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A Contention Based Routing Enhanced MAC Protocol for Transmission Delay Reduction in a Multi-Hop WSN

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***Abstract*—In most of wireless sensor network (WSN) applications, energy-efficiency and low end-to-end transmission delay (E2ETD) are essential requirements. This paper presents a contention based routing enhanced MAC protocol, named as CR-MAC, for E2ETD reduction in a multi-hop WSN. CR-MAC reduces E2ETD by optimizing the time interval between the successively sent data packets of a node in a scheduled flow and using a small size control packet to send the request for data transmission. Reduction in the size of control packet also reduces the energy-consumption in the overhearing. We compare the performance of CR-MAC with [4] through ns-2.35 simulations. Results show that CR-MAC outperforms [4] in terms of average energy consumption, E2ETD, and packet delivery ratio.**

***Index Terms*—End-to-end transmission delay (E2ETD), Energy-efficiency, Medium access control (MAC) protocols, Packet delivery ratio (PDR), Wireless sensor networks (WSNs).**

I. INTRODUCTION

Monitoring of delay-sensitive events (e.g, fire, intruder etc.) in unsafe regions is an important class of wireless sensor network (WSN) applications. In such applications, after deployment, a WSN is expected to work as long as possible without any human intervention. Therefore, in such applications, along with the low end-to-end transmission delay (E2ETD), energy-efficiency is also an essential requirement. Furthermore, due to the low event occurrence rate (EOR), idle listening is a major source for energy-inefficiency.

In SMAC [1], Ye et al. reduce the idle listening period of a node in a cycle with the help of a periodic sleep-wake strategy. The cycle structure used in SMAC contains three windows, named as, synchronization window (SW), data window (DW) and sleep-window (SlpW). In SMAC, in DW, a node can schedule only one-hop forwarding of its data packets. As a result, SMAC provides large E2ETD and low PDR in a multi-hop scenario. In RMAC [2], utilizing the routing layer information, a node is enabled to schedule multi-hop forwarding of one data packet in a cycle. Pipelined routing enhanced MAC (PRMAC) [3], further improves E2ETD and PDR by enabling a node to schedule multi-hop forwarding of multiple data packets in DW. In PRMAC, a node sends its successive data packets at intervals of $\mathrm{T_p}$ duration, where $\mathrm{T_p}$ is termed as a re-transmission period. In a multi-hop scenario, E2ETD and PDR performance of PRMAC mainly depend on the (1) number of hops a node can forward its data packets in a cycle; and (2) number of data packets a node can forward in a cycle. In [4], Singh et al. modified the cycle structure used in [1]–[3] to increase the length of the flow scheduled in DW. In [4], a node can schedule one-hop longer flow than PRMAC in the same duration DW. However, as in [3], in [4], T_p is considered a pre-determined parameter and it is equal to βu where $\beta = 2\left\lceil\frac{\varphi+r}{r}\right\rceil$ and $u = \mathrm{T_{DATA}} + \mathrm{T_{ACK}} + 2\mathrm{SIFS}$. (Here, φ, r, $\mathrm{T_{DATA}}$, $\mathrm{T_{ACK}}$ and SIFS are interference range of a sensor node, average distance between a sensor node and its next-hop receiver, time required to transmit one data packet, time required to transmit one ACK packet, and short inter frame space, respectively.) This value of $\mathrm{T_p}$ ensures that, in a $\beta+1$ hops or longer scheduled flow, nodes lying at β hops distance from each other can transmit simultaneously without collision. Therefore, in an i^{th} $(i \leq \beta)$ hops length scheduled flow, this pre-determined value of $\mathrm{T_p}$ reduces the number of data packets that the source node can forward in a cycle and results in an increase in E2ETD and reduction in PDR.

In the present work, a contention based routing enhanced MAC (CR-MAC) protocol for E2ETD reduction in a multi-hop WSN is proposed. Unlike [3], [4], CR-MAC does not consider $\mathrm{T_p}$ as a pre-determined parameter. In CR-MAC, source node determines $\mathrm{T_p}$ for its scheduled flow with the help of a proposed algorithm. In the proposed algorithm, $\mathrm{T_p}$ is determined based on the geographic locations of the nodes of scheduled flow such that the source node can send the maximum number of data packets. This optimum value of $\mathrm{T_p}$ improves E2ETD and PDR more than [4]. In addition to this, CR-MAC uses a small size control packet to send the request for data transmission in DW which increases the length of the flow scheduled in DW and reduces the energy-consumption in overhearing.

