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Abstract—Delay-tolerant sensor networks (DTSNs) require efficient MAC transmission strategies that include energy constraint, relaxed latency, mobility support and diverse traffic load. Reservation-based and contention-based MAC schemes are used to improve throughput and energy consumption. In this paper, we propose a traffic adaptive, energy-efficient MAC protocol to achieve better data transmissions and as energy consumption, in order to satisfy the requirements in DTSN. In our protocol, reservation and contention modes are adjustable, in order to adapt to the traffic load with a suitable duty cycle length for achieving energy efficiency. The simulation results of our protocol demonstrate better performance in terms of energy efficiency and traffic adaptability than the schedule-based MAC protocol TDMA, the contention-based protocol CSMA, and the traffic adaptive protocol TRAMA under mobile DTSN environments.

I. INTRODUCTION

A large number of applications have been developed within delay-tolerant sensor networks (DTSNs) for various purposes, such as supervising and managing resources, animal migration, and national borders. These applications allow unpredictable and longer delays in data transmission within static and mobile environments. For instance, accelerometer sensors are used to monitor the structural integrity of bridges and buildings in [1]. Volcano activity is recorded using seismic and infrasonic sensors in [2]. The activities of sea birds are monitored in [3] via data collected from sensors detecting humidity, temperature, barometric pressure, and light. Agricultural activities are also examined through various sensors that measure temperature, humidity, and pH level to ascertain efficiency of the use of irrigation, herbicides, pesticides, and fertilizers [4], [5]. Various applications in DTSN employ static or mobile sensors to detect environmental and natural changes, as well as human activity in agricultural, industrial, and environmental areas.

Meanwhile, the sensors in DTSN applications have energy constraints due to their use of battery-powered chips, and energy is essential to network longevity. This requirement has resulted in hundreds of energy-saving MAC protocols for sensor networks. Certain MAC protocols in sensor networks provide low energy consumption schemes with low traffic support, such as S-MAC and TRAMA. Some MAC protocols trade energy for throughput and delay performance. When delay is relaxed in the DTSN, new challenges arise involving energy and data transmission. Data transmissions consider energy consumption when transmitting certain amounts of data packets. Throughput is not enough to evaluate data transmission efficiency, since it is related to latency. MAC strategies in DTSNs require energy efficiency in transmitting and receiving the collected data.

In the multimedia applications, a higher, uneven traffic load in DTSN has become common, which is another challenge in energy efficiency for traditional MAC strategies. Traffic load is often diverse, with a wide range of distributions. Most sensors generate data packets periodically, or in an event-based manner. These sensors may be in a very low traffic environment for a long period, during which less data is generated. When a specific event occurs, these sensors may generate a high volume of data, which requires efficient MAC protocols. Reservation-based MAC strategies can accommodate heavy traffic loads with considerably higher energy consumption. Contention-based MAC protocols perform well at conserving energy in low traffic environments, and experience higher energy consumption, collisions and contentions in high traffic loads, which decrease transmission efficiency. Traffic adaptive MAC strategies are the main solutions for improving energy efficiency.

Sensor mobility in DTSN creates an additional challenge for MAC protocols, with changes in topology and traffic distribution. Moving sensors without specific trajectories form an unpredictable topology. Gathering mobile sensors also create a higher traffic load area, while scattered sensors may hardly find neighbors with which they can communicate. Fixed central nodes experience frequent changes of neighbors, and require more coordinating time and flexible scheduling algorithms. Ad-hoc connected nodes may consume more energy when traffic and contentions are high. MAC approaches within DTSN environments should consider mobility, as well as topology compatibility and traffic load variety, in order to achieve energy-efficient performance.

We propose a novel, traffic adaptive, energy-efficient MAC protocol for the DTSN environment. This protocol considers both contention-based and reservation-based MAC approaches, and combines them under static or mobile sensor networks. The aim of the protocol is to provide a highly energy-efficient scheme to minimize energy consumption with various traffic loads and data transmission requirements.

The paper is organized in the following manner. Section II introduces the current research in traffic adaptive MAC approaches. Section III proposes our MAC protocol, including its work flow and process. Section IV shows the simulation and performance results compared to other MAC protocols.
Finally, Section V concludes the paper.

II. RELATED WORK

Various MAC strategies have been developed in recent years within sensor networks to work under different traffic loads. MAC parameter adjustment is a direct approach to cope with various traffic loads.

