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Research Article

Distributed Velocity-Dependent Protocol for Multihop Cellular Sensor Networks

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Cell phones are embedded with sensors form a Cellular Sensor Network which can be used to localize a moving event. The inherent mobility of the application and of the cell phone users warrants distributed structure-free data aggregation and on-the-fly routing. We propose a Distributed Velocity-Dependent (DVD) protocol to localize a moving event using a Multihop Cellular Sensor Network (MCSN). DVD is based on a novel form of connectivity determined by the waiting time of nodes for a Random Waypoint (RWP) distribution of cell phone users. This paper analyzes the time-stationary and spatial distribution of the proposed waiting time to explain the superior event localization and delay performances of DVD over the existing Randomized Waiting (RW) protocol. A sensitivity analysis is also performed to compare the performance of DVD with RW and the existing Centralized approach.

1. Introduction

In recent years, the idea of *people-centric sensing* or *participatory sensing* has gained considerable significance in urban environments. Ubiquitously used hand-held devices such as cell phones, when additionally empowered with sensing capabilities, form *Cellular Sensor Networks*, [1–5], which collaboratively serve an application. While the cellular backbone resolves issues related to the deployment and provision of energy for the embedded sensors, the mobility of cell phone users provides improved coverage and energy efficiency, [6, 7]. Further, extensive research in *Multihop Cellular Networks (MCN)* have demonstrated their improved coverage and network capacity over conventional cellular networks, [8, 9]. Therefore, *Multihop Cellular Sensor Networks (MCSN)*, where sensor networks are built upon the MCN infrastructure, are advocated in this paper. The schematic of a MCSN is shown in Figure 1. Here, cell phones embedded with sensors transmit sensed data to the BS in a *multihop* manner. A typical MCSN can cater to applications like environmental monitoring, urban planning, natural resource management, civic hazard detection and information sharing. Some of the ongoing projects on various applications of Cellular Sensor Networks are summarized in Section 7.

In our work, we consider a *moving event localization* application of Multihop Cellular Sensor Networks. The moving event that needs to be detected and localized can be gaseous leakage, toxic clouds, or a phenomenon like cyclone or dust storm. In all these applications, since the event as well as sensor nodes are mobile, a new set of nodes detect the event at every instant. Moreover, due to the extensive use of cell phones, enormous data will be generated in the network. For such scenarios, a centralized data aggregation scheme may not be suitable, due to the resulting energy loss and network congestion. Hence, the development of an efficient distributed data aggregation scheme becomes essential. Further, the mobility of the event as well as that of the users entails the design of an *on-the-fly protocol* for routing.

The problem of tracking mobile events using Cellular Sensor Networks is being considered in [4] using a fully

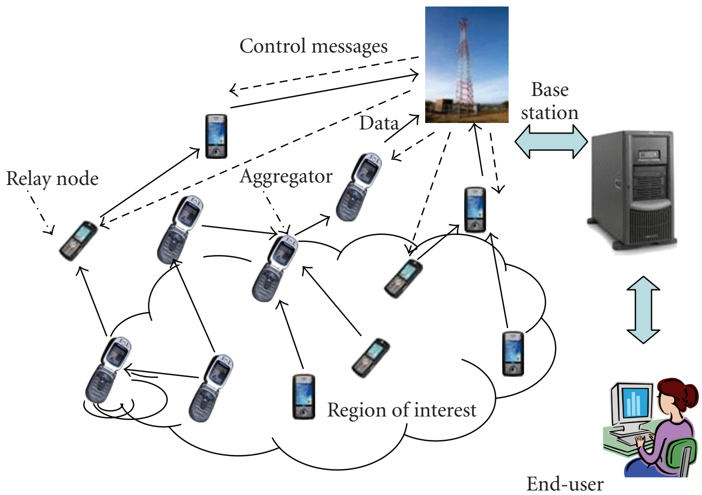


Figure 1: Schematic of a Multihop Cellular Sensor Network.

distributed tracking system called MetroTrack (details of which are currently unavailable). In [4], the issues of time-varying coverage of the event and varying mobile phone density are tackled by a distributed Kalman-Consensus filtering algorithm. We however deal with these issues by proposing a *Multihop* Cellular Sensor Network based framework for localizing the moving event. In [10, 11], a moving point-source target was tracked by *static* sensor nodes using a cluster membership update mechanism and a tree-based approach, respectively. However in a MCN backbone, such a structured approach would incur large communication and computation overhead in structure formation and maintenance. This motivates the idea of a *structure-free* approach for aggregation and routing in MCSN. In [12], a structure-free Data Aware *Randomized Waiting* (*RW*) time protocol had been proposed for detecting a moving target using a static wireless sensor network.

The main contributions of our paper are as follows.

(i) Use of a Multihop Cellular Sensor Network (MCSN) for moving event localization.

(ii) Development of a novel *Distributed Velocity-Dependent* (DVD) Waiting Time protocol for MCSN.

(iii) Analysis of the DVD protocol in terms of the time-stationary probability density function and the spatial distribution of waiting time.

(iv) Perturbation analysis of DVD considering perturbations in location, velocity and sensed data information at nodes.

The salient features of the proposed DVD protocol are as follows.

(i) *Structure-Free*. A distributed structure-free data aggregation is performed in DVD.

(ii) *Moving Event and Mobile Nodes*. In [12], nodes were located at fixed inter-node distances and a moving event was considered. In DVD, we localize the trajectory of a moving event using data gathered by cell phone users.

(iii) *Velocity-Dependent Waiting Time*: Due to lack of structure, the time for which a node delays transmission of its own data in order to promote aggregation, cannot be ascertained a priori without some topology information. In the location-aware, structure-free protocol proposed in [12], a Random Waiting Time had been adopted. The Random Waypoint (RWP) steady state distribution, [13], of users, is typically observed in cellular networks. Therefore, in our work, we determine the waiting time based on the RWP mobility model. The proposed waiting time depends on location and velocity of nodes, resulting in a better trade off between end-to-end delay and connectivity (as explained in Section 3.2).

(iv) *On-the-Fly Routing*: Since we consider a dynamic scenario, the relaying of data is done independently at each hop based on *waiting time connectivity* (Section 3.1).

(v) *Delay Minimization*: To reduce end-to-end delay, routing of aggregated data at each hop is done by the node which has the minimum waiting time amongst nodes that satisfy *waiting time connectivity*. The spatial distribution of waiting time in DVD supports the relay node selection process, resulting in a low end-to-end delay.

The organization of the manuscript is as follows. In Section 2, the system model is described. A brief review of the proposed DVD protocol [14], is described in Section 3. In the current work, we derive the time-stationary probability density function and analyze the spatial distribution of waiting time to provide a better insight into the design and benefits of the proposed DVD protocol. These are discussed in greater detail in Section 4 and Section 5, respectively. We quantify the protocol performance in terms of error in localizing the event, end-to-end delay and energy dissipation.

To evaluate the robustness of DVD, we further perform a sensitivity analysis to study the effect of perturbations on sensed data, location or velocity measurements and obtain 95% confidence intervals for the average performances. Our simulation results (Section 6) show that, with or without perturbations, DVD performs better than RW in terms of event localization error and end-to-end delay. The proposed DVD protocol and the existing Centralized scheme (Cellular Sensor Networks without multihop) have comparable event localization estimates. Even though the Centralized scheme has the lowest end-to-end delay, DVD is found to be more energy-efficient than the centralized scheme. Section 8 concludes the paper.

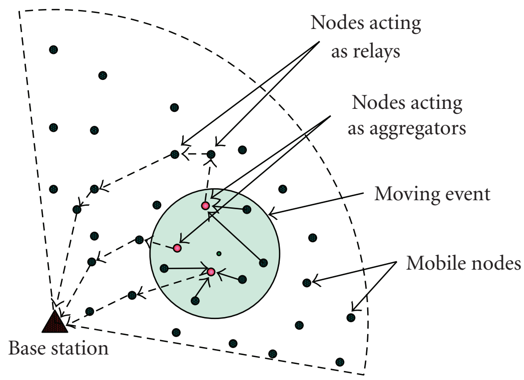


Figure 2: Schematic of proposed DVD for moving event localization in Multihop Cellular Sensor Networks.

