LOW-TRAFFIC AWARE HYBRID MAC (LTH-MAC) PROTOCOL FOR WIRELESS SENSOR NETWORKS

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Abstract: This paper proposes LTH-MAC (Low-Traffic Aware Hybrid MAC), a novel MAC protocol designed to improve energy efficiency and message delivery reliability in Wireless Sensor Networks (WSNs). LTH-MAC achieves this through innovative techniques like flexible timeslots, channel selection, collision-avoiding, parallel transmissions, and efficient backoff schemes. These optimizations lead to reduced idle listening, minimized collisions, and simplified synchronization. Simulations using OPNET environment demonstrate that LTH-MAC significantly reduces energy consumption, especially under light traffic loads. Additionally, LTH-MAC provides lower end-to-end latency and higher message delivery reliability compared to ECoMAC. These advancements position LTH-MAC as a compelling solution for WSN applications demanding efficient and reliable communication.

Key words: Wireless Sensor Network, Energy Efficient, latency, Hybrid MAC Protocol, OPNET.

1. INTRODUCTION

Energy-efficient communication is critical for wireless sensor networks (WSNs) due to their limited battery life. This is particularly true in applications like forest fire monitoring, where low traffic conditions prevail. This paper proposes LTH-MAC, a novel hybrid MAC protocol specifically designed for such low-traffic WSNs.

Existing MAC protocols like CSMA, TDMA, and FDMA offer various advantages, but also have limitations. CSMA, while flexible, suffers from collisions. TDMA and FDMA can be energy-efficient, but their lack of adaptability hinders performance in diverse traffic patterns. LTH-MAC addresses these challenges by innovatively combining elements of CSMA, TDMA, and FDMA.

This paper proposes a novel Energy-Saving Hybrid MAC (LTH-MAC) protocol specifically designed for wireless sensor networks (WSNs). LTH-MAC addresses the challenges of idle listening, collisions, overhearing, and protocol overhead through a combination of innovative techniques. These include multi-band communication with TDMA, a dynamic channel selection algorithm, packet fragmentation with selective repeat ARQ, prioritized broadcast transmissions, and a priority-based backoff algorithm.

LTH-MAC aims to improve network performance by minimizing energy consumption, reducing latency, and enhancing scalability compared to existing protocols.

The remaining sections detail LTH-MAC and its benefits: Section 2 provides an overview of existing WSN MAC protocols; Section 3 details the design principles and algorithms of LTH-MAC; Section 4 presents simulation results comparing LTH-MAC with existing protocols; and Section 5 concludes with key findings and future research directions.

2. RELATED WORK

In Wireless Sensor Networks (WSNs), where battery power is a critical resource, the Medium Access Control (MAC) layer plays a vital role. Existing MAC protocols address this challenge by employing various techniques like Carrier Sense Multiple Access (CSMA) to reduce collision risks, Time Division Multiple Access (TDMA) to assign transmission slots, and Frequency Division Multiple Access (FDMA) to prevent interference [1].

Diverse approaches characterize WSN MAC protocols. Protocols like SMAC and TMAC (combining CSMA/TDMA with sleep-wake schedules) offer improved energy efficiency but require complex synchronization [1, 2]. Zebra-MAC and HyMAC achieve dynamic adaptation for traffic load, scalability, and throughput, respectively, but introduce overhead due to frequent mode switching [2]. Building upon HyMAC, EE-MAC incorporates adaptive priority for diverse traffic scenarios [3]. Notably, ECoMAC, designed for low-traffic WSNs, utilizes a combination of CSMA, TDMA, and FDMA techniques [2, 4]. Beyond these examples, other approaches address specific challenges: channel hopping (CH-MAC/DF-MAC) for dynamic frequency changes [5, 6], and adaptive slot sizes/contention strategies (ASA/CASA) based on network conditions [7, 8].

Recent studies explore diverse methods to enhance WSN energy efficiency. This includes data transmission models leveraging cross-layer design for IoT, leading to significant energy savings and reduced overhead [9]. In smart agriculture, sensor data optimization improves efficiency [10]. Furthermore, research on multi-channel scheduling and routing in wireless mesh networks demonstrates reduced interference and lower energy consumption [11].

These diverse approaches highlight the ongoing efforts towards developing adaptive, dynamic, and intelligent MAC protocols that effectively address the evolving needs of WSNs, particularly in terms of energy efficiency, reliability, and scalability.

