International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (E-ISSN 2250-2459, Scopus Indexed, ISO 9001:2008 Certified Journal, Volume 12, Issue 11, November 2022)
Manuscript Received: 15 September 2022, Received in Revised form: 22 October 2022, Accepted: 01 November 2022 DOI: 10.46338/ijetae1122_04

Optimizing the Data Acquisition Cycle Time of a Sensor MAC in Industrial WSNs

Md Abul Kalam Azad[1], Hoon Oh[2]

Ubicom Lab, School of Computer Engineering and Information Technology, University of Ulsan, P.O. Box 18, Ulsan 680-749, South Korea.

***Abstract*— To reduce the damage of people and properties in industry fields, the response time of a MAC protocol should be kept as small as possible. Among the solutions suggested by various MAC protocols, shortening the data acquisition cycle time (DACT) is considered as the most effective way of reducing the response time. However, a small DACT is often fails to provide the sensor nodes with a sufficient time duration to transmit their data packets in TDMA-based MAC protocols while it surely increases the degree of contention among the sensor nodes in CSMA-based MAC protocols. In summary, a WSN with a small DACT usually fails to attain the satisfactory level of data transmission efficiency in WSNs. On the contrary, a WSN with a large DACT incurs an excess delay in data packet transmission. Therefore, we propose an analytical study for calculating the expected size of time slots so that an optimized DACT can be found. Our optimized DACT is precisely suited to the level-order data transmission that greatly improves the data transmission efficiency in industrial WSNs. In simulation experiments, it is shown that the proposed approach attains a higher packet deliver ratio than that of other competing approaches.**

***Keywords*— data acquisition cycle time, data aggregation, packet delivery ratio, probability distribution function, sharable time slot.**

I. Introduction

By shortening the data acquisition cycle time (DACT), the wireless sensor networks (WSNs) are able to validate the freshness of the collected information about some time sensitive events in industrial fields. The duration of time required by a sink node in order to collect data packets from all of the sensor nodes that have been deployed in a WSN is typically referred to as a DACT. The size of a DACT has a significant impact on the performance of a medium access control (MAC) protocol, particularly in the context of WSN applications that are subject to strict time constraint requirements [1]. In an essence, a reduced DACT usually supports a greater number of time sensitive applications such as soft real-time or hard real-time WSN applications with their dissimilar response time needs for sensor data acquisitions.

The situation is very much similar to the tightly time constraint industrial applications in which the workers are continuously supervised by some monitoring and control applications using WSNs to provide them with the necessary safety measures against any kind of damages or casualties. Nonetheless, reducing the size of a DACT is a very challenging issue when the monitor and control applications require a high packet delivery ratio from the deployed WSNs.

For improving the efficiency of data packet transmission in WSNs, the MAC protocols with carrier sense multiple access (CSMA) such as SMAC [2], DMAC [3], TMAC [4], RMAC [5], and MMSPEED [6] attempt to reduce the response time of data packet delivery. However, they often fail to satisfy the time constraint requirement of industrial monitoring and control applications. Although MMSPEED [6] protocol tries to realize the time constraint requirements with the help of multipath data transmissions, it produces a huge data packet collisions among the sensor nodes and thus, an increase in the size of a DACT is imminent. The works in [7-8] that use the contention level of [9] try to optimize the response time of CSMA-based MAC protocols by reducing the number of re-transmission attempts. However, these works are primarily intended for some AdHoc wireless networks, in which the impact of resource allocation among the nodes is completely different than that of industrial WSNs.

A group of TDMA-based MAC protocols such as TreeMAC [10], SDA [11], DAS [12], and WIRES [13] focuses on an increasing spatial reusing of time slots by generating an effective time slot scheduling for data packet transmissions. With the exception of TreeMAC, a sensor node in [11-13] is allotted a single time slot that is thought to be sufficient for transmitting the largest possible aggregated data packet. This is in contrast to TreeMAC, which has allocated a sensor node with several time slots. Because the size of time slots depends on the maximum number of offspring nodes that a sensor node could have, it appears to be a challenging issue to make an exact prediction regarding the size of such a large time slot.

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Moreover, it is not practically feasible to allocate a large time slot to each sensor node per DACT from the bandwidth utilization perspective. The slot schedules of these protocols cumulatively increase the response time of data packet delivery in industrial WSNs.

Instead of assigning a large single slot, the TreeMAC [10] protocol provides a sensor node with a sequence of frames. Each of these frames contains a set of time slots, the number of which is determined by the total bandwidth demand of the sensor node and all of its children nodes. In this instance, the use of a slot number that is already in use by one of the sensor nodes within a vertical distance of two hops is prohibited. Nonetheless, the sensor protocol is able to reduce the DACT considerably by using small time slots, slot usage sequencing, spatial slot reusing *etc*. However, it fails to remove the interference problem totally since the interference is highly visible within two-hop away nodes. Moreover, the slot disorder problem due to the dynamically changing network topology resists a DACT from minimizing to an expected level.

It has been found that the time constraint requirement of industrial WSNs can be easily satisfied in BSSA [14] by allocating a large time slot among the sensor nodes within an identical tree level. In order to maintain a level playing field, the sensor nodes are granted permission from their own parent nodes for their data packets transmissions. Similarly, SSMA [15] protocol employs a modified form of slotted ALOHA within sharable time slots. The protocol avoids the external interferences by a channel hopping sequence in which a sensor node follows the channel sequences of its parent node. These two slotted MAC protocols successfully achieve the due responsiveness to topology changes by utilizing the candidate parent nodes in industrial WSNs. However, their effort to reduce the size of a DACT is not totally successful since they both fail to utilize slot reusing techniques for their dissimilar sharable slots. Moreover, the switching to candidate parents also increases the response time of data packet transmission.

