent node and update forwarding table (FDT) by incrementing hop distance equal to hop distance + 1 = 0 + 1 = 1 from Null as shown in Table III.

Table III:- FDT at various nodes after network discovery at 1-hop of sink

node 2, 6,7, 8 & 3	Parent's address	Hop distance	Battery %	Flag
At node 2	0x00	1	100	1
At node 0	0x00	0	100	1
At node 6	0x00	1	100	1
At node 7	0x00	1	100	1
At node 8	0x00	1	100	1
At node 3	0x00	1	100	1

Now sink wants to know its 2-hop neighbors, for this purpose sink will send DiscoveryW frame to all 1-hop nodes one by one by adding their address as destination address and parent's address = sink address (sender of DiscoveryW frame). As shown in Fig. 2(i), when DiscoveryW has destination address =2 then all other nodes 6, 7, 8, 3 will not send this to their neighbors (broadcast in range of WuRx), now node 2 will send this DiscoveryW by inserting address of newly added neighbors (say node-1) or broadcast address if it is regular discovery process and parent's address field =2 now node-1 will update its parent address =2 from null and hop distance = hop distance into DiscoveryW (i.e.1) +1=2 and now will prepare a ReplyW frame with sender address
=1 and parent address =2 and hop distance =2, type=ReplyW, BP=100, flag=1 and send it to parent node 2 which will send this frame to its parent I.e. sink and now node-2 & sink will update FDT & topology information as shown in Fig. 2(ii).

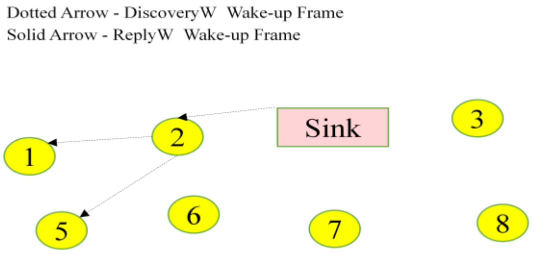

Fig. 2(i) DiscoveryW frame broadcasted by node 2

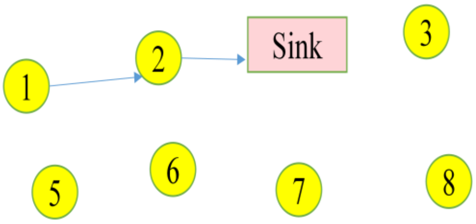

Fig. 2(ii) ReplyW frame with parent of node 1 is sent to sink via node 2

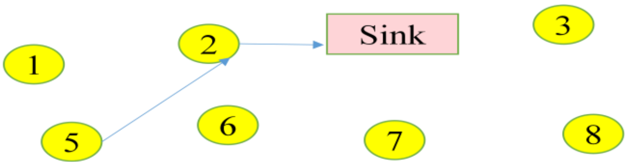

Fig. 2(iii) ReplyW frame with parent of node 5 is sent to sink via node 2

Now if node 2 has another node in its neighborhood (say node 5 which is stored whenever a node in the range send hello messages or hand shaking process) it will also prepare ReplyW message if it is initializing or updating parent address with min hop distance. After the random back off timer, node 5's ReplyW frame is sent to sink via all intermediate chain of Parents of parents as shown in Fig.
2(iii). It should be noted that node 2's discoveryW will be received by node 1, 5, 6 & sink but node 6 and sink do not respond it because they are not updating parent node. Since Battery percentage is 100% for all nodes so parent will be chosen according to hop distance and node 6 will not update FDT but node 1 & 5 will update as shown in Table III:-

Table IV: FDT at nodes 1 & 5 after network discovery at 2-hop of sink via 1-hop neighbor node 2

At node	Parent's address	Hop distance	Battery % (BP)	Flag
At node 1	0x02	2	99.9=100	1
At node 5	0x02	2	100	1

at time 'T_K' new nodes 10, 11, 12, 13, 14 are deployed then they will receive DiscoveryW frames from all possible nodes in the range whenever the sink initiates discovery process again. A node may choose/ update parent node P_i instead of P_{i-1} in FDT with other parameters if new frame provide better ratio of battery percentage and hop distance. if P_i has $BP_i>(BP)_{i-1}$ and $hop_i=(hop)_{i-1}$ then Parent (P_i) would be chosen as new parent with hop distance = $hop_{(i)}$ & $BP=(BP)_i$ in forwarding decision table (FDT). So we can see that node 11 may choose node 6 as parent having maximum Battery Percentage /hop distance value.
After time T_{k+r} , we have chosen parent from node 10 & 11 for node 15 as they have lower hop distance from node 19 and then node 10 would be chosen as parent since it has battery percentage=60>30 % of node 11, as shown in Fig. 3, thus every node will have a unique parent after network discovery phase.