3. LTH-MAC PROTOCOL DESIGN

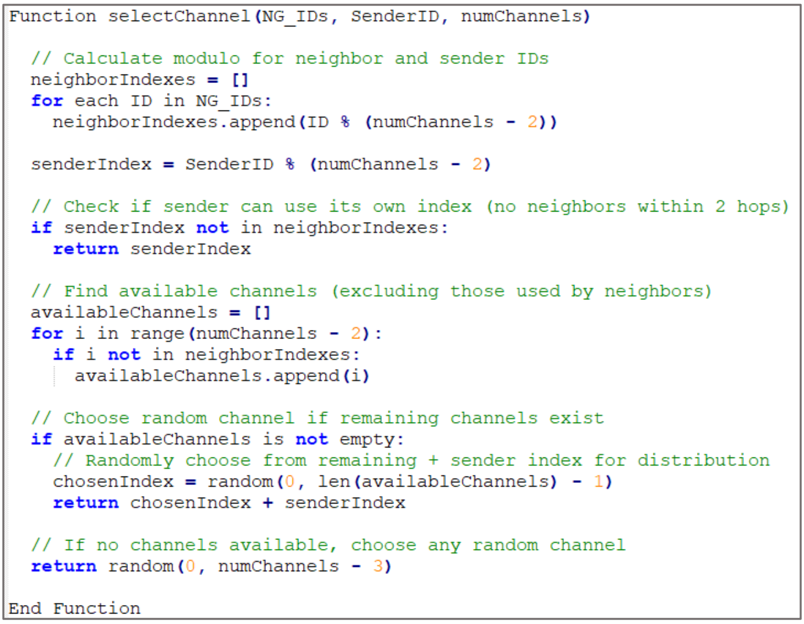
This section introduces the design of our novel Energy-Saving Hybrid MAC (LTH-MAC) protocol, aiming to improve both network lifetime and data delivery speed (latency) in wireless sensor networks (WSNs). LTH-MAC builds upon existing research [2] and addresses four key energy-wasting factors: idle listening, collisions, overhearing, and protocol overhead. It tackles these challenges by combining multi-band communication and time-division multiple access (TDMA) for efficient channel access, alongside innovative strategies for minimizing energy consumption and reducing latency.

3.1. Simplified Timeslot Structure for Enhanced Performance

Our novel LTH-MAC protocol features a single-level structure with equal timeslots, eliminating complex slot assignment and offering benefits like reduced energy consumption, improved latency, and enhanced scalability/mobility. It leverages slotted CSMA with reduced contention for lower traffic scenarios, minimizing idle listening and control packet overhead. Additionally, distributed synchronization and on-demand maintenance further optimize energy efficiency by minimizing unnecessary sleep-wake transitions and collisions. These features collectively contribute to LTH-MAC's superior performance.

3.2. Multi-Channel Communication

This section explores the use of multiple channels to improve data packet delivery and reduce latency in our proposed protocol. To avoid collisions between data and control packets, we designate the last channel (*n-1*) for sending requests (RTS), the one before the last (*n-2*) for synchronization, and the remaining channels for data transmission. This approach eliminates the need for complex channel allocation algorithms typically found in protocols like HyMAC [2], which can be resource-intensive for sensor nodes.



```
Function selectChannel(NG_IDs, SenderID, numChannels)

  // Calculate modulo for neighbor and sender IDs
  neighborIndexes = []
  for each ID in NG_IDs:
    neighborIndexes.append(ID % (numChannels - 2))

  senderIndex = SenderID % (numChannels - 2)

  // Check if sender can use its own index (no neighbors within 2 hops)
  if senderIndex not in neighborIndexes:
    return senderIndex

  // Find available channels (excluding those used by neighbors)
  availableChannels = []
  for i in range(numChannels - 2):
    if i not in neighborIndexes:
      availableChannels.append(i)

  // Choose random channel if remaining channels exist
  if availableChannels is not empty:
    // Randomly choose from remaining + sender index for distribution
    chosenIndex = random(0, len(availableChannels) - 1)
    return chosenIndex + senderIndex

  // If no channels available, choose any random channel
  return random(0, numChannels - 3)

End Function
```

Figure 1. Pseudocode for Channel Selection Algorithm

Unlike pre-assigned schemes, LTH-MAC dynamically selects data channels using a simple two-hop neighbor-based algorithm. This leverages readily available network information and avoids overhead. The algorithm prioritizes unique channels, checking the sender's own index first, then searching for unused channels among neighbors. As a last resort, a random channel is chosen. This balances efficient utilization with minimizing interference.