Burst transmissions [6] introduce an auto-adaptive algorithm capable of adjusting its sampling period and preamble length with different traffic patterns in body sensor networks. This mechanism auto-adapts to the current network traffic, and maintains energy efficiency during burst transmissions by establishing energy-efficient communications over certain paths toward the sink station. The TaMAC [7] protocol is another MAC scheme developed for a star topology of Wireless Body Area Networks (WBAN), in which a central coordinator controls the entire operation of the network. The coordinator schedules and allocates resources to the nodes using their traffic patterns. In the event of emergency and on-demand traffic, resources are allocated using a wakeup radio mechanism. The scheme achieves low power consumption and desired Quality of Service (QoS) for all types of traffic using the TDMA concept. As a result of central fixed coordinators with TDMA concepts, burst transmission [6] and TaMAC [7] are not feasible for use in mobile sensor networks.

ATLAS [8] exploits the superframe structure of the IEEE 802.15.4 standard, and adaptively uses the contention access period (CAP), contention free period (CFP), and inactive period (IP) of the superframe based on the estimated traffic load in WBAN. ATLAS uses the network capacity as the most decisive parameter for adjusting the traffic load status, in order to provide better energy efficiency, high capacity utilization and minimal delay. Another approach, PLA-MAC [9], also uses an adaptive super-frame structure dependent on the amount of traffic load, thereby ensuring minimal power consumption. The limitation of the WPAN topology constrains ATLAS and PLA-MAC for general applications in DTSN.

The TRaffic-Adaptive Medium Access (TRAMA) [10] protocol is a pioneering MAC strategy which provides traffic adaptive schemes for energy saving in sensor networks. TRAMA uses a scheduling-based, collision-free access approach, similar to S-MAC, with local synchronization. It employs a traffic adaptive distributed election scheme that selects receivers based on schedules announced by transmitters. Sensors exchange their neighborhood information and the transmission schedules, specifying which nodes are the intended receivers of their traffic, then selects the nodes that should transmit and receive during each time slot. TRAMA uses an adaptive, dynamic approach based on current traffic patterns to switch nodes to a low power mode, thus saving energy consumption. However, the traffic adaptability only applies to a certain range in which the traffic is relatively high. In addition, local synchronizing and scheduling exhausts local center nodes in TRAMA, and consumes a great deal of energy if the traffic is very low. This has resulted in more efforts to include MAC strategies in diverse traffic environments.

Some MAC protocols have suggested that the hybrid models for the MAC layer of wireless sensor networks take advantage of both reservation-based MAC and contention-based MAC protocols to adapt to different traffic patterns and loads. Contention-based MAC protocols, such as the slotted CSMA/CA, exhibit low energy consumption and efficiency in low density traffic areas, and also cause lower network throughput due to the collisions resulting from multiple simultaneous transmissions in areas of heavy traffic. Reservation-based MAC protocols such as TDMA offer good throughput in heavy traffic load scenarios, exhaust central coordinating nodes, and consume high energy in synchronization and scheduling processes when the traffic is low. Therefore, the hybrid of these two schemes fosters diverse traffic adaptability in the MAC layer.

Gilani et al. [11] propose a hybrid MAC protocol based on the IEEE 802.15.4 standard to reduce energy consumption and improve data throughput in the current IEEE 802.15.4 standard. In this method, the coordinator adaptively divides the contention access period (CAP) between slotted CSMA/CA and TDMA, according to the nodes’ data queue state and the level of collisions detected in the network. Data frame reserved bits have been used to acquire the queue state information from the network nodes. The protocol cannot provide general strategies in mobile DTSN, due to the limitation of the relatively fixed topology in WBAN.

iQueue-MAC [12] is another MAC approach which runs in CSMA in light loads and TDMA in heavy loads. When the load increases, the senders’ queue length will be used to dynamically allocate time slots to the senders (TDMA) according to the queue length of each sensor node. During light traffic periods, iQueue-MAC works as CSMA MAC with low duty-cycle to conserve power. However, sensor mobility is not considered to implement the protocols.