2. System Model

2.1. Intensity Model. At any time instant t, the moving event is defined by a location (*center of event* (*CoE*)) of maximum event intensity I_T, and the event radius R_e, within which the event has an intensity greater than a threshold intensity I_D. In general, moving events like gaseous leakage have an intensity profile which decays with distance from the CoE, [15]. For a node i at a distance of $d_e(i)$ from the CoE, the measured intensity $I(i)$ is given by

$$I(i) = \frac{I_T(t)}{4\pi d_e(i)^2}, \tag{1}$$

where the event intensity $I_T(t)$ at time instant t, is provided by the application based on known models of the event, [15–17]. An application-dependent event detection threshold intensity I_D, is also known at the user end. Node i is an *event node* if it measures an intensity $I(i) > I_D$ and is a *non-event node*, otherwise. Every *event node*, computes its distance d_e from the *center of event* using the known value of event intensity $I_T(t)$ and its measured intensity I using (1). It follows from (1) that all nodes within a distance of $R_e(t) = \sqrt{(I_T(t))/(4\pi/I_D)}$ from the *center of event* at time t, are *event nodes.*

2.2. Path Loss Model. We employ distance dependent variable transmission power levels at nodes [18]. If r is the known distance between source and destination nodes, using the free-space path loss model of radiowave propagation, [19], the transmission power $P_t(r)$ at the source node is computed as

$$P_t(r) = P_d\left(\frac{4\pi r}{\lambda}\right)^2, \tag{2}$$

where P_d is the minimum received power required for successful reception at the destination. For a known receiver sensitivity s in dBm, we compute $P_d = 10^{s/10}\, mW$. λ is the wavelength of the Radio-frequency (RF) signal.

2.3. Energy Model of Mobile Phones. The sensing application is initiated by the mobile phone at regular sampling instants, as specified by the end-user. Between sampling instants, cell phone resources are used for regular (voice/text) applications. For any two time instants, t_1 and t_2, between two consecutive sampling instants, we assume that the residual battery energy B decays linearly in the following manner:

$$B(t_2) = B(t_1) - \frac{(t_2 - t_1)B_{\max}}{T_{\max}}. \tag{3}$$

In (3), $B_{\max}$ is the battery rating of the cell phone and $t_2 > t_1$. $T_{\max}$ is the corresponding talktime rating which determines the maximum duration for which the cell phone can be powered while performing regular applications. Therefore, assuming that a residual energy of $B_{\max}$ would decay within a time duration $T_{\max}$, the energy drained within a duration $t_2 - t_1$ would be $((t_2 - t_1)B_{\max})/T_{\max}$.

2.4. Aggregation Rule. Each aggregator selects the location of the node with minimum d_e as its estimate of the *center of event*, from among the *event nodes* that transmit data to it. For any *event node* i, (x_i, y_i) is its location and $d_e(i)$ is its distance from CoE. From Figure 5, let $S1$ be the set of *event nodes* (say $A1, B1, C1$) transmitting data to an aggregator node $E1$, then by the aggregation rule, $E1$ estimates the location of the *center of event* as (x_{L1}, y_{L1}) where $L1 = \arg\min_i\{d_e(i) : i \in S1\}$. Aggregator $E1$ transmits $[(x_{L1}, y_{L1}), d_e(L1)]$ to the BS. Note that the aggregation rule is chosen to be computationally light on the resource-constrained cell phones. The BS makes the final estimate of CoE by trilateration (for precise data) or a *Least Squares* approach (for imprecise data) using data obtained from many such aggregators ($E1$, $E2$, $E3$ shown in Figure 5). Note that the localization algorithm (trilateration/LS estimation) is implemented only at the BS which is assumed to have sufficient power and computational capabilities.

3. Distributed Velocity-Dependent (DVD) Waiting Time Based Protocol

In this section, we describe the proposed structure-free Distributed Velocity-Dependent (DVD) Waiting Time based protocol used to aggregate sensed data and route it efficiently to the Base Station in a Multihop Cellular Sensor Network. The key components of the protocol are: a distributed data aggregation scheme and an on-the-fly routing protocol.

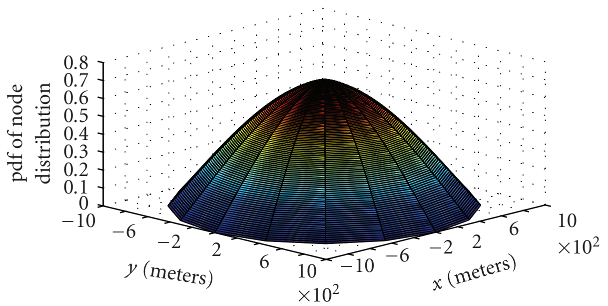


Figure 3: Random Waypoint spatial distribution in Cellular Networks.

Figure 2 shows the schematic of the proposed DVD protocol. The main challenges involved in the design of the protocol are:

(i) *Dynamic Topology*: This necessitates structure-free data aggregation and on-the-fly routing.

(ii) *Non-uniform node distribution*: Cell phone users, in general, closely follow a Random Waypoint distribution, [13], shown in Figure 3. The probability density of the time-stationary distribution of mobile node location, $M(t)$ at a point (x, y), in a circular disk of unit radius, is given as, [13]:

$$f_{M(t)}(x, y) = \frac{45}{32\pi}(1 - r^2)E(r^2), \tag{4}$$

where $r = \sqrt{x^2 + y^2}$, $|r| \leq 1$ and $E(r^2) = \int_0^{(\pi/2)} \sqrt{(1 - r^2 \sin^2(\theta))} d\theta$. From (4), it can be seen that the node density decreases from the center to the boundaries of the circular disk. Therefore, the protocol design must ensure connectivity of all nodes despite the non-uniformity in node distribution. To tackle this, we exploit variable waiting times at nodes, which will be discussed in the following subsections.

3.1. Waiting Time Connectivity in DVD. Each node is associated with a waiting time τ. During τ, the node waits to receive data from other nodes for aggregation or relaying, and transmits the data at the end of its waiting time. Connectivity in DVD is defined based on the waiting time of nodes. We propose the following *Waiting Time Connectivity* (WTC) rule:

Let $\tau(i)$ be the waiting time of node i and d_{ij} be the Euclidean distance between node i and node j. For node j to successfully transmit to node i, the following condition must hold:

$$\tau(i) > \frac{2d_{ij}}{c}, \tag{5}$$

where c is the radiowave propagation velocity. Alternately, i *is connected to* j if waiting time of i, $\tau(i)$, is greater than the round-trip propagation delay from j to i. For i *connected to* j, (5) implies the following.

Implication (a). If $\tau(i)$ is large, d_{ij} *can be large* yet ensuring that node j successfully transmits to i. In this case node i can receive data even from distant nodes and is said to have high connectivity.

Implication (b). If $\tau(i)$ is small, d_{ij} *must be small* to ensure successful transmission from node j to i. Thus node i can receive data only from nearby nodes and has low connectivity. Note that the WTC rule is in general non-reciprocal.

3.2. Waiting Time in DVD. Connectivity is essential in order to favor aggregations and to successfully relay aggregated data to the BS requiring nodes to have large waiting times. At the same time, very large waiting times lead to an increase in end-to-end delay, as the data gets released slowly by each intermediate node in the network. Thus, the design of waiting time is a trade-off between end-to-end delay and connectivity. In DVD, data aggregation is done by *event nodes* while relaying of aggregated data is done by *non-event nodes* (Figure 2). A node chooses its waiting time depending on whether it is an *event node* or a *non-event node*.