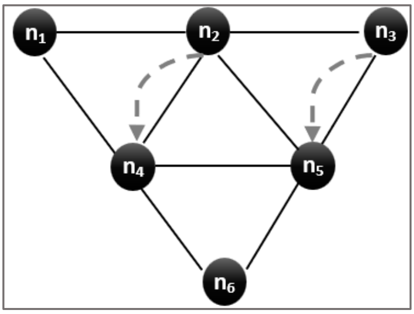


Figure 2. Illustrative Network topology Example with Two-Hop Communication Range

As an example, consider the network scenario in Figure 2 with eight available channels ($n = 8$) and node IDs (n_i) = i. Each node (n_1, n_2, n_3, n_4, n_5, and n_6) will select a unique channel (1, 2, 3, 4, 5, and 0) using the proposed algorithm. This multi-channel approach enables simultaneous data transmission by nodes within two hops during the same timeslot. Figure 2 depicts this scenario, where adjacent nodes n_2 and n_3 (within one hop) can send data concurrently to nodes n_4 and n_5, respectively.

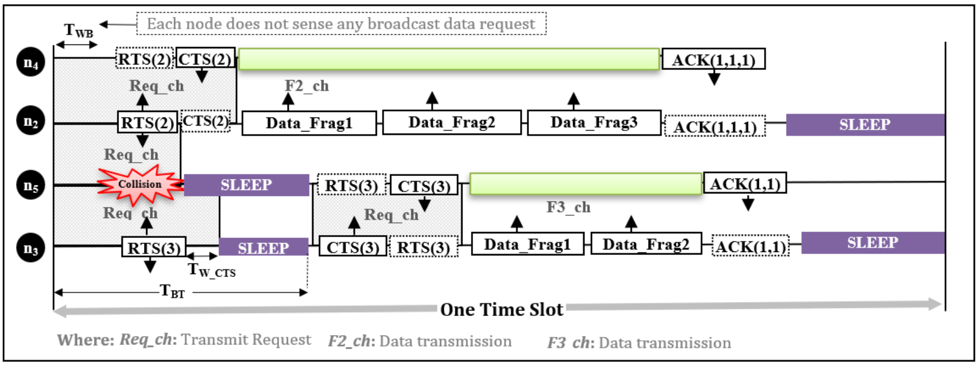


Figure 3. Concurrent Unicast Transmissions in a Single Timeslot

However, using a single request channel (Req_ch) could lead to collisions at common neighbors, as shown in Figure 3. In this example, nodes n_2 and n_3 send RTS packets simultaneously, causing a collision at node n_5. While n_4 successfully receives the CTS and transitions to the data channel, n_5 enters sleep mode due to the ongoing broadcast transmission, unnecessarily wasting energy. Additionally, n_3 fails to receive a valid CTS and enters sleep mode. After the broadcast transmission, both n_3 and n_5 wake up and n_3 retransmits its request, including the chosen data channel (*F3_ch*). By successfully transmitting its data during the retransmission attempt in the same timeslot, n_3 avoids additional delays.

To mitigate these issues, our protocol employs packet fragmentation and selective repeat ARQ. By dividing long data packets into smaller fragments, the impact of collisions is limited to specific fragments, minimizing retransmissions, and improving latency and energy efficiency (Figure 3). Furthermore, selective repeat ARQ ensures that only corrupted fragments are retransmitted, further reducing overhead and energy consumption.

In conclusion, this multi-channel communication strategy, combined with packet fragmentation and selective repeat ARQ, enhances data throughput by enabling concurrent transmissions, reduces the likelihood of collisions on data channels, and improves overall network performance in terms of latency and energy efficiency.

3.3. Enhanced Broadcast and Unicast Transmission in a Single Timeslot

We introduce the Request To Broadcast (RTB) control frame, allowing nodes to initiate broadcasts with priority over unicast transmissions. When a node needs to broadcast data to its direct neighbors (within one hop), it sends an RTB at the timeslot's beginning, specifying the chosen broadcast channel *Fb_ch*. Sender and its neighbors then switch from the request channel *Req_ch* to *Fb_ch* for the broadcast duration (Figure 3). Broadcast data is transmitted as a single packet to avoid fragmentation.

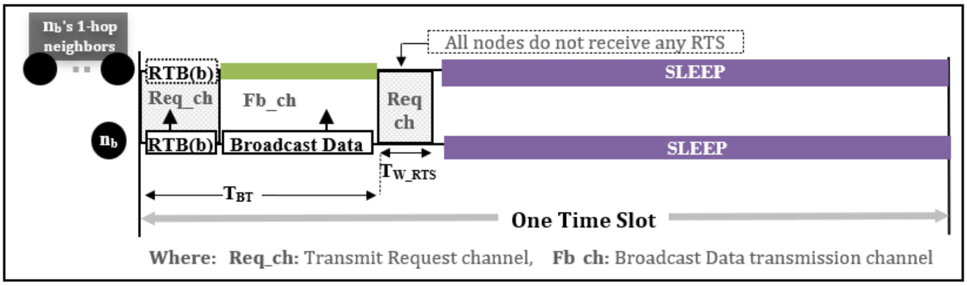


Figure 4. Broadcast Data Transmission Within a Timeslot

Following the broadcast, all participating nodes return to *Req_ch* to handle potential unicast transmissions within the same timeslot. In Figure 4, the absence of RTS packets leads to all nodes entering sleep mode for the remaining timeslot, optimizing energy consumption.