In this article, we try to present an optimization process of a DACT and hence, incorporate it in a sensor MAC protocol, abbreviated as optDMAC. The protocol allocates the sensor nodes with a set of time slots, which are shared among the nodes using CSMA. Consequently, the size of sharable time slots tends to grow bigger compared to other slotted MAC approaches. Therefore, we try to accumulate the necessary mathematical tools to minimize the size of sharable time slots.

With the various probability distribution functions and probability mass functions, we are competent enough to figure out the expected number of neighboring nodes, the upper bound of a sharable time slot, the highest depth of a tree and hence, the average sized sharable slots. Nevertheless, the size of derived time slots often fails to comply with the existing data transmission processes. Therefore, we use the spatial slot reusing technique in level-order data transmission so that an excessive number of data packets do not accumulate at a specific sensor node. Moreover, the data aggregation method is able to bundle all the accumulated data packets into a single MAC protocol data unit (MPDU). Thus, the proposed data transmission technique has the capability of mapping MPDU packets into the minimized time slots. Finally, we are able to determine an optimum size DACT from the above minimized time slots and level-order data transmission for our proposed optDMAC.

This is how the paper is structured: Some related literatures are reviewed in Section II. With regard to our suggested MAC protocol, Section III discusses the mathematical derivations required to determine an optimized DACT for industrial applications. Following a few simulation results in Section IV, a brief summary is given in Section V.

II. Literature Review

In order to facilitate data packet transmission in tree-based network, a staggered slot scheduling scheme is used in DMAC [3], which aims to speed up data packet transmission by employing an automatic repeat request. Nonetheless, with three transmission attempts for rescuing a lost data packet, the protocol is not able to reduce the response time significantly. Therefore, it fails to keep the delay bound of data packet transmissions for the time constraint industrial applications. Combining the benefits of TDMA and CSMA-based channel accessing, Z-MAC [16] optimizes the bandwidth utilization by allocating two-hop away sensor nodes with available time slots so that the interference problem can be avoided. The protocol is able to maximize the time slot usage by CSMA-based channel stealing technique when the traffic volume is low. The stealing process reduces the response time of data packets satisfactorily even though a few time slots are in use. The demand of time slots develops in a linear fashion for the growing number of deployed nodes in WSNs that causes the response time of the protocol to be unsatisfactory when there exists heavy data traffic.

Moreover, a probe-based channel sensing gives a high delay, which makes the protocol less suitable for time constraint applications.

TreeMAC [10] assigns a set of distinct frames to all sensor nodes in a tree topology in which each frame consists of three individual time slots. After that, it allocates a transmittable slot to each sensor node locally, and every three-hop geographically distant sensor nodes are allowed to reuse the time slots gracefully. However, the failure of taking any effective measures against slot disorder problems, irregular interference, and frequent slot scheduling makes the protocol less suitable for industrial WSNs. To resolve the problems, I-MAC [1], which is designed to work with certain kinds of industrial WSNs, does not make use of spatial slot reuse techniques and, as a result, the required number of time slots are allocated by the sensor nodes differently. This protocol tries to enhance the reliability of data packet transmission by message handshaking. The strength of the protocol lies upon the usage of a lost packet salvation scheme using some spare time slots for the noisy and interference prone industrial WSNs. However, a decreasing of slot length alone is not a sufficient remedy to bring the response time of data packets down to an acceptable level. In fact, the response time of the specific MAC protocol grows in a linear fashion for an increasing number of nodes in WSNs.

TSCH [17] enhances the reliability of low-power WSNs by reducing the unavailability of wireless frequency channels in industrial working sites. A sensor node can predict the wake-up time as it shares a time schedule with others. Here, the data packet transmission is done using different frequency channels at different times. However, the exchange of time schedules produces extra delay, which increases the response time. In contrast, WirelessHART [18] and ISA [19] employ a central time slot scheduling, use some channel hopping to dodge co-channel interferences and provide alternative paths in case of link failures. In contrast to TSCH, WirelessHART makes use of a channel hopping algorithm for a time slot of a predetermined size, whereas ISA employs an adaptive form of channel hopping that consists of three hopping sequences for five hopping patterns. However, WirelessHART does not detail any particular slot scheduling policies in any of its documentation. Therefore, the delay bound of these types of standards is not precisely calculated, and the time constraint requirement can be easily violated for industrial WSNs.

In SSMA [15], the sensor nodes of an identical tree level are allocated with a sharable time slot. These nodes are then engaged in a fair competition with each other inside the same time slot for data packet delivery. When two or more sensor nodes allow transmitting some data packets concurrently without interfering, this presents a prospect for the opportunistic reuse of time slots. However, to design a network architecture for reusing spatially, the sharable time slots is not practically cost-effective since the size of sharable time slots varies according to the tree levels. Despite the fact that the protocol allots sharable time slots of increasingly large sizes according to the decreasing tree levels, the sensor nodes that are located at lower tree levels become more congested with data traffic than those that are located at higher tree levels. Missing the opportunity of time slot reusing among the sensor nodes at different tree levels, it does not provide us with an expected level of response time efficiency.