During its waiting time, an *event node* acting as aggregator waits to receive data from other *event nodes* for aggregation, and transmits its data to a relay node thereafter. For an *event node*, i, the waiting time $\tau(i) = \tau_e(i)$, which is defined as:

$$\tau_e(i) = \left(1 - \frac{v(i)}{v_{\max}}\right)\frac{d_e(i)}{c}, \tag{6}$$

where $v(i)$ is the instantaneous velocity of node i, $v_{\max}$ is the maximum velocity of nodes in the network and $d_e(i)$ is the estimated distance of node i from the *center of event*. This proposed definition of $\tau_e(i)$ is explained as follows:

Distance from center of event. From (6), an *event node* close to the *center of event* is given a low waiting time. This is because, the location information of such a node is critical and should be communicated to the BS at the earliest.

Instantaneous velocity . From (6), a slow-moving node has a large waiting time. This permits it to be *connected to* distant nodes (*Implication (a)*) with a lesser chance of packet losses. However, a fast moving node is permitted to receive data only from nearby nodes by assigning a low waiting time (*Implication (b)*) to it, thereby reducing packet losses.

During its waiting time, a *non-event node* waits to receive aggregated data which is further relayed at the end of its waiting time. For a *non-event node*, i, we propose the following definition of waiting time, $\tau_n(i)$:

$$\tau_n(i) = \left(1 - \frac{v(i)}{v_{\max}}\right)\frac{d_s(i)}{c}, \tag{7}$$

where $d_s(i)$ is the estimated distance of node i from BS. Owing to the RWP distribution, nodes occur sparsely at large distances from the center (BS location). Nodes that relay data from these nodes therefore must have large waiting times (*Implication (a)*) to ensure connectivity to them. Since node density is higher near the BS, nodes that relay data from sources near the BS can have small waiting times (*Implication (b)*). Therefore, waiting time of *non-event nodes* can progressively increase with distance from the sink. The dependence of τ_n on instantaneous velocity can be explained as in the case of τ_e for *event nodes*.

3.3. Protocol Description. In this work, we estimate the trajectory of the moving event by localizing the center of event at regular sampling instants. Initially, an event is said to have occurred if a minimum number of nodes report event occurrence directly to the BS. If it decides in favor of event detection, on the basis of the reported intensities and locations of the cell phone users, the end-user application estimates the temporal variation of event intensity $I_T(t)$, and the sampling interval T_s using known models of the event, [15, 16]. The sensor-specific detection threshold intensity I_D is considered to be known both at the nodes and the BS. The application specifies $I_T(t)$ at various sampling instants $t = nT_s$, where $T_s = (1/F_s)$ and $n = 1, 2, \ldots, T/T_s$. The BS broadcasts a query to all cell phones specifying $[F_s, I_T(nT_s), T]$.

Data Aggregation at event nodes. At each sampling instant, $t = nT_s$, if a node senses an intensity $I > I_D$, it sets its *event_detect* flag $= 1$ else it sets its *event_detect* flag=0. The various steps in aggregation in the DVD protocol, as shown in Figure 4 and Figure 6, are as follows.

(i) *Initialization for an Event Node:*

(a) Sets its *data_transmit* flag $= 0$, *aggregator* flag $=$ 0.

(b) Computes its waiting time τ_e.

(ii) *Event Detection Message Declaration*

(a) For an *event node*, *i*, if *data_transmit* flag $=$ 0 and *aggregator* flag $= 0$, it broadcasts an *event_detection* message [*event_detect* flag $=$ 1, $\tau_e(i)$, *location(i)*] at $t \approx nT_s + (\tau_e(i)/10)$ (Figure 4(a)). The shift of $\tau_e(i)/10$ results in different nodes broadcasting the *event_detection* message at different times, avoiding collision and ensuring that the node with the minimum τ_e broadcasts first. Node *i* then waits to receive data from other nodes to be aggregated.

(iii) *Checking for Connectivity*

(a) If node *j* that receives the *event_detection* message of node *i* has *aggregator* flag $= 0$ and *data_transmit* flag $= 0$, then it checks for Waiting time connectivity with node *i*, using (5) where $\tau(i) = \tau_e(i)$. If *i* is connected to *j* and if *j* has not received an *event_detection* message from another *event node* with a lower waiting time, *j* transmits its data to node *i* (Figure 4(b)). Node *j* then becomes a *leaf* node of *i*.

(b) Node *j* broadcasts a *data_transmit* declaration message = [*data_transmit* flag = 1, node ID(j)]. This deters any other *event nodes* from sending data to node *j*, if *j* had already broadcast its own *event_detection* message. Such a case would have occurred if *j* receives the *event_detection* message of node *i* only after it has broadcast its own *event_detection* message although $\tau_e(i) < \tau_e(j)$.

(iv) *Aggregation*

(a) As node *i* receives data from at least one *leaf* node, it sets its *aggregator* flag = 1 and finds a prospective *non-event node* which will relay the data aggregated by node *i* at the end of $\tau_e(i)$. Node *i* aggregates data received from all *leaf* nodes (*j*, *k* and *l* shown in Figure 4(b)), based on the Aggregation rule (Section 2).

From (6), nodes near the *center of event* have lower τ_e compared to nodes near the event boundary. Since nodes having low τ_e broadcast their *event_detection* messages earlier, such nodes have greater chances of becoming aggregators. Therefore, the design of τ_e favors the occurrence of aggregators closer to *center of event*, while leaf nodes tend to occur closer to the event boundary. Consequently, DVD supports *early aggregation*. This means that less critical data sent by boundary *event nodes* gets discarded *early* due to the low τ_e of aggregators. This would not have been the case had DVD favored location of aggregators near event boundaries, since *event nodes* near the event boundary have a larger τ_e. *Early aggregation* has the following advantages.

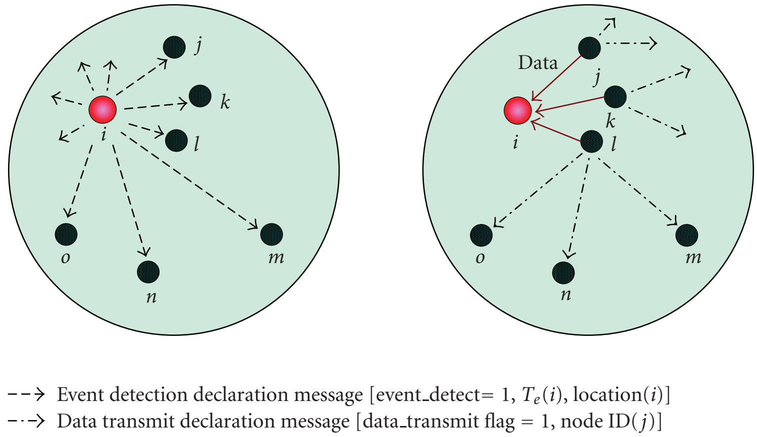
(i) If a boundary *event node* becomes a leaf node of an aggregator even before it has broadcast its own *event_detection* message, it refrains from broadcasting the message and hence saves energy.

(ii) Since a boundary *event node* transmits its data to an aggregator, its data buffer gets emptied *early*. If the boundary *event nodes* had been an aggregator instead, it would have had to retain data for a duration τ_e, which in turn is large.

Relaying of aggregated packets by non-event nodes. The various steps in routing in the DVD protocol, as shown in Figure 8 are:

(i) *Prospective Relay Node Identification*

(a) During $\tau_e(i)$, node *i* broadcasts a RTS packet to find a prospective *non-event* relay node (Figure 7(a)). The RTS packet is given by: [*node ID(i), location(i), event_reply(i) = 0*]. The *event_reply(i) = 0* indicates that the RTS packet is not meant for *event nodes*.



(a) At $t = nT_s + \tau_e(i)/10$ (b) At $t \approx nT_s + \tau_e(i)/10 + d_{ij}/c$

Figure 4: Steps in aggregation in DVD.

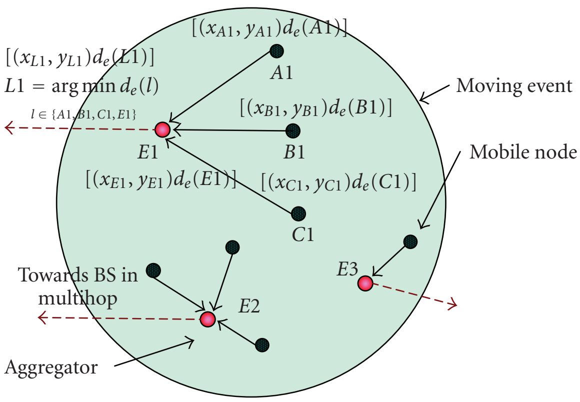


Figure 5: Aggregation in the event region in DVD.