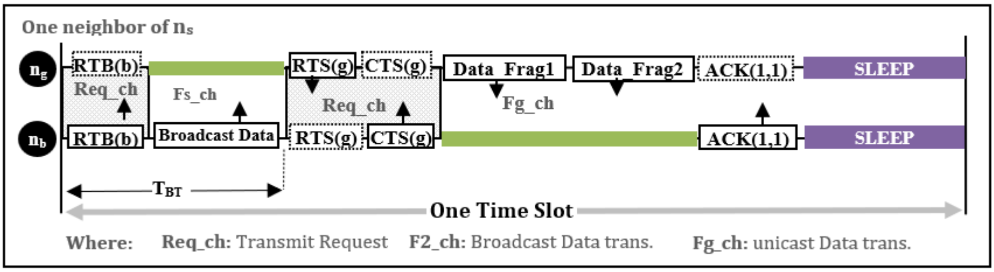


Figure 5. Concurrent Broadcast & Unicast Transmission in a Timeslot

Figure 5 demonstrates the protocol's ability to handle both broadcast and unicast transmissions within a single timeslot. A neighbor node (n_g) sends an RTS and transmits unicast data simultaneously, preventing collisions and minimizing energy waste. Additionally, allowing all nodes to send unicast data after a broadcast within the same timeslot reduces overall network latency.

3.4. Prioritized Channel Access and Backoff Algorithm for Efficient Unicast Transmission:

Following the completion of broadcast data transmission, nodes intending to send unicast data initiate the process by sending an RTS packet. As illustrated in Figure 6, simultaneous RTS transmissions from nodes n_1 and n_3 directed towards n_2 can result in a collision. To efficiently manage such situations and minimize energy waste, node n_2 employs a low power listening technique while waiting for a valid RTS packet or a predetermined timeout (TCW_MAX). Upon detecting a collision (no response within TW_CTS), both n_1 and n_3 utilize a backoff algorithm to determine the waiting time before retransmitting with a second RTS packet.

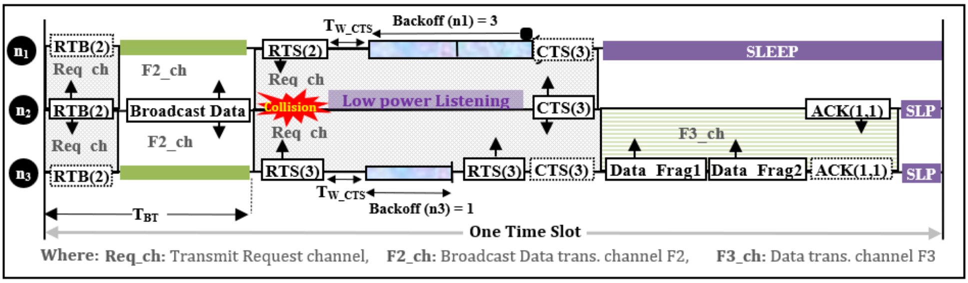


Figure 6. Broadcast and Unicast Transmission Handling Collision Within Timeslot

Choosing the right backoff approach plays a critical role in balancing energy consumption and reducing collision occurrences during data access. This protocol specifically employs a priority-based channel access scheme. Here, a dynamic priority is assigned to each node based on the number of consecutive failed access attempts. By adjusting the initial contention window size (CW_{min} to CW_{max}), the protocol offers increased access opportunities for nodes with higher priority. Figure 7 depicts six distinct priority levels (L_0-L_5) assigned to nodes according to their failed access attempts.