The proposed optDMAC protocol reduces the response time by limiting the data acquisition delay in an elegant way. For a specific network deployment scenario, the protocol estimates the average number of child nodes that any parent node may have. Then, the progressive and parallel data transmission technique allows the parent nodes to collect the data packets from the child nodes of two adjacent tree levels only. Additionally, the data aggregation technique helps the collecting sensor nodes to bundle up all the collected data into a single packet. In WSNs, the size of the aggregated data packets quickly increases as they move from the leaf nodes toward the sink node. Indeed, it is an important fact that the size of aggregated data packets may grow up to its greatest extent at the vicinity of a sink node, and the immediately descendants of the sink node known as the anchor nodes should have the capability to deal with those data packets. We have shown that even for the largest size of data packets, the protocol can still accommodate it within a single MPDU packet. This is only achievable if an accurate determination of the size of time slots used for CSMA-based channel accessing has been made. Additionally, the attempt of reducing the number of time slots for a node reduces the average delay time of data packets. As a consequence, the proposed protocol is able to deliver a significantly quicker response time compared to the other contemporary sensor MAC protocols.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (E-ISSN 2250-2459, Scopus Indexed, ISO 9001:2008 Certified Journal, Volume 12, Issue 11, November 2022)

III. Data Acquisition Cycle Time Analysis

For the uniformly distributed sensor nodes, the network topology of a tree-based WSN can be widely varied depending on a couple of network parameters such as the average neighbour count of a node, and the tree depth (the highest tree level). After estimating these network parameters properly, they can be utilized as the performance improvement catalysts for the data packet transmission in industrial WSNs. With the estimated parameter values that have been calculated by the mathematical formulas in [20-22], we would be in a position to construct a well-accepted tree topology that can be used as a benchmark for comparing the performance of all the competing MAC protocols. Taking such a tree topology not only reduces the undue bias that we generally face while working with an enticing tree topology, but also helps us to conduct a true comparative study that is acceptable to all beneficiaries. Nonetheless, a compromised tree topology that is built on some greedy parameter values may be able to reduce the data acquisition cycle time (DACT) greatly. However, such sensor MAC protocols with a twisted DACT behave very poorly when we try to apply them in real world industry applications. We, therefore, take an unbiased tree topology to calculate an optimized DACT, which is able to support a wide variety of time constraint monitoring and control applications for industrial WSNs.

To determine an optimum DACT is an NP-hard problem, which implies that it is time consuming and memory inefficient to discover such a DACT. Moreover, finding such an optimum DACT faces some technical challenges when its size controls the overall efficiency of WSNs. For example, a too big DACT is responsible for violating the time constraint requirement of industrial applications while a too small DACT is responsible for increasing the degree of contention among the sensor nodes in CSMA-based applications. An increased contention level decreases the data transmission efficiency by lowering the probability of successful data packet delivery. To get an optimum DACT, we use some deterministic and probabilistic functions to calculate the theoretical limits of DACT as described below. With the theoretical DACT, we, thereby, perform some simulation experiments to find out the an optimum DACT for industrial WSNs.

A. Determining DACT of Different MAC Protocols

Let us examine the DACT, which becomes a critical decisive factor of sensor MAC protocols while designing various time constraint applications in industrial WSNs.

Among various sensor MAC protocols, TreeMAC [10] tends to be a strong candidate for the comparative study since its time slot reusing and parallel data transmission are very much similar to our proposed one. In a tree topology, a frame is consisted with three time slots that is allocated to an individual sensor node. Therefore, for *n* number of sensor nodes, the required size of a DACT can be calculated as follows.

$$DACT(TreeMAC) = (n \times 3) \times slotLen \quad (1)$$

where *slotLen* is assumed to be a standard time duration in which an aggregated data packet not exceeding one MPDU can be either transmitted or received gracefully. On the other hand, the depth of a tree topology plays the key role in determining the size of a DACT in I-MAC [1] protocol. It states that the higher the depth of a tree, the more the required amount of time slots. For a sensor node at the tree level *l*, exactly (*l*-1) number of unique time slots is required for its data packet delivery when the depth (the highest level) of a tree is taken to be *L*. Therefore, the protocol can calculate its DACT as follows.

$$DACT(I\text{–}MAC) = (\sum_{l=2..L} (n_l \times (l-1)) \times slotLen \quad (2)$$

In SSMA, if we allow one aggregated data packet to be transmitted by a sensor node during a DACT period, the lower limit of a DACT is determined as below.

$$DACT(SSMA) \geq \sum_{l-2}^{H} (l-1) \times n_l \times E[D] + WTime(H) \quad (3)$$

where *H* is tree depth, n_l is an estimated count of sensor nodes for tree level *l*, the average time delay for a single hop data transmission is *E*[*D*], and *WTime*(*H*) is an wait time for the sensor nodes at depth, *H* prior to begin any data transmission operations as described in [15].

In our approach, the DACT calculation is not as hard as of the other three MAC protocols since the sensor nodes at a tree level starting from the tree level 2 can be satisfied with a single sharable time slot. The proposed optDMAC protocol calculates its DACT for a tree topology of depth, *L* as follows.

$$DACT(optDMAC) = (L-1) \times sSlotLen \quad (4)$$

From the above analysis, we clearly observe that the demand for the required number of time slots of our proposed optDMAC protocol is very low.