The remainder of this paper is as follows. An overview of [4] is given in Section II. CR-MAC's design details, including the algorithm proposed for $\mathrm{T_p}$ determination and its data transmission technique, are given in Section III. Section IV compares the performance of CR-MAC and [4] via ns-2.35 simulations. Section V concludes the paper.

II. Overview of MAC Protocol Proposed in [4]

In this section, we discuss in brief the cycle structure and data transmission technique of [4]. As can be seen in Fig.

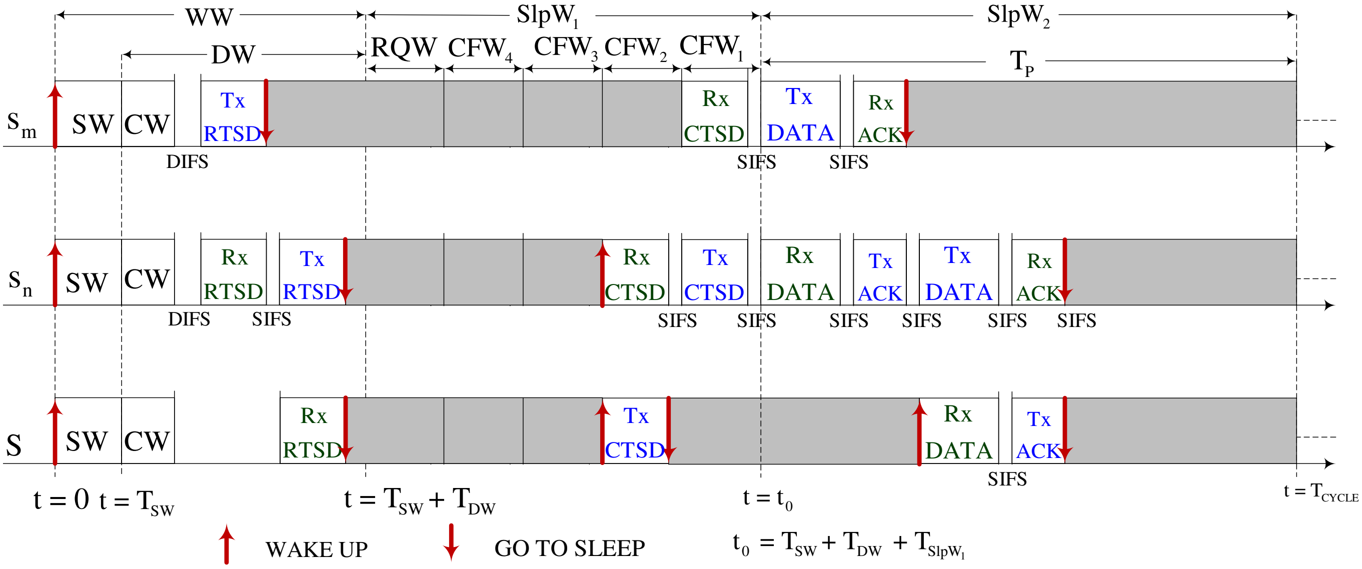

Fig. 1. Data Transmission Process of [4].