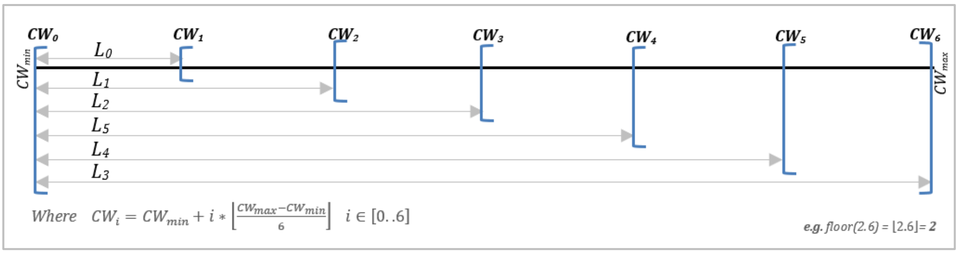


Figure 7. Priority-based Backoff Scheme

This approach further reduces the probability of collisions by assigning specific backoff intervals (BI_i) to each priority level (L_i), as shown in Figure 7. These intervals are represented as [CW_i .. CW_{i+1}]. Nodes within the same priority level select random backoff times from their corresponding interval. This strategy effectively minimizes contention by primarily limiting it to nodes within the same priority group, which are significantly fewer in number compared to the total network nodes within one or two hops.

To prevent collisions, the protocol utilizes a randomized backoff time based on priority levels. This time is calculated using the following equation:

$$Backoff\ Time = Random(CW_i, CW_{i+1}) * T_{CU}$$

Where: i: Represents the assigned priority level (L_i); Random(CW_k, CW_{k+1}): Represents a pseudo-random integer uniformly chosen from the range [CW_k, CW_{k+1}]; T_{CU}: Represents the backoff slot time (contention unit).

The backoff interval is divided into small units called contention units (*CU*). The duration of a CU (T_{CU}) differs from the slot size used in the standard IEEE 802.11 backoff method to avoid collisions caused by hidden nodes. The T_{CU} is calculated using the following equation:

$$T_{CU} = 2 * T_{RxTxTurn} + T_{CCA} + T_{CFtrans}$$

Where: $T_{RxTxTurn}$: Rx-Tx Turn Around Time (time required to switch from receive to transmit mode); T_{CCA}: Clear Channel Assessment time (time required to detect a frame); $T_{CFtrans}$: Time required to transmit a control frame (RTS) calculated as: (*CFlength* / *BitRate*), where *CFlength* is the control frame length and *BitRate* is the data transmission rate.

Nodes with higher priority levels (lower i values) have smaller backoff intervals (CW_i to CW_{i+1}), allowing them to access the channel more quickly after a collision. The Random(CW_i, CW_{i+1}) function ensures fairness within each priority level by randomly choosing a backoff time within the specified range. The T_{CU} accounts for the time needed for various actions like switching modes, detecting clear channels, and transmitting the control frame, ensuring efficient use of the channel, and minimizing collision risks.

4. SIMULATION-BASED PERFORMANCE EVALUATION

The performance of the LTH-MAC protocol is evaluated through simulations using the OPNET Simulator, focusing on energy efficiency and end-to-end latency. To facilitate this evaluation, two distinct node models were designed within OPNET: a Base Station (BS) or Sink node model and a Sensor Node model. The Node model's modular design (Physical, MAC, Network, and Application layers) enables realistic simulation and evaluation of LTH-MAC's performance.

4.1. Simulation Parameters for LTH-MAC Performance Evaluation

Table 1 summarizes key parameters used to evaluate the LTH-MAC protocol, categorized into three groups.

Table 1. LTH-MAC Simulation Parameters

Parameters		Unit	Value	Description
RF Transceiver	Initial Energy	J	1000	Initial energy level of each sensor node.
	Modulation		O-QPSK	Modulation scheme used for data transmission.
	Bandwidth	kbps	250	Available bandwidth for communication.
	Receiver Sensitivity	dBm	-94	Minimum signal strength required for successful reception.
	Maximal Range	m	100	Maximum communication range of a single hop.
	Number of Channels		16	Number of available channels for communication.
	Channel Width	MHz	2	Width of each communication channel.
Power Consumption	TX (@ 0dBm)	mW	52.2	Power consumption during data transmission at 0 dBm power level.
	RX	mW	56.4	Power consumption during data reception.
	IDLE	mW	1.28	Power consumption while actively listening for incoming data.

	SLP	µW	3	Power consumption while in sleep mode.
MAC Protocol	Control Packet Length (RTS/CTS/RTB/ACK)	Byte	14	Length of control packets used for handshaking.
	Data Fragment Length (FRAG)	Byte	40	Length of data fragments transmitted in packets.
	Broadcast Data Length (BROAD)	Byte	40	Length of data transmitted in broadcast packets.
	Packet Header Length (Hdr)	Byte	14	Length of the header information included in each packet.

The table provides a comprehensive overview of the simulation settings, enabling a clear understanding of the specific characteristics and functionalities under evaluation for the LTH-MAC protocol.

4.2. Performance Evaluation of LTH-MAC Protocol in WSNs

This section presents the energy efficiency evaluation of the proposed LTH-MAC protocol compared to two benchmark protocols, SMAC [1] and ECoMAC [4]. The evaluation is based on simulations conducted with a 95% confidence interval and 10 independent runs using different random seeds for each result.