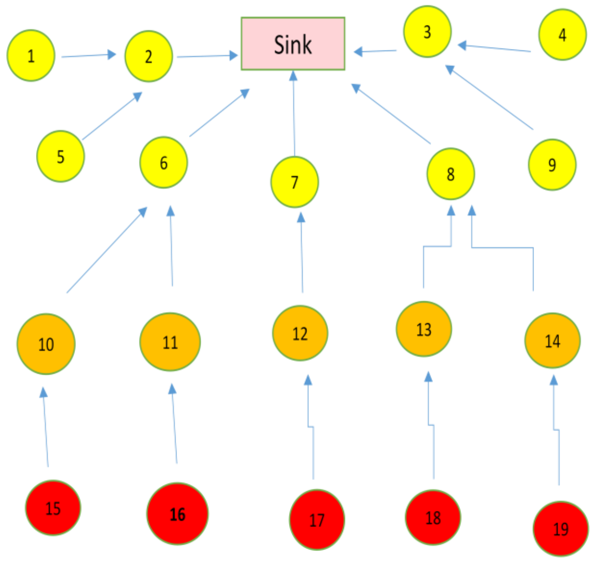

Fig.3. Parent node selection during network discovery process initiated by sink

It should be noted that CCA is done before each transmission to avoid collision. Since only one parent is selected by each S.N. so there is always a dedicated path from S.N. to sink at a particular time. OPWUM suffers from false wake ups while transmitting data frames because bit time for date frame (30x8bits/19.2x10^3 b/s = 12.5x10^{-3}s) is greater than the bit time of wake-up frame (26bits/5x10^3 b/s = 5.2x10^{-3}s). Size of Wake up frames & data rate selection for new approach is chosen such that it avoids false wakeups. The data rate of Wake up frame is taken 10kbps for size 5B=40 bit (H/W Preamble (8bit) + Source/Destination addr. (8bit) + Address of Parent (8bit) + hop distance (4bit) + type (4bit) + Battery percentage (7bit) + flag (1bit)) and the data rate of data frame is taken 500 kbps for size 20B to 40B to ensure time for data bit/frame transmission(0.32ms) is much shorter than the time for wakeup bit/frame transmission(3.2ms) i.e. $T_{frame(data)} < <. T_{frame(Wake\ up)}$ to avoid false wake ups during data frame transmission.

B. Data Transmission Phase

In data transmission phase, sink requests specific nodes to send their sensor data or a sensor node can transmit its data if significant change occurs in sensor readings or emergency data. The sink sends a DataReqW wake up frame at low data rate to a particular node. If the node is out of direct range, the DataReqW frame is forwarded by intermediate nodes until it reaches the target node. The node then sends its data back to the sink at high data rate using its main radio via nearest long range forwarder. This targeted communication minimizes unnecessary energy use because only specific nodes and pathways are activated when needed.

The sink periodically (once or twice in a day) collects data from sensor nodes. For that purpose it reserve T_n time slot for receiving data from each sensor nodes from n- node WSN. During this T_n period no S.N. is allowed to send data except the S.N. which receives the request for data from sink (except emergency data transmission.) by DataReqW wake up frame of 5B [H/W Pre (1B), Sync (1B), Node address (1B), Type of Data (1B)- Sensor, Battery % etc, Reserve time slot for complete data collection – it depends on number of hops from sink and data size with frame size & frame transmission time) (1B)]