The protocol uses CSMA-based channel accessing to attain the expected degree of responsiveness and flexibility for a dynamically changing wireless channel in industry sites. Generally, the CSMA-based channel accessing requires a relatively bigger sharable time slot, *sSlotLen* than the time slot, *slotLen* used by TDMA-based channel accessing as of TreeMAC and I-MAC. Therefore, a theoretical study is required about the calculations of DACTs for different sensor MAC protocols before conducting any simulation experiments

B. Lower Limit of a Sharable Time Slot

In this section, our goal is to assess the maximum length of a sharable time slot (*sSlotLen*) that is the key factor to derive the DACT for our proposed protocol. In a tree-based WSN, the neighbors of a specific sensor node at tree level, *l* are distributed over three adjacent tree levels: some at descendant tree level, *l*+1, some at the same tree level, *l*, and some at ancestor tree level, *l*-1. In the conventional CSMA-based channel accessing technique, a sensor node has to compete with all the neighboring nodes of three tree levels when a sensor node is allowed to transmit a data packet to its parent node. Allowing all neighboring nodes to contend with each other eventually requires a big sharable time slot. However, if some percentage of neighboring nodes are refrained from contending, the size of a sharable time slot can be reduced greatly. The proposed optDMAC protocol exactly does the same thing with the help of level-order data transmission technique so that a sensor node participates in a fair competition only with its neighbour sensor nodes at the identical tree level. Assuming a uniform distribution of sensor nodes across the deployed working area, the lower limit of *sSlotLen* is represented as follows.

$$sSlotLen \geq T_{tx} * (1/3 \times nNbrs + 1) \qquad (5)$$

where *nNbrs* is taken as the average number of neighbor nodes spreading over three adjacent tree levels, and T_{tx} is taken as the time duration for transmitting a data packet successfully. Even in a CSMA-based data transmission, we can restrict a sensor node from competing with the neighbor nodes of two nearby tree levels *i.e.*, the neighbor nodes at tree level, (*l*-1) and (*l*+1) in our proposed level-order data transmission technique. Therefore, a sensor node has to compete with a few neighboring nodes only at its own tree level *i.e.*, tree level, *l*.

A two-third reduction in the number of competing nodes is a substantial achievement of our proposed data transmission process in which a sensor node goes through the *RTS*-*CTS*-DATA-*ACK* transmission cycle like Fig. 1. At tree level, *l*, a sensor node has to send an *RTS* message to its parent node at tree level, *l*-1 if the node wishes to forward a data packet. Upon overhearing this *RTS* message, all the neighboring sensor nodes at tree level, *l* give up their transmission attempts for a while. On receiving an *RTS* message, the parent sensor node at tree level, *l*-1 acknowledges its willingness to receive a data packet by sending a *CTS* message. By overhearing this *CTS*, all the neighboring sensor nodes at tree level, *l*-1 also give up their receiving attempts within the current data transmission cycle. Although we use a slotted approach, the *RTS*/*CTS* handshaking technique we borrowed from IEEE-802.11 standard is used to remove the hidden terminal problem and thereby, increases the reliability of data transmission. For a successful data packet transmission, a sensor node may sometimes require more than one transmission attempt. Therefore, a careful design strategy is taken so that an excessive time delay is not incurred by a sensor node for the successful data packet transmissions.

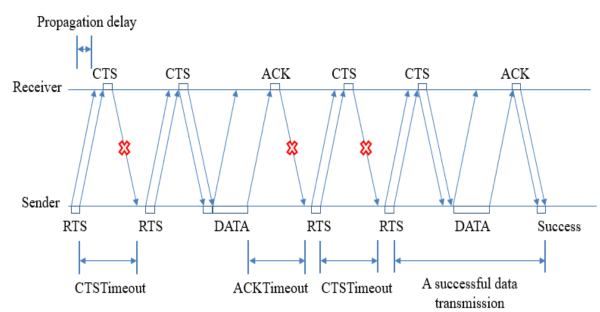

Fig. 1. An RTS-CTS-DATA-ACK transmission cycle of the proposed protocol.

In Fig. 1, we see that a sensor node is failed to collect a *CTS* message when the *RTS* or *CTS* control message is lost due to an unexpected transmission error. In fact, when a sensor node does not receive a *CTS* control message within the *CTS* respiration period (*CTSTimeout*), it is simply unaware of the situations and a failure of the above type is definitely happened. Similarly, the sensor node is failed to get an *ACK* message when a DATA packet or an *ACK* message is lost. If a sensor MAC protocol allows more than one data transmission attempt for a transmission failure, the sequence of message exchanging is illustrated at the same figure for a successful data delivery in the extreme case.

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Generally, the delay encountered for propagating a data packet is very negligible compared to other parameter values. If the maximum time taken for an *ACK* message to be *ACKTimeout*, then the transmission time, T_{tx} taken by a successful data packet can be expressed (in the worst case) as follows.

$$T_{tx} \geq MaxDelayCnt \times delaySlot + 2 \times \{2 \times t(RTS + CTS) + CTSTimeout + t(DATA + ACK)\} \quad (6)$$

where the maximum delay count (*MaxDelayCnt*) is actually the size of a Contention Window (*CW*) for the backoff time calculation, and the size of *delaySlot* is guided by the standard value from IEEE recommendations. Since we allow a maximum of one retry, the time duration of successful data transmission is multiplied by two. Under this consideration, we also allow a maximum of two transmission attempts for *RTS* and *CTS* message exchanging.

C. Estimating Tree Depth and Neighbor Nodes

With some probability distribution functions (*pdf*), we can determine the estimated number of sensor nodes that may reside at each individual tree level of a tree topology [20]. For the square dimension area of ($a \times a$) and a signal coverage range of *R*, we can easily calculate the *pdf* of the sensor nodes of a tree level, *l* for a tree topology that can be defined as $Pr\ (level = l)$. From the empirical data, we have observed that $Pr\ (level = l)$ in fact renders a Gaussian or Normal distribution curve, which may be skewed at the high tree level in a tree topology.