The initial evaluation uses a simple X-shaped topology with a single intermediary node (node 12). Two source nodes (11 and 22) send 100 data messages (40 bytes each) to their respective base stations (BS1 and BS2) through node 12. This configuration allows isolating and analyzing LTH-MAC's fundamental behavior in a controlled environment, providing a baseline before exploring more complex network structures.

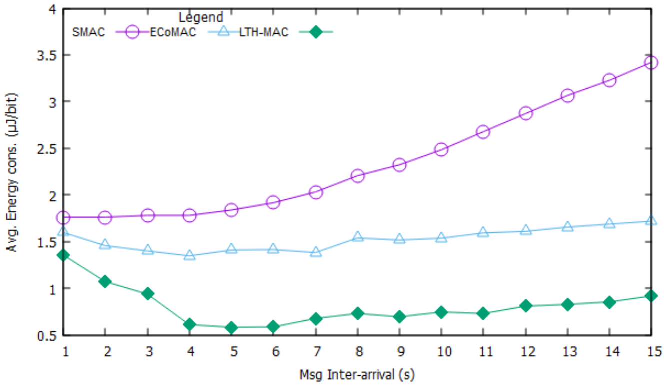


Figure 8. Comparison of Energy Efficiency (µJ/bit) in X-Shaped Topology

The proposed LTH-MAC protocol demonstrates superior energy efficiency compared to SMAC and ECoMAC across various network loads (measured as Joules/bit), as shown in Figure 8. This is attributed to LTH-MAC's ability to minimize contention, prevent collisions, and reduce overhearing. While it excels under light traffic (message inter-arrival periods > 3 seconds), efficiency gains are less pronounced in heavier traffic (< 3 seconds) due to increased idle listening time from collision avoidance mechanisms. Overall, LTH-MAC is well-suited for WSNs with light traffic patterns.

Compared to ECoMAC, LTH-MAC significantly reduces energy inefficiency caused by collisions between unicast RTS and broadcast RTB packets, as shown in Figure 9. This is because LTH-MAC eliminates idle listening time due to this specific collision type, unlike ECoMAC which can also suffer from RTS-RTS collisions. This advantage is especially crucial in light traffic scenarios, making LTH-MAC more energy-efficient, particularly under lower traffic loads.

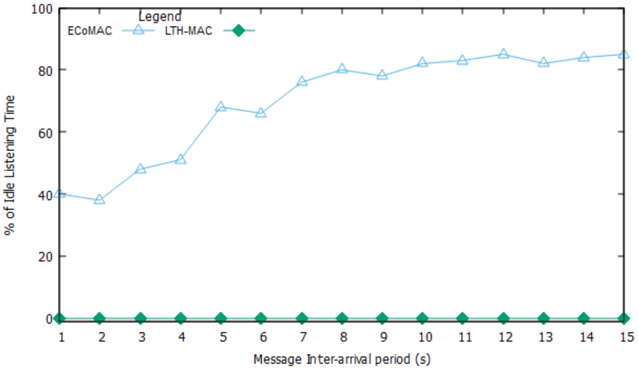


Figure 9. Percentage of Idle Listening Time Caused by RTS-RTB Collisions

To validate our findings in a more complex setting, we evaluated LTH-MAC's energy efficiency in a realistic wireless sensor network simulation. This randomly generated network included relay nodes, with 20 sensor nodes transmitting data to a central sink under varying traffic loads (5-15 seconds inter-arrival period). Results (Figure 10) demonstrate LTH-MAC's consistently superior energy efficiency compared to ECoMAC, measured in energy consumption per bit (*Joules/bit*), highlighting its suitability for real-world applications.

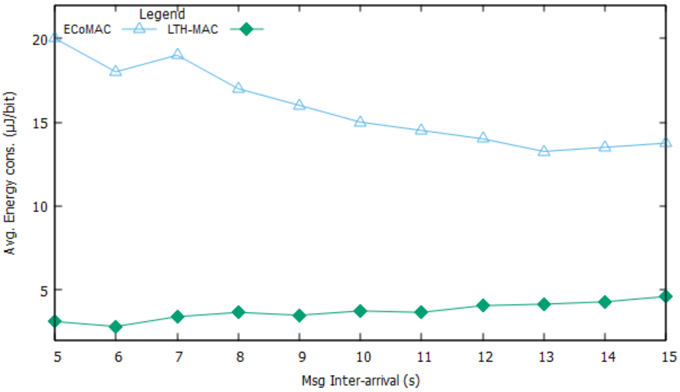


Figure 10. Comparison of Energy Efficiency (µJ/bit) in Random Topology

To validate our backoff technique's efficiency, we compared the energy consumed during backoff states in ECoMAC and LTH-MAC (Figure 11). ECoMAC spends a significant portion of its energy in backoff, highlighting inefficiencies. In contrast, LTH-MAC's backoff scheme consumes significantly less energy, validating its effectiveness in promoting energy efficiency.