All the sensor nodes will receive this (DataReqW) frame by their wake-up receivers and will decode node address and reserved slot for this data collection by sink so that the SN having unmatched address for itself & FDT in CL (Continuous Listening) state, will not contend for channel for this duration of time even for emergency data transmission (which occur when there in sensed data > Threshold value for emergency situation or ACK frame was not received from sink by a sensor node in last data collection cycle). If address is not matched with SN itself but matched with a node in FDT (Forwarding Decision Table) then it will switch on its main transmission and then forward (DataReqW) frame to next relaying / forwarding node in the path to destination but here current forwarding node will remain 'on' with main transceiver to contend for most promising forwarder to sink during data frame transmission process from destined sensor node to sink. Above process of next hop relaying/ forwarding of (DataReqW) wake up frame continuous until it reaches to destined node having its address as given in (DataReqW) frame. During this process all the relaying nodes remain active to support data reception path from destined sender node to sink. Now the requisite sender of data frame, will send RTS control frame from main transceiver using higher data rate (e.g. 500 kbps) that will be detected by the main transceiver of the relaying nodes in the path created by (DataReqW) frame from sink to sender node then each intermediate node listening RTS will compute a back off timer proportional to hop distance from sink and send CTS to sender node after back off timer. Thus the nearest forwarder to sink having minimum back off timer is selected. Since other nodes between sender and this forwarder will detect CTS and switch off their main transceiver.

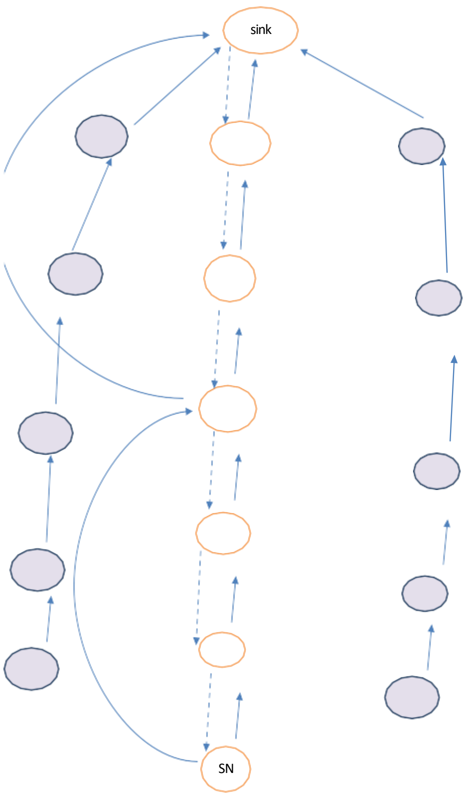

Fig.4. Data Transmission Phase

(solid arrows indicate unique parent node of each node in wsn, Dotted arrows indicate DataReqW wake-up frame transmission at low data rate and received at wakeup receiver range according to FDT. Curved solid arrows indicate the transmission of RTS/CTS/Data/Ack frame at high data rate and received at main receiver range according to optimum forwarder selection using min. hop distance from sink.)

After receiving this (CTS) signal from most nearest possible forwarder-1, the sender will send data frame to forwarder-1, all other relaying nodes from forwarder-1 to sink, will not contend for transmission until they get (RTS) from forwarder-1. After receiving data from sender, the forwarder-1 will choose the min-hop (from sink.) forwarder- 2 to transmit data to sink. This process continues until sink (having hop distance to sink = 0) do not receive RTS from forwarder-K, The Sink will set its back off timer=0 or less than time to CCA (Clear Channel Assessment) and sends CTS immediately after CCA to forwarder-K. Thus sink received the data from (K+1) hop separated sender (Sensor node) in WSN. Now ACK frame is sent by sink to forwarder-K then it forwarded (ACK) to (forwarder-K-1) and so on to reach at sender.

Now these forwarders from (forwarder-1) to (forwarder-K) remain active up to $T_{Retransmission} = T_{frame(FW-(K))} + T_{frame(FW-(K-1))} + \ldots\ldots\ldots\ldots + T_{frame(FW-2)} + T_{frame(FW-1)}$ to support retransmission and then go into continuous listening mode using WuRx by switching off main transceiver where $T_{frame(FW-(K))}$ is the frame transmission time from forwarder-k to sink. Now sender node will go into continuous listening mode using WuRx but switching off main transceiver. If forwarder-1 receive any data frame Retransmission during $T_{frame(FW-1)}$ then (forwarder-1) will wait for data packets from the relaying nodes and each relaying nodes can transmit data frame after [(hop+1) x Frame transmission time (at high data rate)] time if there is a significant change in sensed data from previous transmission. Thus sink can have all intermediate sensors' data with significant change in a queue (buffer) from destined/ desired node to sink for efficient utilization of wake up schedule of this Data Request.