1, the wakeup duration is subdivided into SW and DW. As in other prior works, such as [1]–[3] and [5]–[11], in SW, a separate protocol (as in [12]–[15]) is used to synchronize the clocks of neighboring sensor nodes. In DW, sensor nodes try to schedule forwarding of their data packets. The Sleep Window (SlpW) is subdivided into two parts, SlpW_1 and SlpW_2. SlpW_1 contains N $\left(= \left\lceil \frac{T_{CYCLE}-DIFS-\delta_p}{T_{RTSD}+SIFS} \right\rceil \right)$ confirmation windows (CFWs) and one request window (RQW). (Here, T_{CYCLE}, T_{RTSD}, δ_p and DIFS represent duration of one cycle, time required to transmit one request-to-send data (RTSD) packet, propagation delay and distributed inter frame space, respectively.) The duration of each CFW is the same and is equal to $\text{T}_{\text{CTSD}} + \text{SIFS}$ where T_{CTSD} represents the time required to transmit one confirmation-to-send data (CTSD) packet [4]. A node with position index i, sends confirmation in i^{th} confirmation window (CFW_i). (Note that the position index of a node represents its hop distance from the source node in the scheduled flow.) In SlpW_2, corresponding to the scheduling in DW, nodes transmit and/or receive data packets.

Fig. 1 shows data transmission process of [4] assuming that (1) the sensor node s_m has four data packets to forward; (2) distance between s_m and the sink (S) is two hops; and (3) the sensor node s_n is the next-hop receiver of s_m. Due to the large value of the parameter T_p $\left(= 2 \left\lceil \frac{\varphi+r}{r} \right\rceil u\right)$, only one packet is received by the sink node in a cycle. (In this paper, T_X represents time required to transmit the packet X if X is a packet; in case, X is a window, then, T_X represents the duration of window X.)

III. Description of CR-MAC

In this section we describe CR-MAC assuming that each sensor node and each sink node is aware of its geographical location.

A. Overview of CR-MAC

In CR-MAC, we use the cycle structure proposed in [4]. As in [4], in CR-MAC, a node with data packets to send tries to schedule data transmission in DW using the request-to-send data (RTSD) packet. Unlike [4], in CR-MAC, RTSD contains addresses of sender, receiver and final destination, and the position index of the sender. Note that, here, the size of RTSD is smaller than that in [4] as it does not contain the number of data packets the sender has to send to the intended next-hop receiver node. A node having position index i sends its confirmation for the received RTSD during its CFW_i. Unlike [4], in CR-MAC, a CTSD transmitted in CFW_i contains the addresses of the sender and the next-hop receiver, and the geographical location of the sender and all the nodes which have $i+1$ or more position indices in this scheduled flow. That is, the CTSD received by the source node contains geographic locations of all the other nodes of its scheduled flow. Using the received geographic locations and its own geographic location in the proposed Algorithm 1, a source node determines the T_p for its scheduled flow.

In SlpW_2, a source node sends its successive data packets at intervals of T_p. In a scheduled flow, a node having position index i transmits and receives j^{th} data packet at the time instants,

$$\text{T}_{\text{Tx}}^{\text{DATA}}\left(i, j\right) = t_0 + iu + \left(j-1\right)T_p \qquad (1)$$

and

$$\text{T}_{\text{Rx}}^{\text{DATA}}\left(i, j\right) = t_0 + \left(i-1\right)u + \left(j-1\right)T_p \qquad (2)$$

respectively. Here, t_0 represents the beginning time instant of SlpW_2.

B. Determination of T_p

In Algorithm 1, the T_p determination process is described assuming that (1) the sensor node s_1 schedules L hop forwarding of its data packets in DW through the sensor nodes $s_2, s_3, \ldots, s_{L+1}$; and (2) the sensor node s_i $(2 \leq i \leq L+1)$ lies at $(i-1)$ hop distance from s_1 in the scheduled flow.