(b) Any *non-event node r* connected to node i, is eligible to be a prospective relay node for node i. It replies with a CTS packet: [*location*(r), $\tau_n(r)$, *node ID*(r), *node ID*(i)] (Figure 7(b)). After sending out the CTS packet, it waits to receive data and sends out RTS packets to locate its prospective relay nodes during its waiting time, $\tau_n(r)$.

(ii) *Relaying of Aggregated Packet from Event Region*

(a) From the received CTS packets, i chooses the prospective relay node r_s, with lowest value of τ_n (Figure 7(c)). At the end of its waiting time $\tau_e(i)$, node i transmits the aggregated packet to r_s and sets its *data_transmit* flag = 1.

(b) Note that if an *event node* has both *data_transmit* flag and *aggregator* flag equal to 0 even at the end of its τ_e due to poor connectivity in the event region, it forwards its data to the BS by directly relaying its data to a prospective *non-event* relay node which it identifies during its waiting time.

(iii) *Relaying of Aggregated Packets in Non-Event Region*

(a) During $\tau_n(r_s)$, node r_s broadcasts a RTS packet [*location*(r_s), *node ID*(r_s), *event_detect* = 0]. For temporal convergence of DVD, prospective relay nodes connected to r_s must additionally be closer to the sink than r_s. From the *event_detect* flag, relay nodes connected to r_s identify r_s to be a *non-event node* and reply with CTS packets only if they are closer to the sink than r_s. r_s chooses the next relay node with minimum τ_n from its prospective relay nodes, to further relay data.

4. Time-Stationary Waiting-Time Distribution

In order to get a better insight into the performance of DVD, we derive the probability density function (*pdf*) of the *normalized* waiting time of *non-event nodes*. For a non-event node, i, with waiting time $\tau_n(i)$, we define its *normalized waiting time*, $\tilde{\tau}_n(i)$ as

$$\tilde{\tau}_n(i) = \frac{\tau_n(i)}{\tau_{n,\max}}, \tag{8}$$

where $\tau_{n,\max}$ is the maximum possible waiting time of any non-event node in the network. Specifically, $\tau_n(i) = \tau_{n,\max}$ when $v(i) = 0$ and $d_s(i) = d$, where d is the cell radius (from (7)). Therefore,

$$\tilde{\tau}_n(i) = \left(1 - \frac{v(i)}{v_{\max}}\right) r(i), \tag{9}$$

where $r(i) = (d_s(i)/d)$. In order to derive the probability density function of the normalized waiting time, we first rewrite (9) in its generic form as

$$\tilde{\tau}_n = \psi r. \tag{10}$$

where the velocity-dependent factor, $\psi = 1 - (v/v_{\max})$ (the index i is dropped for brevity). Note that both ψ and r are

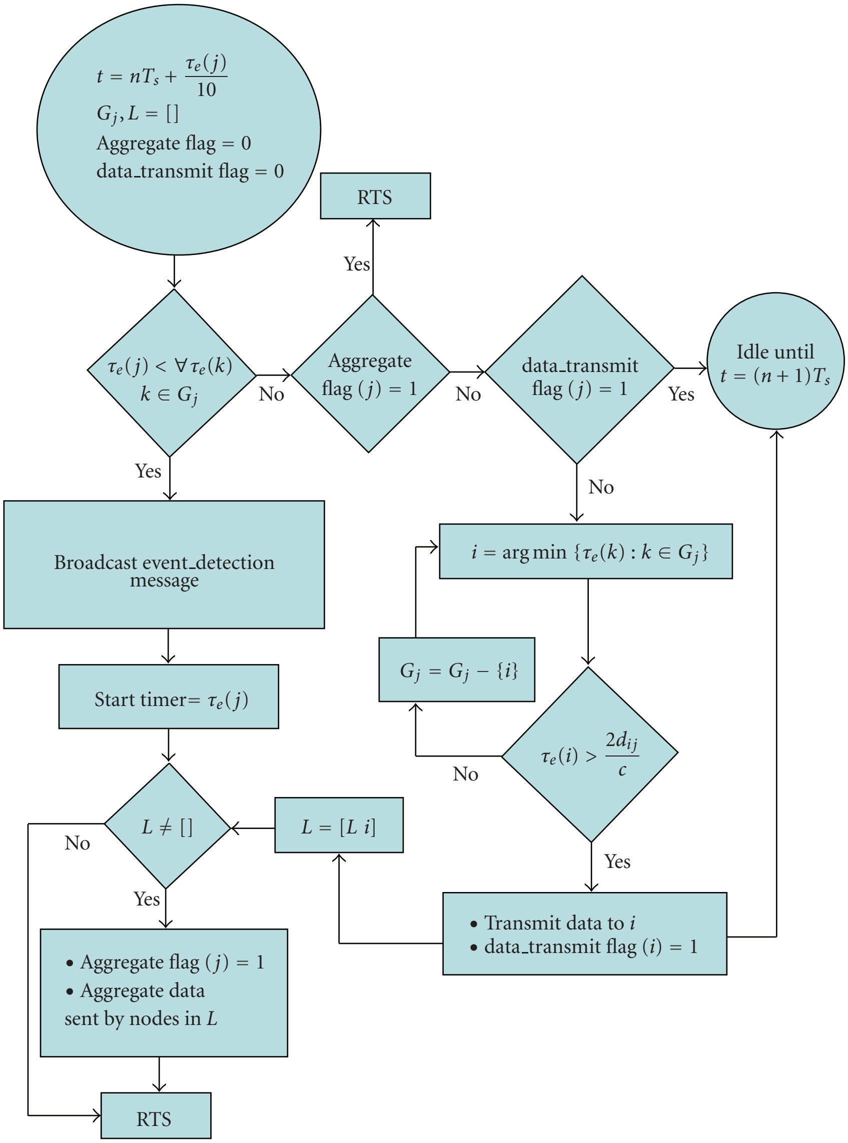


Figure 6: Flowchart of DVD in event region.

≤ 1. Therefore, $\tilde{\tau}_n \leq r$ and $\tilde{\tau}_n \leq \psi$. The probability density function $f_{\tilde{\tau}_n}(\tilde{\tau}_n)$ is given by [20]

$$f_{\tilde{\tau}_n}(\tilde{\tau}_n) = \int_{-\infty}^{\infty} \frac{1}{|\psi|} f_{\psi r}\left(\psi, \frac{\tilde{\tau}_n}{\psi}\right) d\psi, \quad (11)$$

where $f_{\psi r}$ is the joint *pdf* of ψ and r. Since ψ and r are independent (velocity chosen by a node and location of a node are independent of each other), (11) can be re-written as [20]

$$f_{\tilde{\tau}_n}(\tilde{\tau}_n) = \int_{-\infty}^{\infty} \frac{1}{|\psi|} f_{\psi}(\psi) f_r\left(\frac{\tilde{\tau}_n}{\psi}\right) d\psi, \quad (12)$$

where $f_{\psi}(\psi)$ is the *pdf* of ψ and $f_r(\tilde{\tau}_n/\psi)$ is the *pdf* of node occurrence at a distance of $r = (\tilde{\tau}_n/\psi)$ from BS.