As an example, we depict a bar graph for the *pdf* of different tree levels in a tree topology as in Fig. 2. To get the outcomes, we have considered a sensor node with the maximum coverage range, *R* = 25 meter and a square deployment area with the length of an arm, *a* = 100 meter. It is observed from the figure that the number of sensor nodes becomes low to lower when we are approaching toward the maximum tree level in a tree-based WSN. For the given network parameters, we can estimate the exact number of sensor nodes for each tree level. The distribution shows that the number of sensor nodes grows as we approach to the higher tree levels from the lower tree levels up to level 3 in which the highest number of sensor nodes resides. However, the number of sensor nodes lowers down at tree level 4 and the decreasing is very sharp from tree level 5. Interestingly, we found that the existence probability of sensor nodes at tree level 7 is zero.

Therefore, the *pdf* of tree levels suggests that the highest number of tree levels *i.e.*, the depth of a tree for the given parameters is 6.

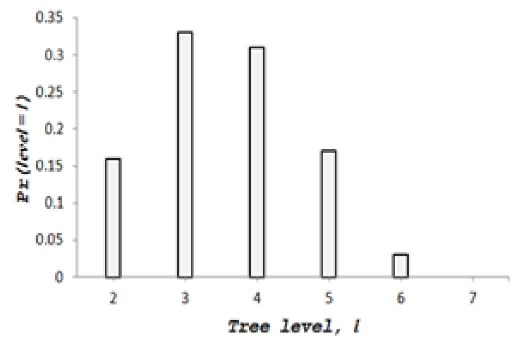

Fig. 2. Node distribution probability of tree levels for *R* = 25m, *a* = 100m.

With the probability mass function (*pmf*) as in [21], we are able to approximate a maximum amount of neighboring sensor nodes that an individual sensor node may hold. As above, the *pmf* of neighbor nodes, $\Pr\ (nNbrs = k)$ can be derived for a given set of network parameters such as for a transmission coverage of *R*, a network deployment area of ($a \times a$), and a total amount of sensor nodes of *n*. From the analytical studies, we get a Normal distribution graph, $\Pr\ (nNbrs = k)$ for the dimension length, *a* = 100 meter, the transmission range, *R* = 25m, and a set of sensor nodes, $n \in \{25, 30, 35, 40\}$ as shown in Fig. 3. For *n* = 25, the outcome of $\Pr\ (nNbrs = k)$ is zero beyond the neighbor count, *k* = 12. The findings of the above calculation are very conclusive in the sense that we have found the maximum count of neighbors to be 12 (approximately) for this specific case.

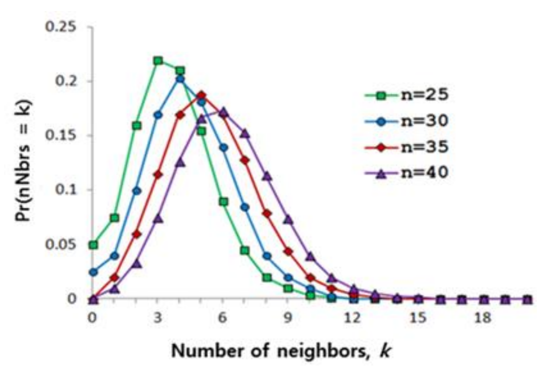

Fig. 3. Probability distribution of neighbor nodes for *R* = 25m, and *a* = 100m.

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D. Deriving the Size of a Sharable Time Slot

For determining the approximate size of *sSlotLen*, we have to calculate the time duration of a successful data packet transmission *i.e.*, determining the value of T_{tx} as in Eq. (6). Generally, a sensor node has to go through a repeating cycle of six chronological execution steps for successfully completing data packet transmission. Among them, the first five steps are executed by a sending node while the last one is executed by a receiving node as follows: (*i*) after generating a data packet from sensor data, a sending node hand overs it to a radio chip buffer from micro control unit (MCU) (t_{ts}); (*ii*) it turns on a radio module to initiate its data packet transmission (t_{turnon}); (*iii*) it executes a clear channel assessment (CCA) procedure to test whether a wireless channel tends to be free or not (t_{CCA}); (*iv*) it performs the PHY layer processing (t_{ppd}); (*v*) it transmits a data packet to a free wireless medium if available (t_{tx}); and (*vi*) a receiving node collects a data packet from its radio chip buffer and transfers the data packet to an MCU (t_{tr}).

Since the time taken by t_{ts}, t_{turnon} and t_{tr} is not included in any simulation software, we can easily ignore them for our simulation-based experiments. In the following discussion, we use the term message instead of data packet since the total transmission time depends on data packet plus control message transmission. Therefore, the required time for transmitting a message, *m* is as follows.

$$t(m) = t_{CCA} + t_{ppd} + t_{tx}(m) \tag{7}$$

For the PHY layer specification of IEEE-802.15.4 standard, the transmission rate of data packets is given as 250 Kbps, which is equivalent to 0.032 ms/byte. The specification also prescribes for a synchronization (SYN) header, a PHY header, a MAC header and trailer - all consist of 11 bytes. Now, we can calculate the value of transmit time, t_{tx} from Eq. (7) as follows.

$$t_{tx}(m) = 0.032 \times (11 + size(m)) \tag{8}$$

From IEEE standard, we can find t_{CCA} = 0.128 ms and t_{ppd} = 0.192 ms, and we can also have $t_{tx}(m)$ = (0.352 + 0.032 × size(m)) ms using Eq. (8). For an equal size of control messages *i.e.*, the size of all control messages is 5 bytes; we can find the maximum size of a data packet as (127-11) = 116 bytes, *i.e.*, max(size(Data)) = 116 bytes.