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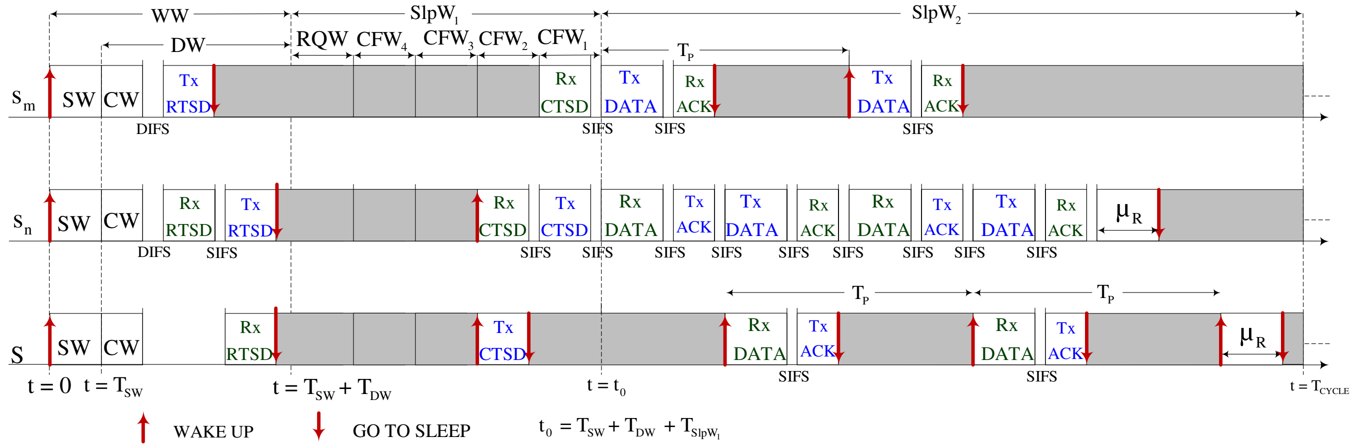

Fig. 2. Data transmission process of CR-MAC.

Algorithm 1 Process followed for $\mathrm{T_p}$ determination.

Definition:
$\mathrm{d}\left(s_p, s_q\right)$: Distance between the nodes s_p and s_q
φ : Interference range of a sensor node
Initializations:
$\alpha_{\min} \leftarrow L$
$\mathrm{d}_\alpha \leftarrow min\left(\mathrm{d}\left(s_1, s_{1+\alpha}\right), \ldots, \mathrm{d}\left(s_{L-\alpha}, s_L\right)\right)$ where $\alpha \in [1, L]$

Process:

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for α ← 1 : 1 : L do
    if d_j > φ ∀ j ∈ [α, L] AND α_min == L then
        α_min ← α
    end if
end for
T_p ← (α_min + 1) u
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In this algorithm, the source node (s_1) first determines the minimum distance between any two nodes lying at α hop distance from each other (d_α) in the scheduled flow where $\alpha \in [1, L]$. After this, it determines the minimum value of α (say, $\alpha_{\min}$) such that $\mathrm{d}_j > \varphi$, $\forall\ j \in [\alpha_{\min}, L]$. This ensures that the nodes lying at $\alpha_{\min}$ or more hop distance from each other do not lie in the interference range of each other. Therefore, the nodes lying at $\alpha_{\min}+1$ hop distance from each other can transmit simultaneously without collision.

In case, no such $\alpha_{\min}$ exists, then, only one node of the scheduled flow can transmit at a time. In such a scenario, $\mathrm{T_p}$ is equal to Lu.

C. Data Transmission Process

We describe the data transmission technique of CR-MAC assuming that (1) the sensor node s_m has four data packets to forward; (2) the distance between s_m and S is two hops; and (3) the sensor node s_n is the intended next-hop receiver of the s_m. As can be seen in Fig. 2, at the beginning of DW, after channel contention, s_m sends RTSD to the node s_n. The sensor node s_n forwards this request to S. Note that, in CR-MAC, RTSD contains the addresses of the sender, the receiver and the final destination, and the position index of the sender.

The sink node S sends CTSD in CFW$_2$ as its position index is 2. This CTSD contains addresses of the sender (S) and the receiver (s_n), and the geographical location of the sender. In CFW$_1$, s_n sends CTSD to the source node s_m as its position index is one. Note that this CTSD contains the addresses of the sender (s_n), receiver (s_m), and geographical locations of S and s_n. On CTSD reception, s_m follows Algorithm 1 to determine the T_p of its scheduled flow.

At the beginning of SlpW$_2$, s_m forwards its first data packet to S through node s_n. Unlike [4], in CR-MAC, the first data packet also contains the value of parameter T_p. As can be seen in Fig. 2, after T_p duration, s_m forwards its second packet to S. In this way, in CR-MAC, two data packets are received by S in one cycle. On the other hand, as can be seen in Fig. 1, in [4], only one packet is received by S in one cycle. This results in E2ETD and PDR improvement compared to [4].