Probability Density Function of ψ. From the definition of $\psi = 1 - (v/v_{\max})$, $f_{\psi}(\psi) = |v_{\max}| f_v(v)$, where $f_v(v)$ is the *pdf* of velocity. From [13], $f_v(v)$ for a Random Waypoint (RWP) model with pauses, is given by

$$f_v(v) = \begin{cases} \dfrac{P_{\text{mo}}}{v \ln(v_{\max}/v_{\min})}, & v_{\min} \leq v \leq v_{\max}, \\ P_{\text{pa}} \delta(v), & v = 0, \\ 0, & \text{otherwise}, \end{cases} \quad (13)$$

where P_{mo} is the probability of a node to be in *motion* state, while P_{pa} is the probability of a node to be in *pause* state. From [13], if Δ is the maximum diameter of the area from which a node can choose its position, and if *t_pause(min)* and

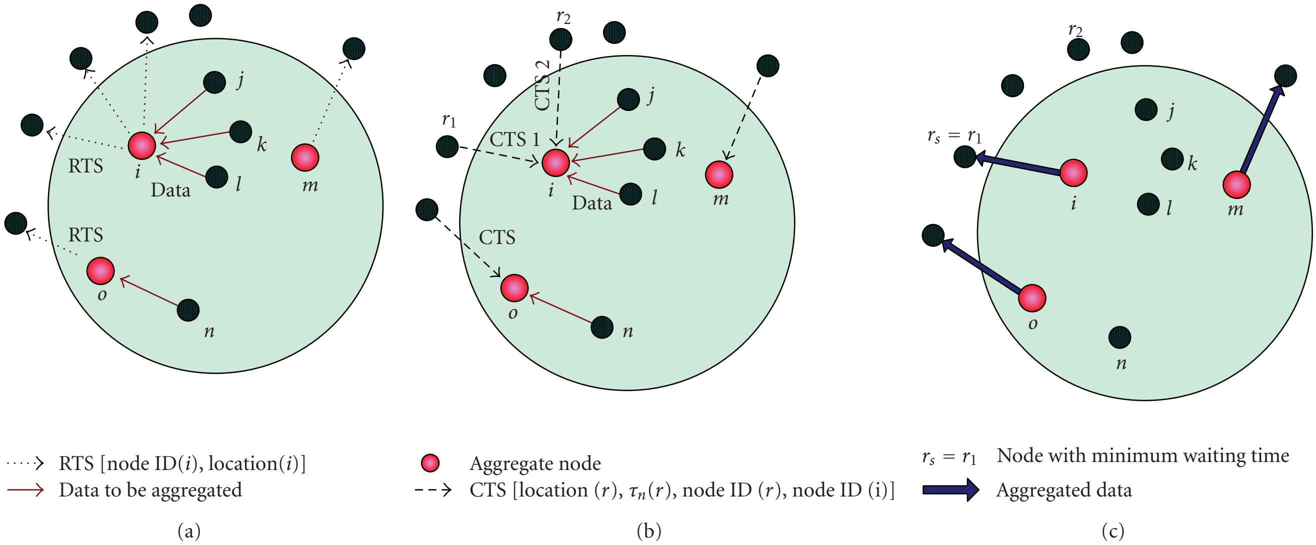


FIGURE 7: Routing in DVD.

t_pause(max) represent the minimum and maximum pause durations, respectively, then

$$P_{pa} = \frac{\alpha}{\alpha + \Delta}, \qquad P_{mo} = 1 - P_{pa}, \tag{14}$$

where $\alpha = 0.5(t\_pause(max)+t\_pause(min))$ and $\Delta = 2d$ for the cell of radius d. Therefore,

$$f_{\psi}(\psi) = \begin{cases} \dfrac{P_{mo}}{(1-\psi)\ln(v_{max}/v_{min})}, & 0 \le \psi \le \left(1 - \dfrac{v_{min}}{v_{max}}\right), \\ P_{pa}\delta(1-\psi), & \psi = 1, \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

Probability Density Function of r. The probability density function $f_r(r)$ represents the probability of node occurrence at a radial distance of r from the BS. For a circular disk of unit radius, from [13, 21]

$$f_r(r) = \frac{45r}{16}(1-r^2)E(r^2), \tag{16}$$

where $|r| \le 1$ and $E(r^2) = \int_0^{(\pi/2)} \sqrt{(1 - r^2\sin^2(\theta))}d\theta$. In (16), $f_r(r) \to 0$ as $r \to 1$ due to low node densities, and $f_r(r) \to 0$ as $r \to 0$ due to low radial distances.

Therefore, the *pdf* of $\tilde{\tau}_n$, $f_{\tilde{\tau}_n}(\tilde{\tau}_n)$ in (12) is given by (17).

In Figures 9 and 11, $f_{\tilde{\tau}_n}(\tilde{\tau}_n)$, is evaluated for a low mobility ($v_{min} = 0.01$ m/s) and high mobility ($v_{min} = 2$ m/s) scenario, respectively. In both cases, the maximum node velocity is $v_{max} = 9.99$ m/s. The corresponding histogram plots, obtained by simulation are given in Figures 10 and 12, respectively.

$$f_{\tilde{\tau}_n}(\tilde{\tau}_n) = \begin{cases} \dfrac{45}{16}\dfrac{P_{mo}}{\ln(v_{max}/v_{min})} \times \displaystyle\int_{\tilde{\tau}_n}^{1-(v_{min}/v_{max})} \frac{1}{|\psi|}\frac{\tilde{\tau}_n}{\psi(1-\psi)} \times \left(1 - \left(\frac{\tilde{\tau}_n}{\psi}\right)^2\right) E\left(\left(\frac{\tilde{\tau}_n}{\psi}\right)^2\right) d\psi \\ \quad + \dfrac{45\tilde{\tau}_n}{16} P_{pa}\left(1 - (\tilde{\tau}_n)^2\right)E\left((\tilde{\tau}_n)^2\right), & 0 < \tilde{\tau}_n \le \left(1 - \dfrac{v_{min}}{v_{max}}\right), \\ \dfrac{45\tilde{\tau}_n}{16} P_{pa}\tilde{\tau}_n\left(1 - (\tilde{\tau}_n)^2\right)E\left((\tilde{\tau}_n)^2\right), & \left(1 - \dfrac{v_{min}}{v_{max}}\right) < \tilde{\tau}_n \le 1, \\ 0, & \text{otherwise.} \end{cases} \tag{17}$$

The following inferences can be drawn from these plots.

(i) *Effect of r on $\tilde{\tau}_n$.* As mentioned earlier, $f_r(r) \to 0$ when r approaches 0 or 1. $f_r(r)$ is high for $0 \ll r \ll 1$ leading to a large number of nodes located at moderate values of r from the BS. Thus, for a given ψ, the factor r results in very few nodes with $\tilde{\tau}_n \approx 1$ or $\tilde{\tau}_n \approx 0$.

(ii) *Effect of ψ on $\tilde{\tau}_n$.* The velocity-dependent factor ψ is < 1 with a probability P_{mo} and is equal to 1 with a probability P_{pa}. When $P_{mo} > P_{pa}$, most nodes are in motion and we have $\psi < 1$. Thus, for any r, this factor lowers the value of $r\psi$, in effect reducing the value of $\tilde{\tau}_n$. Moreover, in a high mobility scenario