Thus, we have,

$$t(RTS) = t(CTS) = t(ACK) = 0.512\ (ms) \tag{9}$$
$$t(DATA) = 4.064\ (ms)$$

For *MaxDelayCnt* = 20 and *delayslot* = 0.32 ms, we can determine the value of *CTSTimeout* = 1.024 ms since *CTSTimeout* = t(*RTS*) + t(*CTS*). Using Eq. (6), we get a modest value of T_{tx} as follows.

$$T_{tx} \geq 21.696\ (ms) \approx 22 (ms) \tag{10}$$

Substituting the value of T_{tx} in Eq. (5), we obtain,

$$sSlotLen \geq 22 \times \left(\frac{1}{3} \times nNbrs + 1\right)\ (ms) \tag{11}$$

According to Fig. 3, *nNbrs* is counted to be 12 (approx.) for the network of (100 x 100) square meters, $R = 25$ meter and $n = 25$. For such a network configuration, we need to replace the expected value of the maximum neighbors that a sensor node may have. Therefore, by replacing 12 for *nNbrs* in Eq. (11), we obtain the lower bound of the size of a sharable time slot *i.e.*, $sSlotLen \geq 110\ (ms)$. This lower bound of $sSlotLen$ is true only for the uniform distribution of sensor nodes and thus, taken as a theoretical reference. In reality, a perfect distribution of sensor nodes in a deployed area is quite unlikely due to the various geographical and technical difficulties. Therefore, the size of a $sSlotLen$ is relatively bigger than what we have found here.

E. Data Transmission Principles

With the advantage of level-order parallel data transmission and data aggregation as discussed in [23], the proposed data transmission technique is able to reduce the DACT to a great extent. For a clear understanding, we demonstrate the power of the proposed technique using a single child tree as shown in Fig. 4. In this simple tree topology, one sink node, S and four sensor nodes A, B, C, and D are used to explain data transmission process. Node A, B, and C has both a parent node, as well as, a child node. However, node D has a parent node only. The depth of this single child tree is 5.

Besides the tree topology, the possible number of transmitted data packets are shown for a clear comparison among the competing MAC protocols. It is assumed that the sink node is responsible for collecting at least one data packet from all the sensor nodes in the deployment area during each DACT. From the figure, we observe that SSMA protocol requires the largest number of time slots because the protocol fails to reuse the time slots spatially.

International Journal of Emerging Technology and Advanced Engineering
Website: www.ijetae.com (E-ISSN 2250-2459, Scopus Indexed, ISO 9001:2008 Certified Journal, Volume 12, Issue 11, November 2022)

However, by reusing the time slots, TreeMAC is able to save a single time slot for the data transmission process in this single child tree. Finally, the proposed optDMAC reduces a large number of time slots using both spatial slot reusing and data aggregation. It is seen from the figure that the saving of time slots is more than 50% compared to either SSMA or TreeMAC protocols.

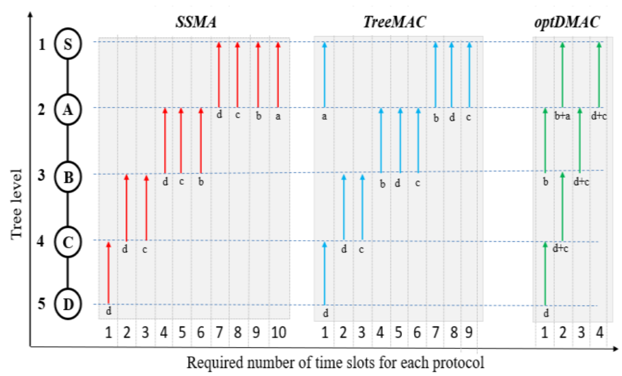

Fig. 4: A single child tree for DACT comparison.

A confusion may arise when the sensor nodes have multiple number of child and how many time slots are required for their data packet transmissions. If the average number of child for a sensor node increases, the required number of time slots does not increase for SSMA and optDMAC protocol, as long as, the depth of a tree is remained fixed. However, the number of time slots increases exponentially in TreeMAC protocol when the average number of child node for a sensor node increases. As the size of a DACT depends on the number of time slots for a sensor MAC protocol, lowering the number of time slots means lowering the size of a DACT. Therefore, the size of a DACT for the proposed optDMAC protocol is shorten considerably by lowering the required number of allocated time slots. In many practical applications where multiple child for a sensor node is common, the proposed technique will show its strength in reducing the size of a DACT.

Since SSMA and optDMAC protocols allow CSMA-based channel accessing technique, they require the sharable time slots of relatively large size. In fact, the size of a sharable time slot for SSMA is in the range of second compared to the millisecond in other slotted MAC protocols. On the other hand, optDMAC protocol is able to reduce the required size of sharable time slots by parallel data transmission spatially. However, the protocol is not able to reduce the size of a time slot in millisecond range.

Therefore, one might guess that the size of a DACT for our proposed approach would be very large. In reality, the thing turns out to be the opposite since for a tree of depth, L, the protocol requires a maximum number of (L-1) sharable time slots only, and the value of L is a small number in practice. For further clarifications, we are going to compare our proposed optDMAC with other slotted MAC protocols in terms of DACT.

F. Lower Bound of DACTs

Suppose that a fair size of *slotLen* (= 20ms) is taken to calculate the DACTs of TreeMAC and I-MAC sensor MAC protocols. The depth of a tree, L and the average number of neighbor nodes, n_l can be calculated for the different number of sensor nodes in WSNs as shown in Fig. 2 and Fig. 3, respectively. Using Eq. (1) to Eq. (4), the size of a DACT of the comparing MAC protocols *i.e.*, TreeMAC, I-MAC, SSMA and the proposed sensor MAC protocols can be calculated for an increasing number of sensor nodes (up to an acceptable level). As we see in Fig. 4, the theoretically calculated values of DACT of four comparing sensor MAC protocols are shown for the varying number of sensor nodes. It is shown that the DACT of the proposed MAC protocol is much smaller than that of other three approaches since the proposed MAC, optDMAC supports data aggregation along with some spatial slot reuse techniques.

