A Region-based Reporting Scheme for Mobile Sensor Networks

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***Abstract*—The *mobile sensor networks* (MSNs) have been widely deployed to provide an ubiquitous solution for time-sensitive applications in a specific area with low deployment cost. The monitoring area of an MSN can be divided into several *sensing regions* (SRs). In an SR, the *mobile sensor* (MS) is responsible for reporting the sensed data to the sink node. For the time-sensitive applications on MSN, the time is divided into multiple monitoring periods (MPs). During every MP, a sensing report transmission in an SR is invalid if the sensing report is generated before the beginning of the MP. In this paper, we propose a region-based reporting mechanism, namely *Energy-Efficient Distributed-Control Reporting* (E^{2}DCR) mechanism, for the MSNs. During every MP, the E^{2}DCR mechanism attempts to have only one MS transmit the sensing report in an SR, and the other MSs in the same SR can stay in the sleep mode for power saving. Simulation experiments are conducted to investigate the performance of the proposed mechanism. Our study shows that E^{2}DCR can meet the delay constraint of the time-sensitive applications with less power consumption.**
Keywords: Mobile sensor networks, Region-based reporting mechanism, Time-sensitive applications

I. INTRODUCTION

The *mobile sensor networks* (MSNs) have been widely deployed to provide an ubiquitous solution for real-time monitoring applications in a specific area with low deployment cost [1], e.g., the traffic data collection in Vehicular Ad-hoc Networks (VANETs) [6][15], and the ocean data collection in Underwater Sensor Networks (UWSNs) [7][11]. Figure 1 illustrates an example for the general MSN architecture, which comprises fifteen *mobile sensors* (MSs) and a *sink* node. The monitoring area of an MSN can be divided into several *sensing regions* (SRs). For example, there are four SRs in Figure 1. There may be one or more MSs residing in an SR. An MS consists of one or more *sensing modules* (SMs) and one *reporting module* (RM). The SM is responsible for monitoring and producing the sensed data, such as temperature, humidity, air quality, and so on. The RM equipped with a wireless transceiver is responsible for reporting the sensed data to the sink node. Due to the limited power supply of MS, less computation and transmission in the MS results in longer operating life of an MSN. The miniature technology makes the MS practically be installed on other objects (e.g., vehicles or human bodies). The MS can obtain its location information by the location determination system, such as

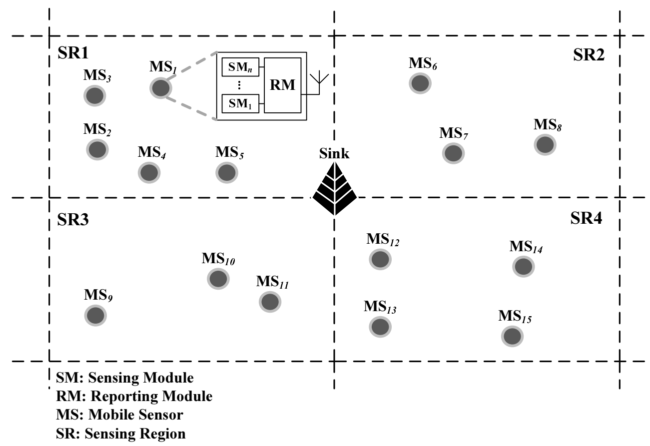

Fig. 1. A general mobile sensor network

the Global Positioning System (GPS). Another feature of the MS is the mobility. The MS moves among different SRs, and sends a report (carrying the sensed data and its location information) to the sink node. The sink node is the data processing center and responsible for collecting the reports from the MSs for monitoring. The sink node is often with permanent power supply, and has powerful computation and transmission capability.

For the time-sensitive applications on MSN, the time is divided into multiple Monitoring Periods (MPs). During every MP, a sensing report transmission in an SR is invalid if the sensing report is generated before the beginning of the MP. The detail definitions for the valid sensing report and the MP will be elaborated in the next section. Due to correlation of MSs' locations (e.g., two reporting MSs are in the same SR), there may be redundant reports transmitted during an MP. Carefully scheduling the sensing report transmissions of the MSs in an SR by considering its location may prevent non-redundant sensing report transmission, save the power consumption of MSs, and extend the life time of an MSN. The sleep mode technology [5][13][14] by shutting down MSs' transceivers have been widely adopted to save MSs' power consumption. However, prolonging the time period when the MS stays in the sleep mode may increase the possibility for invalid sensing report transmissions. We name this tradeoff as the "energy-validity" tradeoff, which is a challenging for the design of the MSNs.