C. Emergency Data Transmission

Whenever a node has sensed data greater than threshold value that may be hazardous for the system if ignored then it will switch on its main transceiver with some light signal or fume signal from node and will listen/ sense the carrier from ongoing transmission from a distance apart within the range of main transceiver if there is any ongoing transmission then it will wait for time equal to ((hop distance from sink) x (frame transmission time)) to sense channel again and again until channel is free. Now if channel is free then it will broadcast a urgent data request frame (UD_Req) using high data rate by main transceiver which can be heard by all nodes in the range of this SN which are part of any data collection path created by some DataReqW frame. Then all active nodes will wait until the time of data transmission mentioned (UD_Req) frame. If this (UD_Req) frame is listened/ received by some intermediate SNs which are in the path created by (DataReqW) frame during data collection process of sink then those intermediate nodes may contend to become forwarder-1 by sending (UD_Rep.) frame to the sender node of UD_Req after waiting for the back off time proportional to (hop distance from sink).The sender of first UD_Rep received will be selected as forwarder-1(FW-1). Now SN will send urgent data in (UD_data) frame to (FW-1) and then (FW-1) will send (UD_Req) frame to the all nodes in the path from this (FW- 1) to sink. It will avoid other future transmission in the range of (FW-1)'s transmission and all active nodes can contend to become (FW-2) for UD transmission. The above mentioned process is repeated at each forwarder node until a forwarder gets a (UD_Rep) from sink and then it will send (UD_data) to sink. After this (UD_data) frame transmission, sink will send (ACK) frame to original sender node of UD_data frame via all intermediate forwarders. When ACK received by all forwarders they will wait for the time = n x T(fr) where n = max hop distance from sink to terminal node of wsn and T(fr)= frame transmission time using high data rate.

Now if S.N. having urgent data does not receive any (UD_Rep) frame by any node at its main receiver then it will send a (UD_Wup) using low data rate of main transceiver to its parent node with destination address as sink address and all nodes receiving this (UD_Wup) frame will forward it using low data rate to their parent node until it reaches to sink and will remain in active mode until the time mentioned in (UD_Wup) frame for this complete transmission. After receiving (UD_Wup) frame the sink broadcast control frame named (UD_Wup_Rep) frame via high data rate, the intermediate node with min. hop distance from SN having urgent data will set min. back off timer to send this (UD_Wup_Rep) frame and above process continues until this reply control frame reaches to originated SN having UD_data frame. After receiving (UD_Wup_Rep) frame, the SN will choose that transmitting node as next forwarder (FW-1) for (UD_data) frame and sink will receive it via all forwarder as chosen in downward path.

Note that each transmission of wakeup, control and data frames is done after CCA done by main transmission to avoid collision and the data collection by sink in a periodical process but urgent data transmission by a S.N. is very rare process so it is very rare that both can happen same time and collision may occur, however (UD_Req) and (UD_Rep) frame will play the same role as RTS CTS in CSMA/CA with some modification as per wsn requirements only.

IV. ENERGY ANALYSIS

In this section, we will derive the equations for energy consumption in data collection phase initiated by sink to collect sensory data of a sensor node 'k' at k-hop distance from sink (say E_K), here if we take E_{DRW}, E_{RTS}, E_{CTS}, E_{Data}, E_{ACK}, E_{IDLE} and $E_{on\text{-}off}$ as total energy consumed in transmission and reception of DataReqW wakeup frame, RTS, CTS, data & ACK frames and total energy consumed in idle listening & switching on/off of main transceiver by each node in the path from sink to node 'k' respectively, then E_k can be calculated as follows:-

$$E_K \cong E_{DRW} + E_{RTS} + E_{CTS} + E_{DATA} + E_{ACK} + E_{IDLE} \quad (1)$$