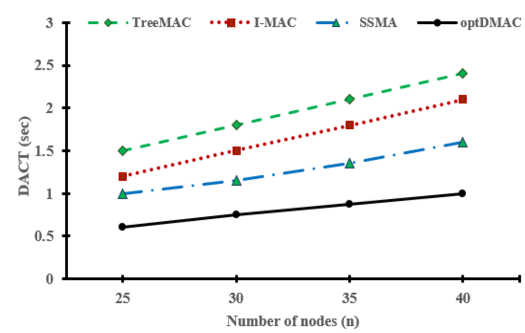

Fig. 4. A required size of DACT for an increasing number of nodes.

If we increase the number of sensor nodes in the deployed area, TreeMAC shows a rapidly increasing size of DACT. Allocating three time slots to a sensor node makes the protocol very inefficient when the number of sensor nodes becomes large. With an optimized size time slots, I-MAC protocol somehow lowers down the requirement of large DACT. However, merely reducing the size of time slots is not a very effective means of reducing a DACT as shown in Fig. 4.

International Journal of Emerging Technology and Advanced Engineering
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On the other hand, by sharing a time slot among the sensor nodes, SSMA protocol is able to reduce the size of a DACT considerably. In addition to decreasing DACTs, it also reduces the tendency of increasing DACTs for an increasing number of sensor nodes. Allowing both the spatial slot reusing and data aggregation within time slots, optDMAC is able to give the lowest DACT among all the competing sensor MAC protocols. Moreover, the proposed MAC is very responsive and efficient in DACT usage for an increasing number of nodes in WSNs.

IV. Evaluation Of DACTs

The size of data acquisition cycle time (DACT) plays an important role in achieving the required performance level of the time sensitive applications in industrial WSNs. For any time-constraint applications *e.g.*, the monitoring and control applications in WSNs, we have to choose a DACT as small as possible. However, finding such a DACT for a specific WSN scenario is not very easy. Sometimes, a small size DACT gives a poor performance in the contention based WSNs since the degree of contention level increases exponentially with a linear decrease in DACT.

A. Simulation Experiment Preliminaries

In our simulation experiments, we use a QualNet simulator with version 5.0.2 to compare the data transmission efficiency of our proposed protocol with other competing MAC protocols. We often try to abide by the IEEE standards to select the values of simulation parameters. Otherwise, we follow the standard practicing rules that we have found from academia and research. In the simulation experiments, we use some key parameter values as shown in TABLE I; where the first column represents parameter name and the second column represents parameter values.

TABLE I.
Values of Simulation Parameters.

Parameter	Value
Number of node (*nNodes*)	1 sink and 25 sensor nodes
Maximum size of a packet	127 bytes
T_x range	25 m
a (SSMA)	0.7 s
Channel frequency	2.4 GHz
Path loss model	2-ray
Shadowing model	Constant (*Mean* = 4 dB)
Fading model	Rician
Noise factor	10 dB
Sensor energy model	MicaZ
Current draw in MicaZ	Transmitting =17.4 mA (0 dBm) Receiving = 19.7 mA, Idle = 20 µA, Sleep = 1 µA
Battery model	Linear
Number of packets	600

B. Network Deployment Scenarios

We take a square dimension area of (100 x 100) square meters as the network deployment scenarios as shown in Fig. 5. All the sensor nodes are distributed uniformly within the deployed network area and a sink is placed at the middle of the top of the same area. Within a DACT, the sink node is supposed to collect a data packet of 127 bytes from all the sensor nodes in the network coverage area.

Here, all sensor nodes remain static once they are deployed in the working field. Therefore, the effect of link breaks due to some ambulatory events such as Doppler effect, shadowing effect *etc*., is very negligible. However, the links can be instantaneously broken due to small scale fading and large-scale fading effects. As for the wisely deployed nodes, the Line-Of-Sight (LOS) is often present between two communicating sensor nodes.

International Journal of Emerging Technology and Advanced Engineering
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Therefore, the scenario suggests us to choose the Rician fading model in which the key parameter K is defined as the ratio of P_{LOS} and $P_{other\ paths}$; where the signal power along the LOS and that of from the indirect paths are shown by P_{LOS} and $P_{other\ paths}$, respectively. We take K = 12, which realizes a moderate level of fading effect in our simulation experiments.

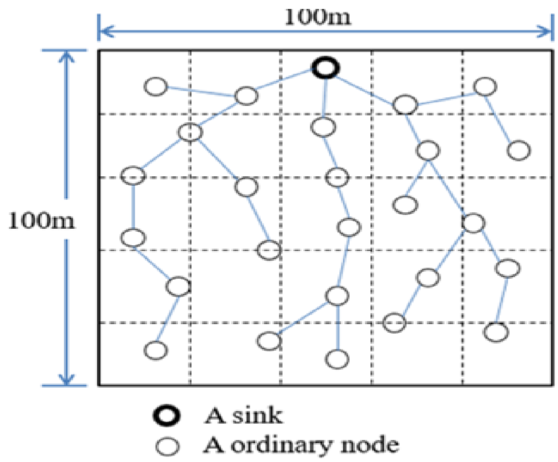

Fig. 5. Square dimension area of 100 x 100 m^2.