The "energy-validity" issue related to *wireless sensor networks* (WSNs) has been treated in the previous researches [2][5][14]. The previous researches consider the fixed locality of a sensor node, and did not discuss the time-sensitive applications on MSNs. The mechanisms proposed in the previous WSN works can be divided into two categories [10]: scheduler mechanisms and non-scheduler mechanisms. The scheduler mechanisms [8][14] attempt to make the sensor nodes report in order. A central controller is introduced to maintain the report scheduler for the sensor nodes. The sensor nodes must keep on updating the scheduler as that received from the sink node. If the network topology changes frequently, which is one of the main characteristics of MSNs, the maintenance of the scheduler incurs high signaling cost, and the sensor nodes consume more power. This makes the scheduler mechanisms impractical to the MSNs. On the contrary, the non-scheduler mechanisms [13] allow the sensor nodes to operate independently without scheduling of a central controller. This is typically achieved by the contention-based media access control (MAC) protocols, e.g., the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol for its simplicity. In the non-scheduler mechanisms, there is no need to exchange the reporting scheduler, and thus there is less power consumption of the sensor nodes. However, the validity of the sensed data and the redundant sensing report transmission are not put into consideration in the non-scheduler mechanisms for WSNs in the previous works.

In this paper, we propose a region-based reporting mechanism, *Energy-Efficient Distributed-Control Reporting* (E^2DCR) mechanism, for the MSNs. The E^2DCR mechanism is a non-scheduler mechanism based on the IEEE 802.11 protocol (that has been adopted in several previous studies [2][8][12][13][14] as the MAC protocol of WSNs). During every MP, the E^2DCR mechanism attempts to have only one MS transmit the sensing report in an SR, and the other MSs in the same SR can stay in the sleep mode for power saving. In the following sections, we briefly describes the IEEE 802.11 protocol and details the E^2DCR mechanism. Then, we study the performance of the E^2DCR mechanism. Finally, we conclude our work.

II. Region-based Time-Sensitive Applications on MSN

This section describes the system model and proposes the region-based reporting mechanism for region-based time-sensitive applications on MSNs.

A. System Model

The service area of a sink node is divided into m SRs, SR_1, SR_2, ..., SR_m. To simplify our discussion, an SR is shaped as a circle with the radius Δ, and the center of SR_j is denoted as $C_j = (\hat{x}_j, \hat{y}_j)$.

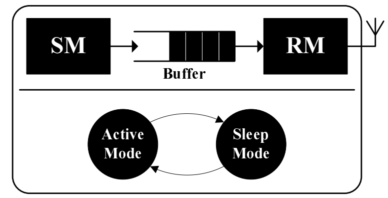

Fig. 2. Two operational modes: active mode and sleep mode

As shown in Figure 2, we assume that an MS MS_i has one SM, one RM, and a data buffer. MS_i operates in one of the two modes: active mode and sleep mode. In the active mode, both SM and RM of MS_i are turned on. The sensing report is generated by the SM and inserted into the buffer. The RM activates the DCF procedure to transmit the buffered sensing reports to the sink node. The management policy applied for the buffer is first-come-first-served (FCFS). For time-sensitive applications, the MS always keeps one latest sensing report in the buffer, and drops the older one when a new generated sensing report is inserted to the buffer. When the sensing report transmission is successful (i.e., MS_i receives the ACK frame for the transmitted sensing report), MS_i removes the sensing report from the buffer. In the sleep mode, MS_i turns off the SM and RM, and drops the buffered sensing report.

To simplify our discussion, we consider a two-dimensional coordinate system for the location of an MS. Our model can be easily extended to a three-dimensional coordinate system. Let $L_i(t)$ and $D_i(t)$ denote the location of MS_i and the data sensed by MS_i at time t, respectively. A sensing report generated by MS_i at time t consists of $L_i(t)$ and $D_i(t)$, which is denoted as $\mathbb{R}_i(t) = \{L_i(t), D_i(t)\}$.