To evaluate end-to-end latency, we expanded the second topology to a larger area (300m x 300m) and repositioned the sink node to the top-left corner. This modification aimed to assess the protocols' performance in a larger network environment. We then resimulated the previous scenario, measuring the average time taken by all data packets to reach the sink across different traffic loads.

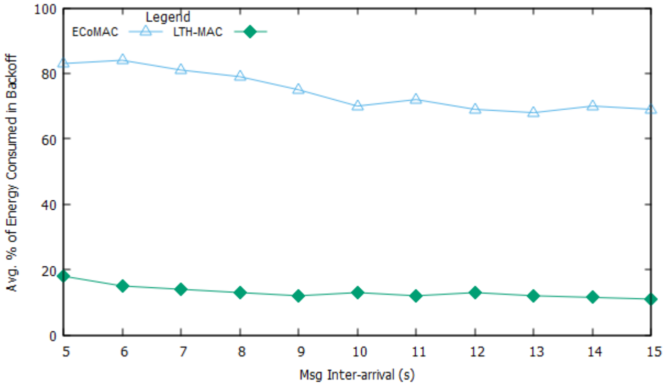


Figure 11. Percentage of Energy Consumed in Backoff States

The results, shown in Figure 12, demonstrate that LTH-MAC consistently achieves lower latency than ECoMAC. Interestingly, LTH-MAC's latency seems to become less affected by traffic load as the inter-arrival time between packets increases (above 10 seconds). This latency advantage is due to LTH-MAC's efficient access technique. LTH-MAC allows for parallel transmissions within a single timeslot, whereas ECoMAC does not. To verify this, we compared the average number of parallel transmissions per timeslot (N_{PT}) for both protocols under low traffic conditions. LTH-MAC achieved a significantly higher N_{PT} (almost double) compared to ECoMAC. This confirms that LTH-MAC's frequency assignment strategy is more efficient than ECoMAC's, leading to lower overall latency.

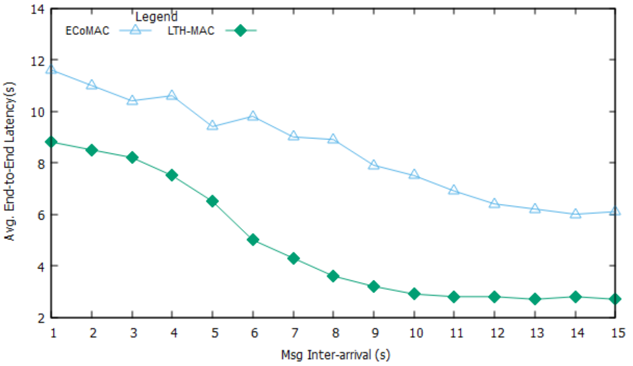


Figure 12. Impact of Traffic Load on End-to-End Latency

We assessed LTH-MAC's data delivery reliability by measuring its Message Delivery Ratio (MDR) – the percentage of data messages successfully reaching the sink. Using a fixed inter-arrival period (10 seconds), we increased source nodes (1 to 49) to simulate varying densities. LTH-MAC consistently outperforms ECoMAC in MDR across all densities (Figure 13), primarily due to its ability to eliminate RTB-RTS collisions that cause packet loss in ECoMAC. While LTH-MAC maintains a high MDR up to 30 nodes, it experiences a slight decline under heavier loads due to congestion. This highlights LTH-MAC's reliable data delivery, especially in moderate traffic scenarios.

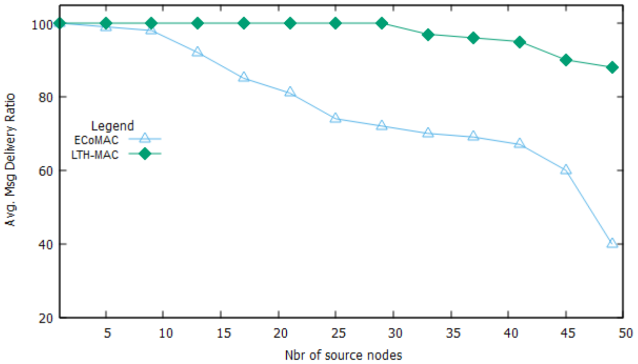


Figure 13. Impact of Network Density on Message Delivery Ratio

5. CONCLUSION

This paper introduced LTH-MAC, a novel hybrid MAC protocol specifically designed for energy-efficient communication in low-traffic Wireless Sensor Networks (WSNs). LTH-MAC effectively addresses the unique challenges of these scenarios by combining the strengths of CSMA, TDMA, and FDMA techniques.