The Intelligent Hybrid MAC (IH-MAC) [13] is a hybrid MAC protocol that combines CSMA, broadcast scheduling, and link scheduling dynamically to improve energy efficiency. It also reduces energy consumption by suitably varying the transmission power, and reduces latency by exploiting the concept of parallel transmission. However, latency reduction and energy conservation strategies in this protocol are not suitable for delay-tolerant sensor networks. The hybrid strategy can be applied in DTSN for the purpose of increasing energy efficiency.

The duty cycle is widely used in sensor networks to save energy, reduce latency and improve throughput. Byun et al. [14] propose an adaptive duty cycle control mechanism based on queue management for power conservation and delay reduction. The scheme uses the local queue length to indicate traffic variations or changes in network conditions, and provides a control-based MAC approach with a distributed duty cycle to conserve energy and reduce latency. Self-Adaptive Duty Cycle MAC (SEA-MAC) [15] is another duty cycle adjustable scheme which makes the nodes’ active duration adaptive to variable traffic loads. The SEA-MAC strategy is designed to schedule more data transmissions in bursty and high traffic loads to reduce latency, and assign nodes into the Sleep mode in a timely manner under the light traffic loads to
save energy. However, as opposed to latency, energy efficiency is more essential in delay-tolerant environments [16], [17]. We could adjust the duty cycle to improve energy efficiency in DTSN.

III. PROPOSED MAC PROTOCOL

MAC protocols are designed to share common wireless channels between many sensor nodes, and to manage communication in the MAC layer. There are two major prototypes of MAC approaches, according to the methods of access to the medium: contention-based and reservation-based approaches [18]. In reservation-based approaches, some nodes periodically send synchronization packets to inform neighboring nodes about time cycle, address, frame length, scheduling list etc. The neighboring nodes listen to the channel for synchronization packets, then follow the cycle. From the synchronization and scheduling frames, the listener may find a transmission opportunity for a sender, or a receiving slot from the scheduling list. Multiple transmissions can be scheduled during the contact period. In a contention-based approach without global synchronization, sensor nodes compete for the use of the wireless channels, and only the winner of this competition is allowed to access the channel and transmit, enabling rapid dissemination of data and reduction of latency. Within the light traffic loads, nodes enter the sleep mode in a timely manner, mitigating idle listening and conserving energy. When the node finds the channel busy, it postpones the transmission to avoid interfering with the ongoing transmission. If the node determines that the channel is clear, it starts transmitting after back-off time.

We propose a traffic-adaptive MAC approach to improve energy efficiency in DTSN environments. The proposed MAC protocol works under variable traffic loads and mobile environments. Reservation-based and contention-based schemes are applied to different traffic load scenarios. Since there are no fixed central nodes to maintain the topology of the DTSN, the protocol can scale to large networks. The aim of our protocol is to provide energy-efficient transmissions when sending and receiving the same number of data packets under DTSN scenarios.

A. Protocol Scenarios

The sensors in DTSN can move or be static in our MAC protocol scenario (Fig. 1). Sensor mobility changes the network topology. Sensors sometimes form a group and then separate. Sometimes only a few sensors are nearby. The connections and topology between sensors change as the sensors move. Therefore, no central node permanently exists that can coordinate the sensor communications, and global synchronization does not exist in this scenario. However, local accumulated sensors may form a temporary cluster and transmit data packets among them. A single node seeks nearby sensors to set up connections to transmit.

The sensors may stay in active mode and sleep mode to conserve energy. During active mode, sensors can transmit and receive data packets or listen to wireless channels. During sleep mode, sensors shut down the transceivers for transmitting and receiving, and stay in sleep mode with very low energy consumption. The time duration of one duty cycle of all these active and sleep modes is fixed with value $T_{dc}$.

Each node has a fixed transmission radius $r$ and a fixed sensing range $R$. We assume a single, time-slotted channel for both data and signalling transmissions.

B. Sensors Work Flow

As indicated in the Fig. 1 illustration of topology, when multiple sensors are in one transmission range, multiple transmissions may be required during a single duty cycle. Therefore, the central coordinator can reserve several timeslots for these sensors and schedule their transmissions. When only one sensor can be connected during one duty cycle, reservation timeslots and scheduling are unnecessary. We design a traffic adaptive MAC protocol that combines reservation-based and contention-based strategies in mobile sensor networks, in order to improve energy efficiency in DTSN.