Suppose that the system is turned on at time t_0. Assume that the sink node successfully receives a sensing report $\mathbb{R}_i(t_1) = \{L_i(t_1), D_i(t_1)\}$ from MS_i at time t_2, where $t_0 < t_1 < t_2$. The sink node determines that $\mathbb{R}_i(t_1)$ belongs to SR_j if the distance between $L_i(t_1) = (x_i, y_i)$ and C_j satisfies the following condition:

$$|L_i(t_1) - C_j| = \sqrt{(x_i - \hat{x}_j)^2 + (y_i - \hat{y}_j)^2} \leq \Delta. \quad (1)$$

In time-sensitive applications, the time is divided into multiple MPs, 1st MP, 2nd MP,...,ith MP. The length of an MP is a pre-defined interval θ. Let the time-sensitive application start at time t. Then, the beginning and the ending of the ith MP are $t + (i-1)\theta$ and $t + i\theta$ (where $i \geq 1$), respectively. Suppose that the sink node receives the jth sensing report $\mathbb{R}_x(t'_j)$ (generated by MS_x at time t'_j and $t'_j \leq t_j$) at time t_j in the ith MP (i.e., $t+(i-1)\theta \leq t_j \leq t+i\theta$). The jth sensing report $\mathbb{R}_x(t'_j)$ is valid if

$$t'_j \geq t + (i-1)\theta. \quad (2)$$

For example, the beginning and the end of the 1st MP are t and $t+\theta$. The first sensing report $\mathbb{R}_x(t'_1)$ received by the sink node at time t_1 in the 1st MP is valid since $t'_1 \geq t$ and $t \leq t_1 \leq t+\theta$. On the other hand, the second sensing report $\mathbb{R}_x(t'_2)$ received by the sink node at time t_2 in the 2nd MP is invalid due to that $t'_2 < t + \theta$. Let M_i denote the number of valid sensing reports received by the sink node in the ith MP. For continuous monitoring, the sink node should receive at least one valid sensing report in every MP (i.e., $M_i \geq 1$). A larger M_i implies that there are *"redundant"* sensing reports received by the sink node in the ith MP. $M_i = 0$ indicates that the monitoring of the SR in the ith MP is *"interrupted"*. For example, there are two valid reports received by the sink node in the 1st MP and no valid sensing report received by the sink node in the 2nd MP. Therefore, $M_1 = 2$ indicates that the SR has continuous monitoring during the time period between t and $t+\theta$. On the other hand, $M_2 = 0$ indicates that the monitoring of the SR is interrupted during the time period between $t+\theta$ and $t+2\theta$.

B. Region-based Reporting Mechanism

In this subsection, we propose a region-based reporting mechanism, namely *Energy-Efficient Distributed-Control Reporting* (E^2DCR) mechanism, to have MSs transmit the valid sensing report more efficiently for region-based time-sensitive applications on MSNs. The E^2DCR mechanism consists of two parts: sink part and MS part, which exercises in the sink node and the MSs, respectively. The details of E^2DCR are given in the following subsections.

1) Sink Part: The sink part maintains the following information for each SR_j.

- The set $\mathbb{S}[j] = \{C_j, \hat{D}_j\}$, where $\hat{D}_j$ is the sensed data in the latest valid sensing report received for SR_j.
- The sink node starts to monitor SR_j by activating the $T_{p,j}$ timer. The expiration of the $T_{p,j}$ timer implies the end of an MP. The threshold of $T_{p,j}$ is equal to θ.
- The counter $CR_{v,j}$ counts the number of valid sensing reports received by the sink node in an MP. At the beginning of an MP, $CR_{v,j}$ is reset to zero.
- In the end of the ith MP, the variable $I_j(i)$ is maintained to indicate the ith MP is an interruption period or not, that is,

$$I_j(i) = \begin{cases} 1, & \text{if the } i\text{th MP is an interruption} \\ & \text{period (i.e., } CR_{v,j} = 0\text{);} \\ 0, & \text{otherwise (i.e., } CR_{v,j} \neq 0\text{).} \end{cases} \quad (3)$$