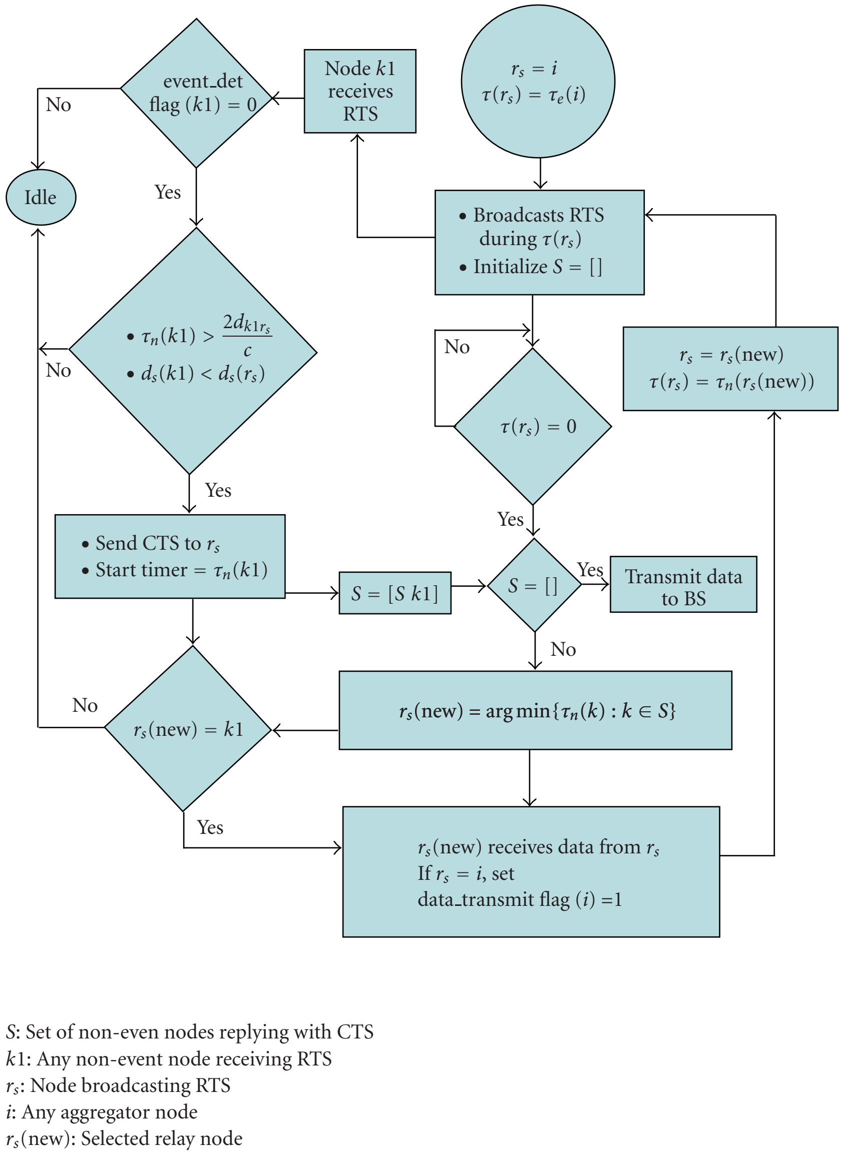


Figure 8: Flowchart of Routing in DVD.

($v_{\min} = 2$ m/s), nodes move with higher velocities (and lower ψ values), compared to the low mobility scenario ($v_{\min} = 0.01$ m/s). This in turn reduces $\widetilde{\tau}_n$ of nodes, resulting in a larger number of nodes with low $\widetilde{\tau}_n$. Thus, for a high mobility scenario, more number of nodes have low waiting times in comparison with the low mobility scenario.

4.1. Mean and Variance of $f_{\widetilde{\tau}_n}(\widetilde{\tau}_n)$. The mean and variance of $\widetilde{\tau}_n$ for $v_{\min} = 0.01$ m/s, 2 m/s and $v_{\max} = 9.99$ m/s in both cases, are shown in Table 1. As expected, the mean value of $\widetilde{\tau}_n$ is lower for the higher mobility scenario with a $v_{\min} = 2$ m/s, since the corresponding ψ values are lower. For $v_{\min} = 0.01$ m/s, at any waypoint, a node can choose a velocity $v \in [0.01, 9.99]$, while for $v_{\min} = 2$ m/s, a node can choose a velocity $v \in [2, 9.99]$, which is a smaller range.

Table 1: Analytic and simulation results for mean and variance of $f_{\widetilde{\tau}_n}(\widetilde{\tau}_n)$.

$v_{\min}$ (m/s)	Mean (analytic)	Mean (simulation)	Variance (analytic)	Variance (simulation)
0.01	0.4365	0.3791	0.0508	0.0494
2	0.2633	0.2513	0.0285	0.0345

Therefore, the range of $\psi \in [0, 0.8]$ is also smaller in the latter case. Thus, the variance is lower when $v_{\min} = 2$ m/s than when $v_{\min} = 0.01$ m/s.

4.2. Cumulative Distribution Function (CDF) $F_{\widetilde{\tau}_n}$. In order to verify that the design of $\widetilde{\tau}_n$ results in low waiting times with a greater probability than high waiting times, we evaluate the Cumulative Distribution Function (CDF),

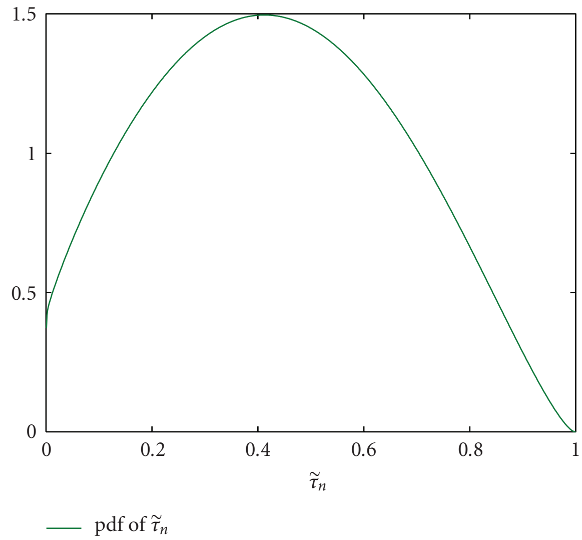


Figure 9: Analytical plot of $f_{\tilde{\tau}_n}(\tilde{\tau}_n)$ for $v_{\min} = 0.01\,\text{m/s}$.

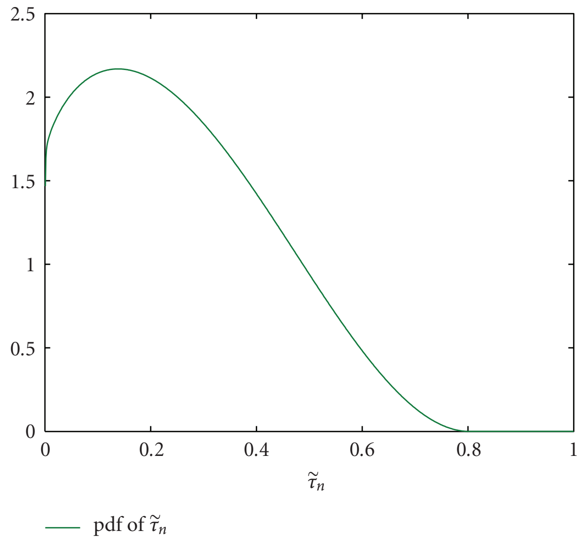


Figure 11: Analytical plot of $f_{\tilde{\tau}_n}(\tilde{\tau}_n)$ for $v_{\min} = 2\,\text{m/s}$.

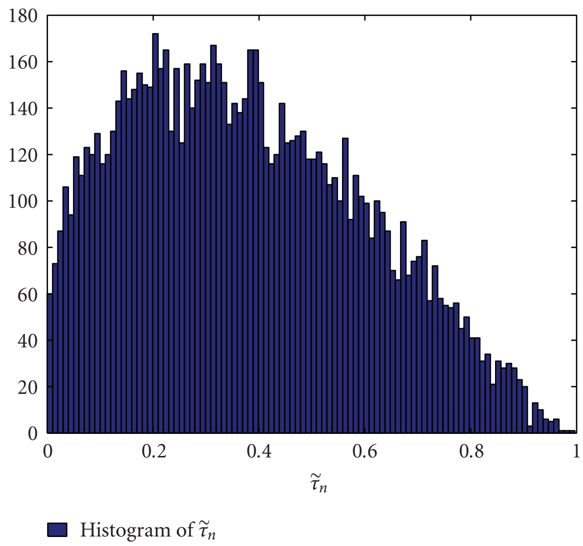


Figure 10: Histogram plot of $\tilde{\tau}_n$ for $v_{\min} = 0.01\,\text{m/s}$.