For each node 'i' during this data collection process, if $P_{(i)R}^{WuRx}$ denotes power consumed by WuRx in reception of DataReqW wakeup frame at low data rate and $P_{(i)T}^{ML}$ is the power consumed in transmission of DataReqW wakeup frame by main transceiver at low data rate. $P_{(i)R}^{MH}$ *and* $P_{(i)T}^{MH}$ denotes power consumed in reception and transmission of a frame by main transceiver at high data rate then energy calculations can be approximated as per discussion in section III.

$$E_{DRW} \cong \sum_{i=1}^{k}\left(P_{(i)R}^{WuRx}\, T_{DRW} + P_{(i)on}^{M}\, T_{wakeup}\right) + \sum_{i=1}^{k-1} P_{(i)T}^{ML}\, T_{DRW} \quad (2)$$

$$E_{RTS} \cong \sum_{i=1}^{\lceil k/3 \rceil}\left(C_1\, P_{(i)R}^{MH}\, T_{RTS} + P_{(i)T}^{MH}\, T_{RTS}\right) \quad (3)$$

$$E_{CTS} \cong \sum_{i=1}^{\lceil k/3 \rceil}\left(C_2\, P_{(i)R}^{MH}\, T_{CTS} + P_{(i)T}^{MH}\, T_{CTS}\right) \quad (4)$$

$$E_{DATA} \cong \sum_{i=1}^{\lceil k/3 \rceil}\left(P_{(i)R}^{MH}\, T_{DATA} + P_{(i)T}^{MH}\, T_{DATA}\right) \quad (5)$$

$$E_{ACK} \cong \sum_{i=1}^{\left\lceil \frac{k}{3} \right\rceil}\left(P_{(i)R}^{MH}\, T_{ACK} + P_{(i)T}^{MH}\, T_{ACK}\right) \quad (6)$$

$$E_{IDLE} \cong \sum_{i=1}^{k} P_{(i)IDLE}^{M}\, T_K \quad (7)$$

where T_{DRW},T_{RTS}, T_{CTS}, T_{DATA}, T_{ACK}, denotes frame transmission time of DataReqW wakeup frame, RTS, CTS, Data and ACK frames at low data rate and T_{wakeup}, $P_{(i)on}^{M}$ is time & power required to switch on main transceiver from sleep state on receiving wakeup frame via WuRx, T_K is the time allotted by sink for data collection from node 'k' at k-hop distance and $P_{(i)IDLE}^{M}$ is the power consumed in idle listening by each node 'i' during this data collection. Here C_1 & C_2 are positive integer constant representing the number of intermediate node receiving RTS & CTS signals respectively which are typically 3 & 6 for the selected reception range of main and wakeup receiver. For the next (k-1) pipelined data transmission in the path from node 'k' to sink will consume energy less than $E_K - E_{DRW}$ i.e. $E_{k-1} < (E_K - E_{DRW})$ for K=K-1 to 1.

Now following equation (8) will define the approximate energy consumption by a node 'i' (E_{Node}^{i}) to transmit its data to sink, here T_i is same as T_K i.e. the time allotted by sink for data collection from node 'i' at i-hop distance from sink.

$$E_{Node}^{i} \cong P_{(i)R}^{WuRx}\, T_{DRW} + P_{(i)on}^{M}\, T_{wakeup} + P_{(i)T}^{MH}\, T_{RTS} + C_2\, P_{(i)R}^{MH}\, T_{CTS} + P_{(i)T}^{MH}\, T_{DATA} + P_{(i)R}^{MH}\, T_{ACK} + P_{(i)IDLE}^{M}\, T_i \quad (8)$$

V. SIMULATION SETUP

A 24-hour multi-hop network simulation is conducted with one sink and varying spatial node densities (5 to 50 sensor nodes, SNs) randomly deployed over a 10,000 m^2 area. This WSN setup is simulated using the OMNeT++ network simulation engine, with the MiXiM framework for wireless sensor networks (WSNs) applied to model a dual- radio hardware platform. For the experiments, WSN PowWow platform [46] is used which combines the CC1101 RF transceiver and the MSP430 microcontroller made by Texas Instruments. Since the wake-up receiver (WuRx) of this work employs only On-Off Keying (OOK) modulation, it is within the permissible modulation techniques specified by the CC1101 RF chip in the 868 MHz frequency band. The configurable set of the transceiver offers a variety of data rates from 0.6 kbps to 600 kbps. It is shown in these simulations that all Wake-up frame (whichever the purpose of Wake-up frame, be it Wake-up frame for discovery frame or Data Request frame), all Wake-up frame were sent to SN's at lower data rate of 19.2 kbps. Packets of data and those for the acknowledgment were sent with a transmission rate of 500 kbps.