LTH-MAC incorporates innovative features to optimize energy consumption and improve communication performance. It utilizes dynamic timeslots and channel selection, reducing idle listening and simplifying synchronization compared to traditional TDMA approaches. Additionally, prioritizing broadcast data and dedicating channels for control messages minimize collisions and enhance reliability. For unicast data transmission, LTH-MAC employs a dynamic backoff scheme that adapts access attempts based on past success and failure, further optimizing energy usage. Extensive simulations compared LTH-MAC's performance against ECoMAC, demonstrating significant improvements in energy efficiency, end-to-end latency, and message delivery ratio, particularly under light traffic loads. LTH-MAC's innovative mechanisms effectively reduce idle listening, collisions, and unnecessary backoff periods, leading to improved overall network performance.

These findings position LTH-MAC as a promising solution for WSN applications demanding efficient and reliable communication, especially in low-traffic environments. Future research could focus on implementing LTH-MAC on a real-world testbed for practical validation and exploring its performance under diverse and dynamic network settings.

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REFERENCES

[1] Angelina Ankah Amengu, Jamal-Deen Abdulai, Ferdinand Apietu Katsriku, Kofi Sarpong Adu-Manu, SMAC-Based WSN Protocol-Current State of the Art, Challenges, and Future Directions, *Journal of Computer Networks and Communications*, vol. 2022, Article ID 6707413, 2022, 29 pages. https://doi.org/10.1155/2022/6707413.

[2] A. Kumar, M. Zhao, K. -J. Wong, Y. L. Guan and P. H. J. Chong, A Comprehensive Study of IoT and WSN MAC Protocols: Research Issues, Challenges and Opportunities, in *IEEE Access*, vol. 6, 2018, pp. 76228-76262, https://doi.org/10.1109/ACCESS.2018.2883391.

[3] Ranjan, R., Debasis, K., Gupta, R. and M. P. Singh, Energy-Efficient Medium Access Control in Wireless Sensor Networks. *Wireless Personal Communications*, Vol 122, 2022, pp.409-427. https://doi.org/10.1007/s11277-021-08905-2.

[4] H. Zayani, K. Barkaoui, R. Ben Ayed, Probabilistic verification and evaluation of Backoff procedure of the WSN ECoMAC protocol, *International Journal of Wireless & Mobile Networks*, vol. 2, no. 2, 2010, pp. 156-170.

[5] M. Mohammadi, M. R. Abolhassani, and A. G. Panjehany, CH-MAC: A channel hopping medium access control protocol for wireless sensor networks, Computer Networks, vol. 132, 2018, pp. 142-157.

[6] Y. Wang, Y. Sun, and X. Li, DF-MAC: A dynamic frequency selection MAC protocol for multi-channel wireless sensor networks, in *2019 IEEE International Conference on Networking, Sensing and Control (ICNSC)*, 2019, pp. 1-6.

[7] X. Li, L. Sun, and J. Niu, An adaptive slotted ALOHA protocol for low-traffic wireless sensor networks, *Sensors*, vol. 19, no. 8, 2019, pp. 1849.

[8] J. Zhang, Y. Wu, M. Zhao, Y. Li, and Z. Li, Channel-aware slotted ALOHA for reliable and energy-efficient data gathering in wireless sensor networks, *International Journal of Distributed Sensor Networks*, vol. 15, no. 5, 2019, pp. 15542466.

[9] Naveen Kumar, D. Annapurna., Energy efficient data transmission model for Internet of Things application. *International Journal on Information Technologies and Security*, vol.14 , no.2, 2022, pp. 3-14.

[10] Jakup Fondaj, Mentor Hamit, Samedin Krrabaj, Xhemal Zenuni, Jaumin Ajdari., Proposal of model for prediction of grape processing and spraying time by using IoT smart agriculture sensor data. *International Journal on Information Technologies and Security*, vol.16 , no.1, 2024, pp. 3-14. https://doi.org/10.59035/DOQN6033.

[11] K. S. Mathad, M. M. Math., Inference and performance aware multi-channel scheduling and routing scheme with call admission control in wireless mesh networks. *International Journal on Information Technologies and Security*, vol.15 , no.1, 2023, pp. 15-26. https://doi.org/10.59035/XUYS3831.

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