Further, in CR-MAC, RTSD does not contain the number of data packets that the sender has to send. Therefore, as shown in Fig. 2, if a node having position index i does not receive its j^{th} data packet in between the time instants $\mathrm{T}_{\text{Rx}}^{\text{DATA}}\left(i, j\right)$ and $\mathrm{T}_{\text{Rx}}^{\text{DATA}}\left(i, j\right) + \mu_R$, it goes into sleep assuming that the sender does not have a data packet to send. (Here, μ_R is the receive timeout [11].)

IV. Results

We compare the performance of CR-MAC and [4], using ns-2.35 simulator, in terms of AEC (average energy consumption), PDR and E2ETD. (Definitions of AEC, PDR, and E2ETD can be found in [16].) We construct a network by uniformly deploying 900 sensor nodes in a 1800m $\times$ 1800m area. A sink node is placed at the center of the network area. We consider each node to have an omnidirectional antenna. It is assumed that the propagation model is two ray ground reflection. In our simulations, the source node generates constant bit rate (CBR) traffic with packet arrival interval (PAI) 0.1, 0.2 and 0.3 seconds. For performance analysis, we vary the packet arrival interval (PAI) at the source node and the hop distance (h) between the source node and the sink node. Table I contains the frame size parameters. Table II contains the durations of SW, DW, SlpW$_1$ and SlpW$_2$. Other parameters are similar to that of [3]. Results are averaged over 60 simulations

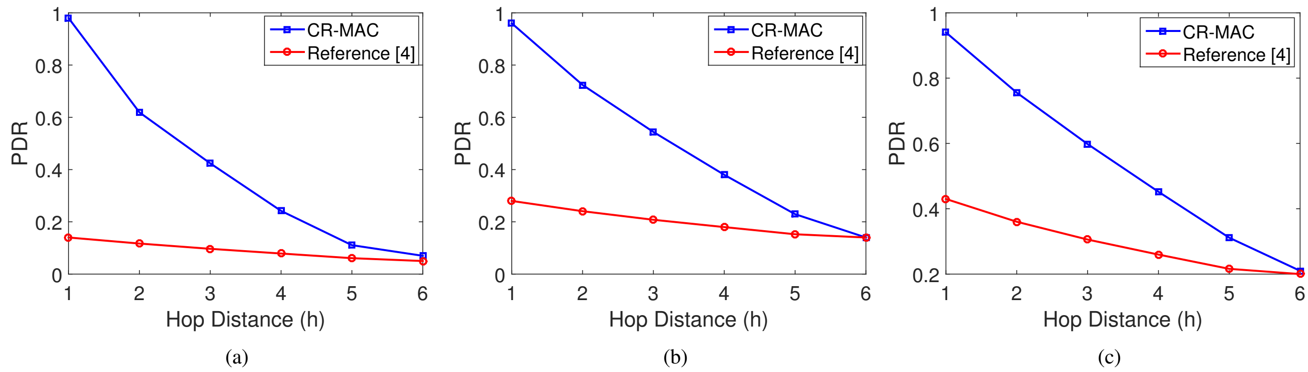

Fig. 3. PDR comparison in case of (a) PAI = 0.1 seconds, (b) PAI = 0.2 seconds and (c) PAI = 0.3 seconds.