Every SN present in the simulation has a wake-up radio prototype with a -46 dBm sensitivity which provides a communication range of about twenty meters when using an antenna with a gain of 2 dBi and an effective transmission power of 12 dBm. The clock frequency of the MSP430 microcontroller is 5 MHz and consumes 3.1mA & 3.2uA in active mode and sleep mode respectively. The energy usage of a PowWow node with a WuRx has been thoroughly studied, and the resulting energy profiles are given in Table V. The MSP430 provides one active and five low-power modes that can be selected via software. In that regard, size of wakeup frames are 4B and size of data and acknowledgment frames are 20B. The current consumption of wake up receiver in idle listening and reception per bit is 0.33 uA and 44 uA while these values are 16.9 mA for main transceiver.

The transmission requires 34.2 mA by main radio at 12dBm. At a data rate 0f 500 kbps with a receiver sensitivity of -82dBm the main radio can communicate up to 91.5 meters(theoretically) 60 meters (practically) in free space conditions and for non line of sight environments, the path loss exponent (n) may increase and range may be reduced to 40-60 meters for n={3,4}.

Table V: Simulation Parameters

Parameter	Value
Simulation Duration	24 hours
Network Type	Multi-hop Wireless Sensor Network (WSN)
Simulation Area	100m X 100m =10,000 m^2
Number of Sensor Nodes (SNs)	5–50 (uniformly deployed)
Sink Node	1 (fixed)
Simulation Tool	OMNeT++
Framework	MiXiM for WSN
Hardware Platform	PowWow (CC1101 RF transceiver + MSP430 microcontroller)
Wake-Up Modulation	On-Off Keying (OOK)
Frequency Band	868 MHz
Wake-Up Frame Data Rate	19.2 kbps
Data Transmission Rate	500 kbps
Wake-Up Receiver Sensitivity	-46 dBm
Receiver Sensitivity (Main)	-82 dBm
Communication Range (WuRx)	20 m (at antenna gain: 2 dBi, transmission power: 12 dBm)
Communication Range (Main)	91.5 m (theoretical), 60 m (practical), 40–60 m (non-line-of-sight, for n={3,4})
Clock Frequency (MSP430)	5 MHz
Current Consumption (Active)	3.1 mA (3.1 mA (MCU), 16.9 mA (main transceiver), 0.33 µA (WuRx idle))
Current Consumption (Sleep)	3.2 µA (3.2 µA (MCU), negligible for WuRx)
Wake-Up Frame Size	4-10 Bytes
Data Frame Size	20-128 Bytes
Acknowledgment Frame Size	10-20 Bytes
Idle Listening (WuRx)	0.33 µA
Reception (WuRx)	44 µA
Main Transceiver Idle	16.9 mA
Main Transceiver Transmission	34.2 mA (at 12 dBm)
Path Loss Model	Free-space propagation
Traffic Model	Poisson traffic
Event Generation Interval	Twice a day
Energy Model	Battery-powered nodes with energy consumption profiles

VI. RESULTS AND DISCUSSION

A. Collision

The percentage of average collision rate is calculated according to the ratio of total packets collided out of total packets transmitted. As shown in Fig. 5, IA-MAC has the minimum average collision rate than OPWUM & FAWR- MAC for the various node densities in WSN, IA-MAC has maximum package delivery ratio. In OPWUM, collision may occur due to simultaneous transmission of RTS.