C. Performance of Different DACTs

The data transmission efficiency of a sensor MAC protocol is seen to be quite satisfactory when the size of a DACT remains bigger than the threshold theoretical value. We analytically determine the theoretical threshold limit of a DACT for different sensor MAC protocols in the previous section. Here, we want to validate those calculated values in the real-world network scenario. *Firstly*, we compare the PDR of different MAC protocols for an increasing size of DACT. *Secondly*, we keep the size of a DACT to a fixed threshold value, and examine the PDR of different MAC protocols by varying the number of sensor nodes in the deployment area.

1) Impact of DACT on PDR: For *nNodes = 25*, the PDR value of optDMAC has a decreasing tendency at DACT ≤ 0.8s; however, the inclination is very small as can be seen in Fig. 6. It is found that this value of DACT is almost similar to the analytical value as in Fig. 4 that we have got from the previous section. On the other hand, the PDR value shows a decreasing tendency at the DACT ≤ 1.2s for SSMA protocol since the protocol is not capable of integrating the parallel data delivery due to its unequal slot size and hence, fails to decrease the DACT as per our expectations.

However, owing to parallel data transmission capability, our proposed optDMAC protocol is able to sustain its PDR efficiency even at the reduced level of DACT.

As a numerical illustration, it is realized that the achievable PDR of optDMAC is almost 100% for DACT = 1 second as shown in Fig. 6. In other words, for *nNodes* = 25, the minimum size of a DACT that is required to achieve the highest level of data transmission efficiency by our optDMAC is 1 second. For the same size of DACT, SSMA protocol, however, gives an approximately 95% PDR. The situation becomes worse in case of TreeMAC and I-MAC sensor MAC protocols. For attaining the same PDR efficiency, they both require a very larger DACT compared to our proposed one. Therefore, our optDMAC protocol is able to outperform other MAC protocols in the context of DACT shortening.

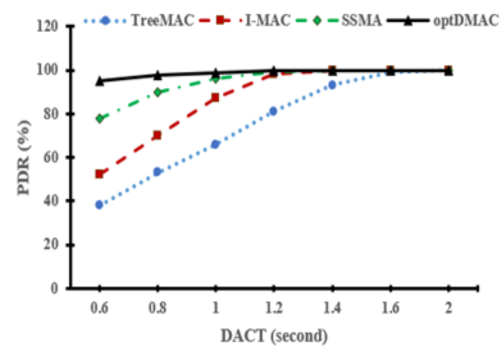

Fig. 6. Comparing PDR for varying *DACT* (*nNodes* = 25).

2) Impact of nNodes on PDR: Among the competing sensor MAC protocols, the PDR value is compared among the sensor MAC protocols for an increasing number of sensor nodes (*nNodes*) in WSNs as shown in Fig. 7. It is found that the size of a DACT of all MAC protocols increases for an increasing number of sensor nodes. However, the initial DACT and its rate of increasing varies very widely among the sensor MAC protocols. Therefore, the attainable PDR for all MAC protocols also vary accordingly.

The PDR of optDMAC is highly stable against an increasing number of sensor nodes in WSNs as shown in Fig. 7. However, for the same number of sensor nodes, the PDR value of SSMA goes down remarkably. The required size of DACT for SSMA is increased considerably as the number of sensor nodes increases.

When the number of sensor nodes becomes 30 or more, the asking value of DACT for SSMA is growing very high. Therefore, the decreasing value of PDR is highly visible from this count of sensor nodes.

Comparing to SSMA protocol, TreeMAC and I-MAC sensor protocols give a very poor PDR value for an increasing number of sensor nodes. Their demand for time slots grows very highly for an increasing count of nodes. When they are given a short DACT than the required one, the nodes often fails to deliver their data packets to their respective parents. Therefore, their attainable PDR value drops very sharply compared to SSMA protocol, and especially to our proposed optDMAC protocol. It is interesting to note that the growing differences of PDR among the sensor MAC protocols is quite high when the number of sensor nodes becomes more than 30.

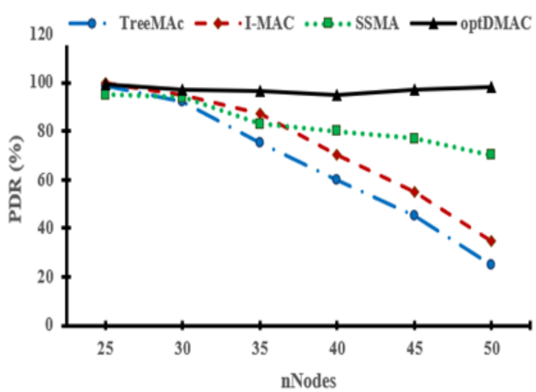

Fig. 7. PDR with varying nNodes (DACT = 1.6).

V. CONCLUSIONS

We are able to optimize the data acquisition cycle time (DACT) by reducing the size of sharable time slots, which is derived from an analytical study of the average number of children and the average depth of a tree. The calculated DACT perfectly accommodates the level-order data packet transmission in industrial WSNs with the help of spatial slot reuse and data aggregation. The spatial slot reuse technique reduces the required number of data packets to be processed by sensor nodes, and the data aggregation method bundles all the collected data packets into a single MAC protocol data unit. As a result, the size of a data packet becomes as small as possible and hence, the required size of a sharable time slot becomes very small. Therefore, the reduction in the size of a DACT by our proposed optDMAC protocol is highly significant compared to other contemporary sensor MAC protocols. Generally, a reduced DACT has a negative effect on the data transmission efficiency in industrial WSNs.

However, even with a small sized DACT, our proposed MAC protocol is able to attain an expected level of PDR compared to other MAC protocols.

As a future work, we can improve the response time of the proposed optDMAC by allowing the sensor nodes at same tree levels to initiate the data transmission in a cooperative mode. Moreover, the use of frequency hopping among the available channels can further improve the response time of industrial WSNs.

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