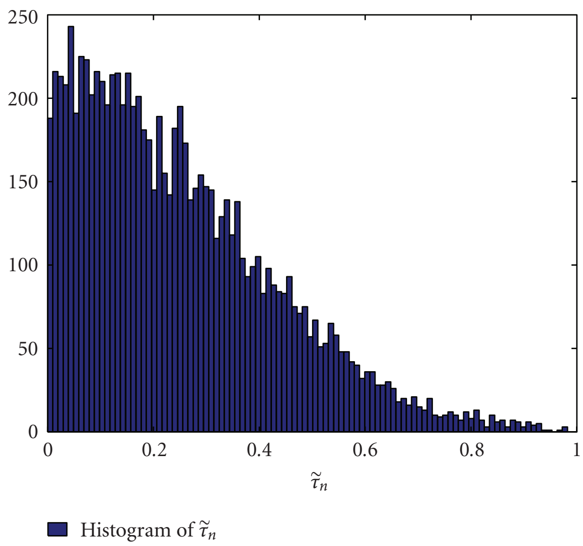


Figure 12: Histogram plot of $\tilde{\tau}_n$ for $v_{\min} = 2\,\text{m/s}$.

$F_{\tilde{\tau}_n}(\tau) = \text{Prob}(\tilde{\tau}_n \leq \tau)$. Specifically, if $F_{\tilde{\tau}_n}(0.5) > 0.5$ is satisfied, it testifies that the probability of nodes having low waiting times ($\tilde{\tau}_n \leq 0.5$), is higher than the probability of nodes having high waiting times ($\tilde{\tau}_n > 0.5$). Figures 13 and 14 evaluate the CDF, for $v_{\min} = 0.01\,\text{m/s}$, $2\,\text{m/s}$, respectively. As can be seen, $F_{\tilde{\tau}_n}(0.5) \approx 0.603$, 0.895 for $v_{\min} = 0.01\,\text{m/s}, 2\,\text{m/s}$, respectively. The value of $F_{\tilde{\tau}_n}(0.5)$ is higher for the high mobility scenario where $v_{\min} = 2\,\text{m/s}$, since a larger number of nodes have higher velocities (and hence lower $\tilde{\tau}_n$) compared to the low mobility scenario, where $v_{\min} = 0.01\,\text{m/s}$. Hence, *in DVD, nodes have low waiting times with a high probability*. This probability further increases in high mobility scenarios.

5. Effect of Waiting Time Design on Performance of DVD and RW

The design of the waiting time of *event nodes* and *non-event* nodes primarily impacts the performance of the Distributed Velocity-Dependent (DVD) protocol and that of the Randomized Waiting (RW) time protocol in terms of localization error, delay, energy dissipated and the number of hops.

5.1. Waiting Time of Non-Event Nodes in DVD and RW. In [12] a structure-free Data Aware Randomized Waiting (RW) time protocol had been proposed to detect a moving target using static wireless sensor networks. Nodes used *anycast* at the MAC layer, to promote data aggregation at neighbors having packets with the same aggregation ID

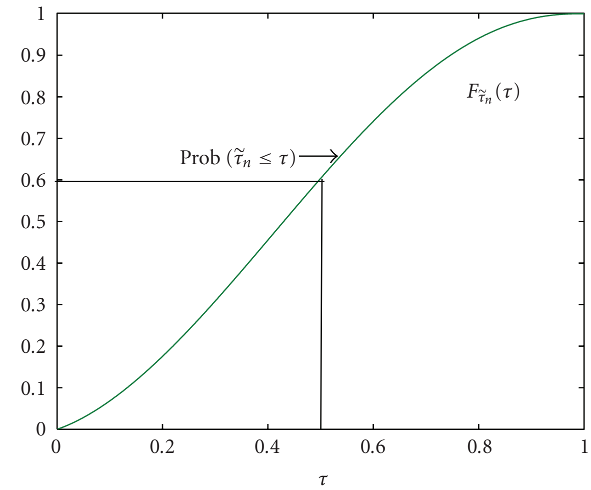


Figure 13: CDF of $\tilde{\tau}_n$, $F_{\tilde{\tau}_n}(\tau)$ in DVD for $v_{\min} = 0.01$ m/s.

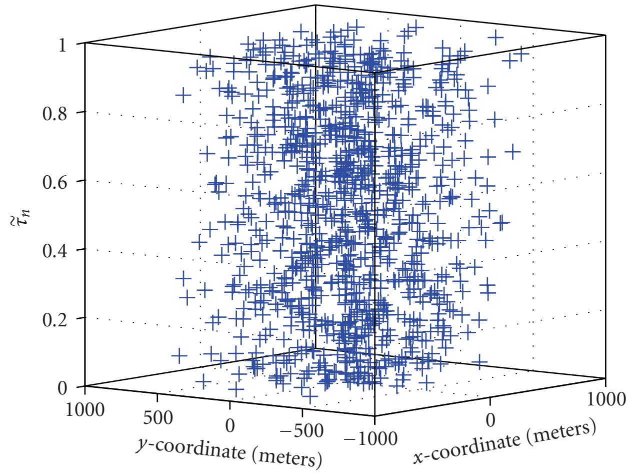


Figure 15: Spatial distribution of $\tilde{\tau}_n$ in RW.

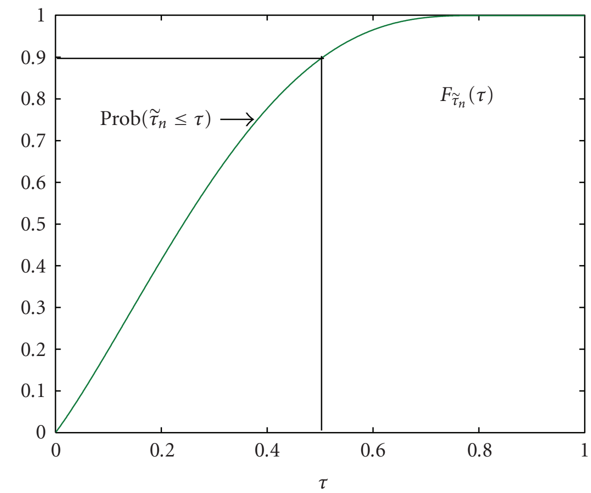


Figure 14: CDF of $\tilde{\tau}_n$, $F_{\tilde{\tau}_n}(\tau)$ in DVD for $v_{\min} = 2$ m/s.

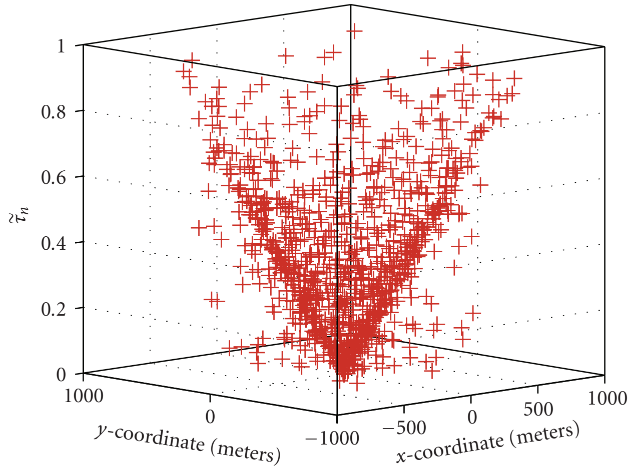


Figure 16: Spatial distribution of $\tilde{\tau}_n$ in DVD.

(temporal/spatial). In order to further enhance aggregation, nodes delayed anycasting of their own packets by a *random waiting time* (RW). In the proposed DVD protocol, a *unicast* approach is adopted, where each node transmits to the node with the minimum waiting time from amongst the nodes that satisfy the *Waiting time Connectivity* rule. For a fair comparison, we incorporate this criteria in the RW protocol, where the waiting time is *random* and not location or velocity-dependent (as is the case with DVD).

In Figures 15 and 16, the spatial variation of the waiting time chosen by *non-event* nodes in RW and DVD, are, respectively, plotted. As is to be expected, in DVD, since the waiting time of nodes depends on d_s (distance from sink), a waiting time negative gradient is observed from the boundaries, towards the center. This structure favors the choice of a relay node with minimum waiting time (the chosen *prospective relay node*), to be a node that is closer to the center, at every hop. This in turn *reduces the average number of hops in* DVD *compared to* RW. As will be shown through simulations, the combined influence of *fewer number of hops and low waiting times at relay nodes results in the low end-to-end delay of* DVD *compared to* RW.