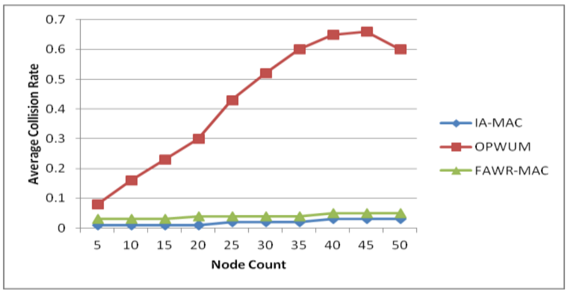

Fig.5. Node Count vs. Average Collision Rate (%)

Besides, CTS frame may also collide as randomization of back off timer can't guarantee different time period every time. False wake-ups may also incur collision in OPWUM. Network discovery phase of FAWR suffers collision when some nodes perform CCA at same time period and then transmit the data at the same time to sink. Similarly in data transmission phase, a node may falsely wake up during wake up frame transmission and may start data transmission during the transmission of requisite data by an actual sender since FAWR does not perform RTS CTS before data transmission. IA-MAC uses RTS, CTS using main transceiver with higher data rate which refrain data transmission by another node in a better coverage area while OPWUM uses RTS, CTS at low data rate for wake up frame and FAWR directly start data transmission to sink ignoring any transmission due to false wakeup. OPWUM also suffers from false wake-ups during data transmission since difference in bit-time of wakeup frame and data frame is not sufficient. FAWR and OPWUM may suffer very high collision for urgent data transmission by various nodes at same time and/or regular data frame may collide with UD frame, however it is not discussed by authors.

B. Latency

The latency is very high for synchronous, pseudo synchronous and asynchronous MAC protocols without wake-up radio if we count the latency from the time stamp when the data is available to send but here we calculate the latency from the time when data transmission phase is started by sink or sensor node and data is successfully received by sink. Thus latency includes wakeup/control frame transmission and processing time from source to destination with the propagation, transmission, processing and queuing time of data frame during data transmission phase. That is how average latency is calculated to transmit sensory/ emergency data from sensor node to sink.

As depicted in Fig. 6 FAWR outperforms IA-MAC due to assumption that sink is in the direct range of each sensor node and vice versa but IA-MAC has low latency than OPWUM since OPWUM uses hop by hop transmission using WuRx range while IA-MAC uses main Transceiver range based hop by hop transmission of data frame using promising forwarder having minimum hop count from sink.

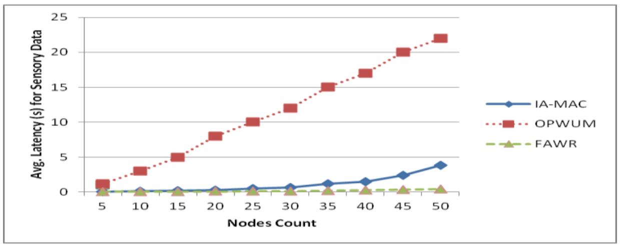

Fig.6. Node Count vs. Avg. Latency (s) for Sensory Data

Although there is no mechanism to send emergency data transmission until sink starts or initiate data transmission phase in FAWR, yet it has lowest latency (as depicted in Fig. 7) since this waiting time is not considered in latency and single-hop data transmission support. However a sender can transmit emergency data in OPWUM and IA-MAC by multi-hop communication. Whereas OPWUM suffers from collision and low range transmission, the IA-MAC creates a path from sender to sink and transmit data hop by hop using nearest forwarder to sink mechanism by avoiding collision using RTS and CTS.

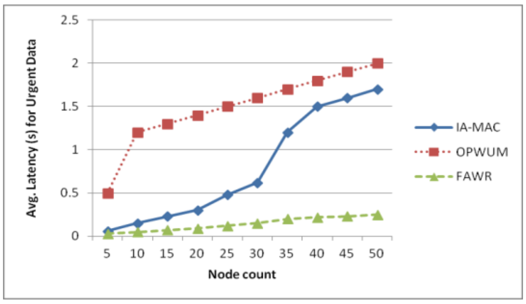

Fig.7. Node Count vs. Avg. Latency (s) for Emergency Data

C. Idle Listening

In IA-MAC, all intermediate node in a data transmission path is created by wake up frames, suffers from idle listening whereas OPWUM only encounter negligible idle listening when it starts RTS CTS process and CCA after each transmission of data and ACK but suffers from false wake ups but FAWR encounters idle listening by sender to receive ACK after data transmission and during neighbor discovery process. In IA-MAC, all intermediate node in a data transmission path is created by wake up frames, suffers from idle listening. As it can be observed in Fig. 8 that for IA-MAC, there is no significant change in average idle listening for node count 35-50 because hop count from sink to sensor nodes does not change for data transmission via main radio with higher range at higher data rate.