- In the end of every MP for SR_j, the sink node computes the ratio $\Gamma_j(i)$:

$$\Gamma_j(i) = \begin{cases} \Gamma_j(i-1) + I_j(i), & \text{if } i \bmod K \neq 0; \\ \dfrac{\Gamma_j(i-1) + I_j(i)}{K}, & \text{otherwise (i.e.,} \\ & i \bmod K = 0\text{),} \end{cases} \quad (4)$$

  where by convention, $\Gamma_j(0) = 0$.
  In the end of every K MPs, the ratio $\Gamma_j(i)$ is broadcasted by the sink node through a *notification* message that is used to notify the MSs in the SR_j to dynamically adjust the sleeping period of the MSs. After broadcasting the notification message, $\Gamma_j(i)$ is reset to 0. The details of the dynamic adjustment will be elaborated later.

The following two events trigger the execution of the sink part.

- **E1**: The sink node receives a sensing report for SR_j;
- **E2**: The $T_{p,j}$ timer expires.

The details of the execution in the sink part are given below:

Step 1. When the monitoring starts, the index i is set to one, which indicates the 1st MP is being processed.

Step 2. The counter $CR_{v,j}$ is set to 0, and the timer $T_{p,j}$ is set to θ. The sink node starts monitoring the ith MP for SR_j by triggering the $T_{p,j}$ timer.

Step 3. The sink node waits for the occurrence of the **E1** or **E2** event. When **E1** occurs, goes to Step 4. When **E2** occurs, goes to Step 5.

Step 4. The sink node checks whether the received report is valid by using equation (2). If the received sensing report is valid, the sink node updates $\hat{D}_j$ to the sensed data in the received sensing report and $CR_{v,j}$ is incremented by one. Otherwise (i.e., the received sensing report is invalid), the sink node ignores the received sensing report. Then the mechanism goes back to Step 3.

Step 5. The sink node checks the $CR_{v,j}$ counter. If $CR_{v,j} = 0$, we set $I_j(i) = 1$. Otherwise (i.e., $CR_{v,j} \neq 0$), we set $I_j(i) = 0$. Then the sink node compute $\Gamma_j(i)$ by equation (4). If $i \bmod K = 0$, a notification message is broadcasted by the sink node (see Step 16), which contains the center C_j, the radius Δ, and the ratio $\Gamma_j(i)$ to have MSs estimate the length of sleeping period, whose details will be described in the MS part. After that, $\Gamma_j(i)$ is reset to zero. Then the index i is incremented by one and the sink node goes back to Step 2.

2) MS Part: The MS part of E^2DCR is described as follows. When the MS is initially powered on, the MS stays in the active mode and executes the DCF function to transmit the sensing report, and the MS also listens to the notification message for the dynamic adjustment of the sleeping period. When the MS receives a notification message for SR_j (containing C_j, Δ, and Γ_j), the MS checks whether the distance between its current location and C_j is smaller than Δ. If so (i.e., the MS is in the SR_j), the MS executes the Dynamic Sleeping Adjustment (DSA) algorithms (to be elaborated later) to adjust the T_s timer. Otherwise (i.e., the MS is not in the SR_j), the received notification message is ignored. When the MS successfully transmits a sensing report, the MS switches to sleep mode for power saving and triggers the T_s timer. When the T_s timer expires, the MS switches back to the active mode.

3) Dynamic Sleeping Adjustment: Two DSA algorithms are proposed to adjust the T_s timer in the MS, which are described as follows. Let $V(k)$ denote the kth configuration for the T_s timer.