During one transmission cycle, a reservation-based approach requires the synchronization of neighbor nodes, information gathered from sensors present, and/or transmission requests. A single sensor then acts as a temporary coordinator, broadcasting the schedules of transmitting and receiving timeslots to nearby sensors, and reserving the timeslots in the cycle. After that, the sensors go into sleep mode and wake up in another cycle to save energy.

The protocol transmission procedure can be described as follows (Fig. 2):
1) Every node listens to at least one data transmission cycle $T_{dc}$ before it sends any packets. This ensures that the node receives messages in one $SYNC$ slot, and is aware of the following data transmission cycle in reservation mode and contention mode. In active mode, the sensor listens to the $SCHED$ or $DATA$ frame in $T3$ to decide the timing of $SYNC$ $T1$ and the working mode: reservation or contention.

2) If the sensor carries data and receives $SCHED$ frames in $T3$ of its last duty cycle, it listens to the $SYNC$ frame and sends random access in Reservation Mode to request transmission and timeslots. It follows the $SCHED$ information, and transmits in the specific timeslots. The ACK message from the receiver indicates the successful transmissions.

3) If the sensor carries data and receives $DATA$ frames in $T3$ of its last duty cycle, it sends $RTS$ during $T1$ with carrier sensing and back-off counter in Contention Mode. If no $CTS$ is received in $T2$, the sensor will sleep until the arrival of the next $T1$. If the $CTS$ received is not its receiver, the sensor will listen to the $DATA$ in $T3$ to receive information that the next duty cycle is in reservation or contention mode. It then falls asleep and wakes up in the next duty cycle. If a $CTS$ is received from its receiver, it counts the $RTS$ received in $T1$ and calculates its Mode in the next duty cycle. It then sends $DATA$ with Mode indication, and expects ACK in $T3$ and $T4$. The sensor may change its working mode to Reservation as a temporary coordinator after this duty cycle.

4) The coordinator sends $SYNC$ in $T1$ and listens to random access in $T2$. The working mode of the next duty cycle is decided according to the number of random access messages and requests from senders and receivers. It is then sent out as $SCHED$ in $T3$, along with the scheduling list. The next duty cycle may change to Contention Mode.

5) If the sensor carries data and hears no $SCHED$ or $DATA$ frames, it sends $RTS$ according to its own time schedule.

6) If the sensor carries no data, it wakes up and listens for $SCHED$/$DATA$ or $RTS$. If no $SCHED$/$DATA$ or $RTS$ is received, it falls asleep according to its own schedule.

### C. Mode changes

The condition for changing modes is decided by the number of nodes which have transmission requests $t$ and the duty cycle length $T_{dc}$. Transmission requests $t$ are interpreted as $RTS$ requests in Contention Mode and random access requests in Reservation Mode. When the received $RTS$ requests $RT$ in this duty cycle exceed the pre-set threshold $Cm_r$ during an examined period $T_e$, the working mode changes to Reservation Mode (Mode=R) in the next duty cycle. If the received random access requests $RT$ in this duty cycle are less than the pre-set threshold $Cm_c$, the working mode changes to Contention Mode (Mode=C) in the next duty cycle.

#### D. Duty Cycle Adjustment

The length of the duty cycle is stored in each sensor, and broadcast when it becomes a coordinator. In order to save energy in the Contention Mode, the length of the duty cycle can be extended when $RTS$ or $CTS$ messages $RT$ from nearby sensors, as it is lower than the threshold $D_{c_{low}}$ during an examined period $Ta$. While the request of $RTS$ goes up to $D_{c_{high}}$, the duty cycle is shortened to adapt to the traffic.

### IV. Evaluation and Simulations

In order to demonstrate the energy efficiency, our proposed MAC protocol is implemented through the NS2 simulator and is compared to traditional MAC sensor protocols CSMA and TDMA as well as the traffic-adaptive protocols TRAMA. Mobile sensors are used for different traffic loads. The data packet generator uses Exponential object/Pareto/CBR to simulate the different traffic generation.