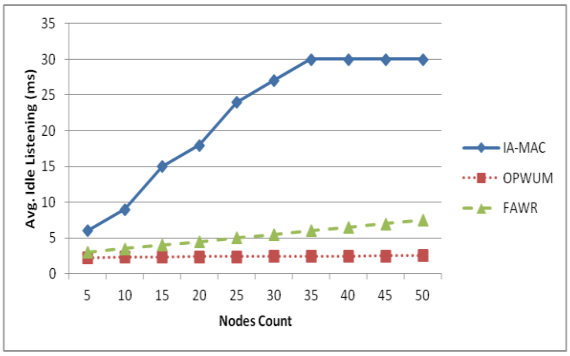

Fig.8. Node Count vs. Average Idle Listening

It should be noted that the idle listening is very high for synchronous, pseudo synchronous and Asynchronous MAC protocols without wake-up radio since they use high power main receiver for idle listening waiting for possible data transmission in each duty cycle or synchronization phase, thus not suitable for 24x7 continuous monitoring applications.

D. Energy Consumption

For various node densities, Fig. 8 depicts average energy consumed to transmit a data frame from sender to sink during data transmission process including energy consumed to transmit and receive wakeup frame with address decoding. It can be observed that energy consumption is approximately same for IA-MAC and FAWR up to 20 nodes because sink is in direct range of sensor nodes of IA-MAC so it also transmit data directly to sink like FAWR after receiving pipelined wakeup frame from sink. But after 20 nodes, IA-MAC transmits data by more than 1 hop where FAWR consumes less energy due to the assumption that direct data transmission is feasible from each node to sink by main transceiver. OPWUM consumes more energy since it uses hop by hop data transmission via nodes in WuRx range.

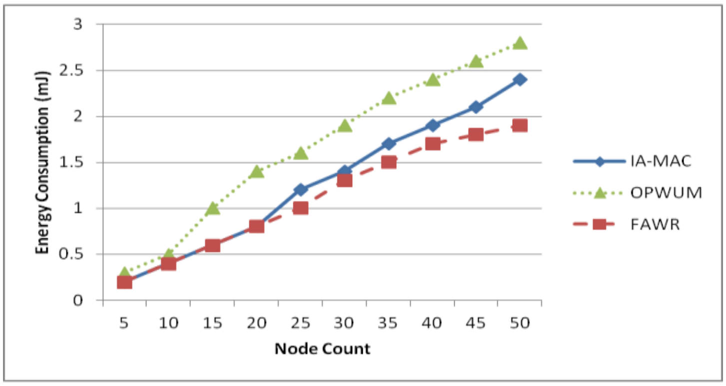

Fig.9. Node Count vs. Average Energy Consumption

VII. CONCLUSION AND FUTURE DIRECTIONS

The proposed IA-MAC protocol demonstrates significant improvements in energy efficiency, latency reduction, and collision minimization for Wireless Sensor Networks (WSNs), making it a robust solution for low-duty- cycle and critical surveillance applications. By leveraging ultra-low-power wake-up receivers and a novel multi-hop communication strategy, IA-MAC outperforms existing protocols like OPWUM and FAWR in terms of collision reduction, average latency, idle listening, and energy efficiency. The use of high-range main transceivers combined with wake-up radio technology allows IA-MAC to achieve efficient data transmission with minimal energy consumption, even in high-density node deployments. The findings demonstrate that IA-MAC effectively mitigates issues like false wake-ups and unnecessary energy usage, which are prevalent in other protocols. Furthermore, the protocol ensures reliable multi-hop communication and supports emergency data transmission, making it highly suitable for critical applications such as environmental monitoring and disaster management. These results validate the potential of IA-MAC to enhance network longevity and performance in energy-constrained environments.

Future work could explore the integration of IA-MAC with advanced energy harvesting technologies and adaptive machine learning algorithms to enhance its performance under dynamic network conditions. Additionally, real-world deployment and testing in diverse environments such as urban IoT systems or remote monitoring scenarios will further validate the protocol's scalability and robustness while uncovering opportunities for further optimization.

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