- **Basic DSA (BDSA):** Without any control, the configuration for the T_s timer is randomly generated by the MS using the geometric distribution with mean $A\theta$.
- **Threshold-based DSA (TDSA):** We define a threshold

ρ to being a criteria for adjustment. Initially, $V(1)$ is set to θ. We determine if $V(k+1)$ is to be adjusted to $V_1 = V(k) + \omega$ (i.e., $V(k)$ is incremented by θ), $V_2 = V(k)$ (no change), and $V_3 = \max\{V(k) - \omega, \theta\}$ (i.e., $V(k)$ is decremented by ω or reset to θ). The ω value is fixed to the value $A\theta$. That is, based on the ratio Γ_j in the received notification message, $V(k+1)$ is adjusted as follows:

$$V(k+1) = \begin{cases} V_1, & \text{if } \Gamma_j = 0; \\ V_2, & \text{if } \Gamma_j < \rho; \\ V_3, & \text{otherwise (i.e., } \Gamma_j \geq \rho). \end{cases} \quad (5)$$

III. Performance Evaluation

This section conducts simulation experiments to investigate the performance of the proposed E^{2}DCR mechanism in terms of the power saving probability P_{ps} (for the MS) and interrupted monitoring probability P_{im} (for an SR). We apply the discrete-event driven approach to construct the experiments written in C++. Due to the page limitation, the details of the simulation are not given in this paper. The P_{ps} and P_{im} performances are are defined as follows:

$$P_{ps} = \lim_{t\to\infty} \Pr\{\text{an MS is in the sleep mode at time } t\},$$

and

$$P_{im} = \Pr\{\text{no sensing report is received during an MP}\}.$$

We consider the discrete-time domain, that is, the system time t is in the integer domain ($t \in \mathbb{N}$). We consider an SR in the MSN. Suppose at most one MS arrives at the SR in a time slot, and MS arrivals to the SR form the Bernoulli process with parameter λ. Thus the probability that an MS arrival occurs in a slot is λ, no MS arrival occurs in a slot with the probability $1 - \lambda$, and the inter-MS arrival time period is geometrically distributed with mean $1/\lambda$. The SR residence time for an MS is assumed to be geometrically distributed with mean $1/\eta$. From [4], the expected number of MSs that reside in the SR can be expressed as λ/η. We assume that the random backoff interval is the geometric distribution with mean $1/\mu$. That is, an MS has probability μ to transmit the RTS frame if the wireless medium is sensed idle in a time slot.

Based on [3] and [9], the transmission rate is set to 1Mbps. The size of the RTS (Request to Send) frame is 20 bytes, and the sizes of the CTS (Clear to Send) and ACK (Acknowledgement) frames are 14 bytes. The sensing report is fixed to 400 bytes, which is the recommended value for maximum packet length at 1Mbps. A slot time is assumed to 20 microseconds, and θ is set to 1000 time slots (i.e., 20 milliseconds). The input parameters λ, η, μ, SIFS (Short Interframe Space), and DIFS (DCF Interframe Space) are normalized by θ. For example, $1/\eta = 360\theta$ means that the expected residence time of an MS is 7.2 seconds. The impacts of the input parameters are discussed below.

- **Effects of A and λ/η.** Figure 3 plots P_{ps} and P_{im} as function of λ/η, where we set $1/\eta = 360\theta$, $1/\mu = 0.064\theta$, $K = 4$, $\rho = 0.4$, SIFS $= 0.001\theta$ and DIFS $= 0.0025\theta$. Figure 3(a) shows the intuitive result that P_{ps} decreases as λ/η increases. We observe that TDSA outperforms BDSA significantly, especially in the larger λ/η. In BDSA, the P_{ps} performance degrades faster when λ/η is larger due to that the occurrence of collision becomes more frequently. Thus the contention process causes more power consumption. However, in TDSA, the dynamic sleeping adjustment reduces the number of MSs that simultaneously contend the wireless medium, so that TDSA has the better Pps performance. The figure also shows that P_{ps} increases as A increases, which indicates that the sleep period increases, the MS has better chance to stay in the sleep mode.
Figure 3(b) shows that P_{im} decreases as λ/η increases. This phenomenon is explained as follows: As λ/η increases, the inter-report time (i.e., the time interval between two valid sensing report received by sink node) is smaller due to that more MSs attempt to transmit the sensing report. Therefore, P_{im} decreases. This figure also shows that BDSA has better performance than TDSA in P_{im} when A is smaller, but BDSA and TDSA have almost the same performance when λ/η is larger. However, TDSA outperforms BDSA significantly when A is larger (e.g., $A = 4$ and $A = 8$) and λ/η is smaller. This is due to that the MSs using BDSA have longer sleep period at the beginning, so that P_{im} becomes larger especially when λ/η is smaller.