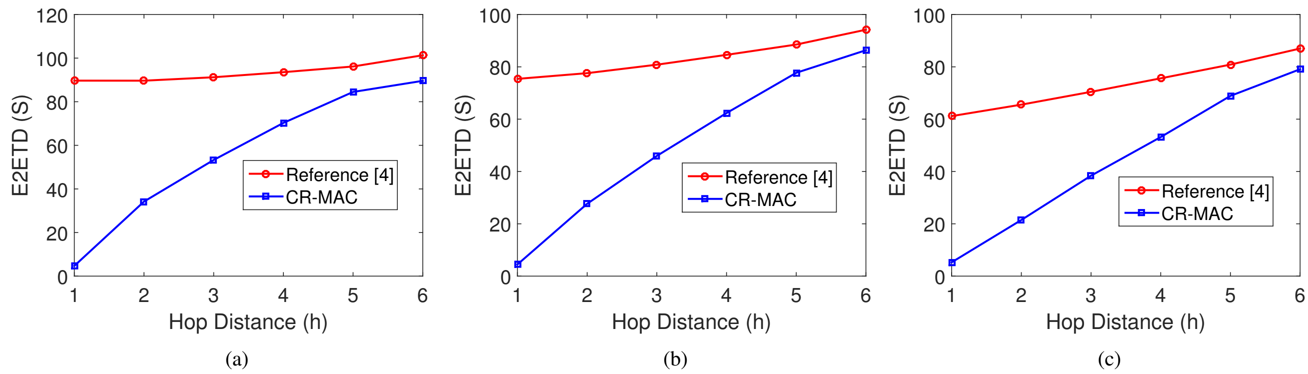

Fig. 4. E2ETD comparison in case of (a) PAI = 0.1 seconds, (b) PAI = 0.2 seconds and (c) PAI = 0.3 seconds.

with different seeds and the duration of each simulation run is 400s.

TABLE I
FRAME SIZES

Frame Type	Size	Frame Type	Size
RTSD (in CR-MAC)	11 bytes	RTSD (in [4])	12 bytes
CTSD (in CR-MAC)	13 bytes	CTSD (in [4])	12 bytes
DATA (in CR-MAC)	50 bytes	DATA (in [4])	50 bytes
ACK (in CR-MAC/ [4])	10 bytes	SYNC (in CR-MAC/ [4])	9 bytes

TABLE II
CYCLE DURATION PARAMETERS

Protocol	SW (ms)	DW (ms)	$SlpW_1$ (ms)	$SlpW_2$ (s)	T_{CYCLE} (s)
Proposed	55.2	117.0	500.0	14.328	15.0
Proposed	55.2	117.0	550.0	14.278	15.0

A. PDR Comparison

Fig. 3 (a), 3 (b), and 3 (c) show comparisons of PDR of CR-MAC and [4] for PAI = 0.1 s, 0.2 s and 0.3s, respectively. In all the three cases, PDR of CR-MAC is better than [4]. Moreover, the difference in PDR of CR-MAC and [4] reduces with an increase in h. This happens because, with an increase in h, the difference in T_p of [4] and CR-MAC reduces. Furthermore, the difference in PDR of CR-MAC and [4] also reduces with an increase in PAI. This happens because the increase in PAI reduces the number of data packets generated by the source in a cycle.

B. E2ETD Comparison

Fig. 4 (a), 4 (b), and 4 (c) we show comparison of E2ETD of CR-MAC and [4] for PAI = 0.1 s, 0.2 s and 0.3s, respectively. In all the three cases, E2ETD of CR-MAC is less than [4]. The reason is, in [4], due to the large value of T_p, a source node can not forward as many data packets as in CR-MAC. As can be seen in Fig. 4, difference in the E2ETD of CR-MAC and [4] reduces with an increase in PAI and h. This happens because (1) increase in PAI reduces the number of data packets generated at the source node in a cycle and (2) with an increase in h, the difference in the T_p of [4] and that of CR-MAC reduces.

C. AEC Comparison

We have also compared the AEC of CR-MAC and [4] for PAI = 0.1 s, 0.2 s and 0.3 s, respectively. It is observed that, in all the three cases, AEC in CR-MAC is less than [4]. However, the difference in AEC of CR-MAC and [4], in all the three cases, is very small ($< 0.1\%$). A possible reason for this is that, in CR-MAC, the size of RTSD is smaller than RTSD used in [4] which reduces overhearing.

V. Conclusions

We proposed a contention based routing enhanced MAC (CR-MAC) protocol for E2ETD reduction in a multi-hop WSN. CR-MAC optimizes the retransmission period $(\mathrm{T_p})$ to maximize the number of data packets that the source node can forward through its scheduled flow. In addition to this, CR-MAC uses a small size control packet to send the request for data transmission which increases the length of the flow scheduled in DW and reduces the energy-consumption in overhearing. Simulation results suggest that CR-MAC would be a better choice for monitoring delay-sensitive events in unsafe regions.

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