The simulation area is $500m \times 500m$ with sensors in traffic generation rate from $100kbps$ to $1000kbps$. The simulation results, with transmission of energy consumption and data packets, are accumulated every 5 seconds. The simulation time is 100 seconds. Each simulation scenario is executed 20 times. TREE is referred to as our proposed protocol in the following simulation results. Table I shows the simulation parameters.
TABLE I
SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Routing Protocols</td>
<td>AODV/GPSR</td>
</tr>
<tr>
<td>Mobility Model</td>
<td>Static/Random Waypoint</td>
</tr>
<tr>
<td>Traffic Generator</td>
<td>Exponential/Pareto/CBR</td>
</tr>
<tr>
<td>MAC Protocols</td>
<td>TREE/CSMA/TDMA/TRAMA</td>
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<td>Radio Range</td>
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<tr>
<td>Number of Nodes</td>
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<tr>
<td>Mobility</td>
<td>Random mobility</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>100s</td>
</tr>
</tbody>
</table>

A. Received Data

We examine received data throughout the simulation process using these four protocols. In our analysis, the wireless channel condition is not considered. However, by using a specific propagation model and routing protocols in simulations, the communication between sensors may experience poor conditions and error transmission. The sent data packets may not be received by the correspondent nodes. Therefore, as the traffic load becomes heavier from 100kbps to 1000kbps, the received data from the correspondent nodes is shown in Fig. 3. TDMA and our protocol demonstrate good performance in received data from low to heavy traffic. TRAMA works in low traffic status, and cannot handle heavy traffic loads. Received data in CSMA works well in low traffic, and performs fairly in heavy traffic loads.

Fig. 3. Received Data Comparison

B. Packet Loss

We also examine packet loss during transmission, in order to find the transmission efficiency of each MAC protocol with static sensors. With an increase in traffic loads, CSMA, TDMA and our protocol begin to lose more data packets during transmissions (Fig. 4). CSMA shows more packet loss than the other three protocols. The collision and hidden terminal problems are severe, and cause packet loss when traffic is high. The other three protocols use schedule-based transmission strategies, which avoid the hidden terminal and collisions, thus exhibiting better performance than CSMA.

Fig. 4. Packet Loss Comparison

C. Energy Consumption

The initial energy for each node is set to 1000 Joules. The transmission, receiving, listening and sleep power consumption are set to 0.6, 0.3, 0.3, 0 Joules per node respectively. The energy residue after the simulation is calculated in static environments, and is shown in Fig. 5. TRAMA and CSMA exhibit low energy consumption throughout the simulations. The TDMA scheme shows high energy consumption due to more overhead messages and involved nodes. Energy consumption in our protocol shows more energy than CSMA and TRAMA and less energy than TDMA, since our protocol adapts both CSMA and TDMA strategies and combines them.

Fig. 5. Energy Consumption Comparison

D. Energy Efficiency

Energy efficiency is essential for finishing transmission tasks and conserving energy in DTSN. When traffic is less than 600kbps with static sensors, CSMA exhibits better energy efficiency than the other three protocols (Fig. 6). However, with an increase in traffic load larger than 600kbps, our protocol demonstrates energy efficiency that is approximately 20 percent greater than other protocols. When the traffic load is diverse in a large range, our protocol will show good
performance in data throughput and energy consumption. For overall dynamic traffic environments, our protocol performs better than the other three protocols.

![Energy Efficiency Comparison-mobile](Image)

**Fig. 6. Energy Efficiency Comparison**

**E. Traffic adaptability**

From the overall simulations, our protocol exhibits better performance in terms of traffic adaptability and energy efficiency than the schedule-based MAC protocol TDMA, the contention-based protocol CSMA, and the traffic adaptive protocol TRAMA. As traffic adaptability and energy efficiency are very important in mobile delay-tolerant sensor networks, our strategy is a strong choice for MAC protocol in these environments.

**F. Mobility and Scalability Considerations**

By using temporary coordinators, our protocol has no requirements for fixed central nodes or coordinators. This allows for easy compatibility between mobile nodes and our protocols. In unevenly distributed traffic environments, our protocol can adjust its working mode and duty cycle to save energy and accommodate data transmissions. This protocol is scalable to varying amounts of nodes and types of areas.

**V. CONCLUSION**

Delay-tolerant sensor networks require energy-efficient MAC transmission strategies with flexible traffic loads and mobility supports. This paper proposes a traffic adaptive, energy-efficient MAC protocol to achieve better data transmission and energy consumption. In our protocol, reservation and contention modes are combined to adapt to traffic load and to improve energy efficiency. The duty cycle is also adjustable, to conserve energy. The simulation results demonstrate that our protocol shows better energy efficiency under high dynamic traffic DTSN environments than other MAC protocols.

**REFERENCES**