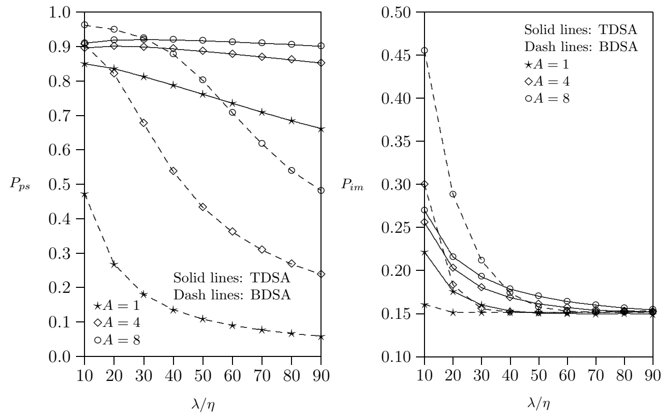

Fig. 3. Effect of A and λ/η ($1/\eta = 360\theta$, $1/\mu = 0.064\theta$, $K = 4$, $\rho = 0.4$, SIFS $= 0.001\theta$ and DIFS $= 0.0025\theta$).

- **Effects of K and λ/η.** Figure 4 plots the P_{ps} and P_{im} performances as function of λ/η for TDSA, where we set $1/\eta = 360\theta$, $1/\mu = 0.064\theta$, $A = 8$, $\rho = 0.4$, SIFS $= 0.001\theta$ and DIFS $= 0.0025\theta$. Figure 4(a) shows the intuitive result that the P_{ps} decreases as K increases. When K is small, the dynamic sleeping adjustment becomes very frequently and therefore P_{ps} has the better performance. Figure 4(b) shows that P_{im} has the better performance when K is larger. But the curve of P_{im} will rise while K and λ/η is larger (e.g., $K = 16$ and $\lambda/\eta > 50$) due to that the low adjustment frequency and the excess collisions.

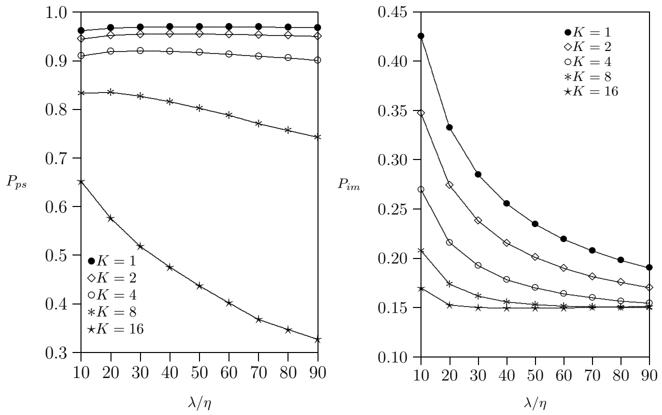

Fig. 4. Effect of K and λ/η ($1/\eta = 360\theta$, $1/\mu = 0.064\theta$, $A = 8$, $\rho = 0.4$, SIFS $= 0.001\theta$ and DIFS $= 0.0025\theta$).

IV. Conclusion

This paper proposed the *Energy-Efficient Distributed-Control Reporting* (E^2DCR) mechanism to have MSs transmit the valid sensing report more efficiently for region-based time-sensitive applications on MSNs. In E^2DCR, we applied the BDSA and TDSA algorithms to dynamically adjust the sleeping period for the MSs to save the power consumption. We conducted simulation experiments to study the P_{ps} performance for the MS and the P_{im} performance for the SR. Our study indicates that

- TDSA has the better performance than BDSA in P_{ps} when λ/η is larger. On the other hand, BDSA outperforms TDSA in P_{im} only when λ/η and T_s are smaller.
- The P_{im} in both BDSA and TDSA are concave curves. That is, as λ/η increases, P_{im} first drops quickly and then slightly increases.
- In both BDSA and TDSA, as A increases, the P_{ps} significantly increases. On the contrary, the P_{im} decreases when A increases.
- For TDSA, as K decreases, the P_{ps} increases significantly.

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