5.2. Waiting Time of Event Nodes in DVD and RW. The waiting time of *event nodes* in DVD is in the range $0 \leq \tau_e < (R_e/c)$, where R_e is the event radius. On the other hand, the waiting time of *event nodes* in RW is in the range $0 \leq \tau_e < (R/c)$, where R is the cell radius. A comparison plot of an upper bound on these waiting times with varying event radius is shown in Figure 17. Since we consider $R > R_e$ for all R_e, the average waiting time of *event nodes* in DVD will also be lesser than that of RW.

In DVD, *event nodes* have event intensity-dependent waiting times. This follows from (6) which relates τ_e to d_e, and (1) which relates d_e to sensed intensity, I. The effect of choosing such waiting times for eventnodes in DVD, which are in turn lower than that of RW, is that, fewer number of aggregations occur in DVD, in comparison with RW. Both in DVD and RW, in addition to the aggregated packets from

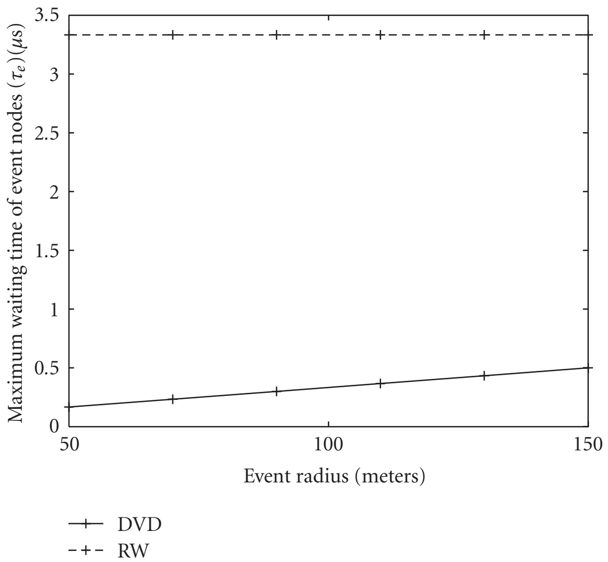


Figure 17: Upper bound on waiting time of event nodes τ_e with event radius in DVD and RW.

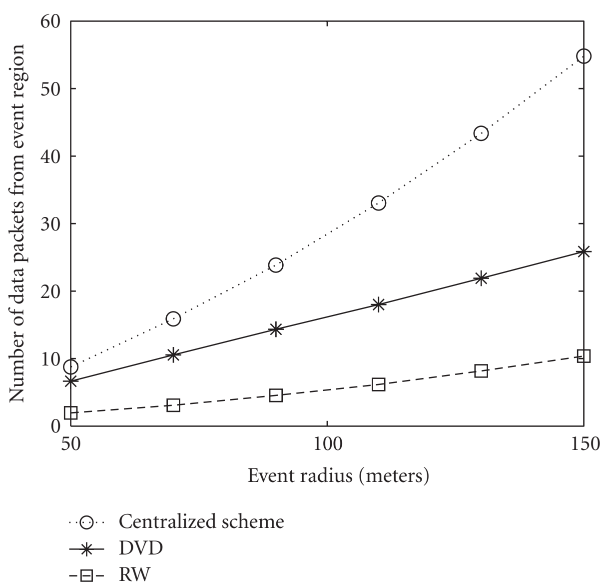


Figure 18: Number of packets generated in event region in Centralized, DVD and RW schemes.

the event region, nodes whose packets do not get aggregated within the event region, must also be relayed to the BS by the *non-event nodes*. Thus, in DVD, more number of unaggregated packets have to be relayed to the BS, in addition to the aggregated packets. Figure 18 shows the number of packets that are to be communicated from the event region to the BS in DVD, RW and in a Centralized scheme. The greater number of packets communicated from the event region in DVD improves localization accuracy, while the smaller waiting times in the event region lowers the delay in the event region. However, this comes at a cost of slightly higher energy dissipation in DVD in comparison with RW. In the Centralized scheme where no aggregation takes place, all packets from event region are communicated to the BS in single hop. This means that the localization accuracy would be highest for the Centralized scheme compared to DVD and RW. However, as will be shown in Figure 24, for the case of perturbations in location and velocity measurements, the localization performance of the Centralized scheme deteriorates due to non-zero packet losses caused by long-range transmissions. The performance becomes comparable to that of DVD, especially for small event radii, when the number of packets generated in the event region are nearly the same for both the cases.

5.3. Dependency of a Waiting-Time-Based Approach on the Mobility Model. The proposed approach has been designed specifically for the Random Waypoint distribution [22] of cell phone users (Section 3). The design of waiting time will have to be modified depending on the underlying mobility model. The Random Direction mobility model [23] demonstrates a *uniform* spatial distribution of cell phone users, where node distribution is independent of distance from BS. Therefore, the waiting time of *non-event nodes* need not vary with distance from BS, and need only be velocity-dependent. For temporally correlated mobility models, such as the Gauss-Markov [24] and the Smooth Random Mobility model [25], the velocity of nodes demonstrates temporal correlation. This correlation gets carried over to the velocity-dependency of waiting time. In the Smooth Random Mobility model, the direction chosen by a node is also a function of time. The correlation in velocity and direction can be exploited by nodes to get neighbourhood knowledge. This in turn would reduce communication overhead associated with relay node discovery. In spatially correlated mobility models, such as the Reference Point Group Mobility (RPGM) model [26], nodes occur in groups centred around certain Reference Points (for instance, in a disaster relief operation composed of various teams). The velocities within a group are spatially correlated. The waiting time chosen by a node while gathering/relaying data within a group can be small, since the node density is high within the group. However, the waiting time chosen by the node while relaying/gathering data from a node located in another group must be large in order to ensure connectivity. In both cases, the waiting time must still be velocity-dependent. Without loss of generality, for all the mobility models considered, the waiting time of *event nodes* can be intensity and velocity-dependent as in (6).

6. Simulation Results

A circular area of radius 1000 m with 1000 nodes is considered. Node locations and velocities in the range 0.01–9.99 m/s are drawn from the RWP steady state distribution [13] at sampling intervals of $T_s = 5$ s. The pause time of nodes is uniformly distributed between $0 - 100$ s. The battery rating is $3.7\,\text{V} \times 1250$ mAh, and users recharge their batteries if the residual energy falls below $0.2 \times$ battery rating. A talk-time of six hours is considered. Initial residual energy of each user is assumed to be different. Cell phone receiver sensitivity is chosen as -60 dBm, and duration of the application is $T =$

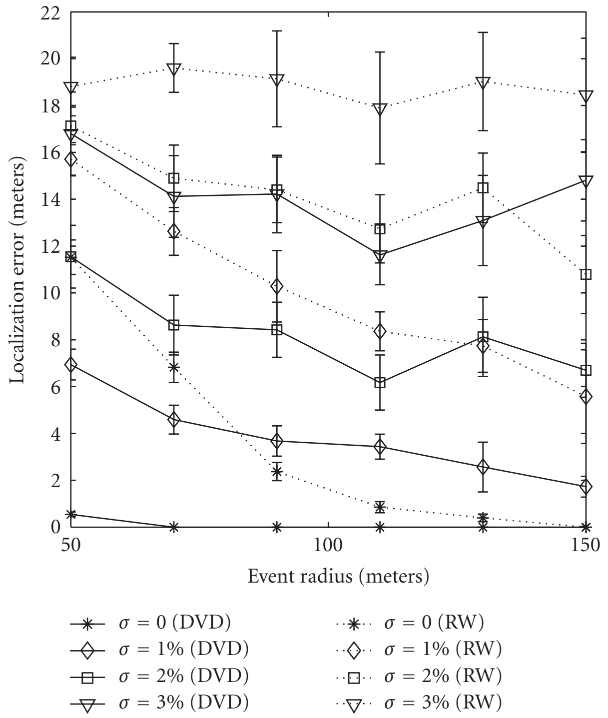


Figure 19: Sensitivity of Center of Event localization error for DVD and RW.

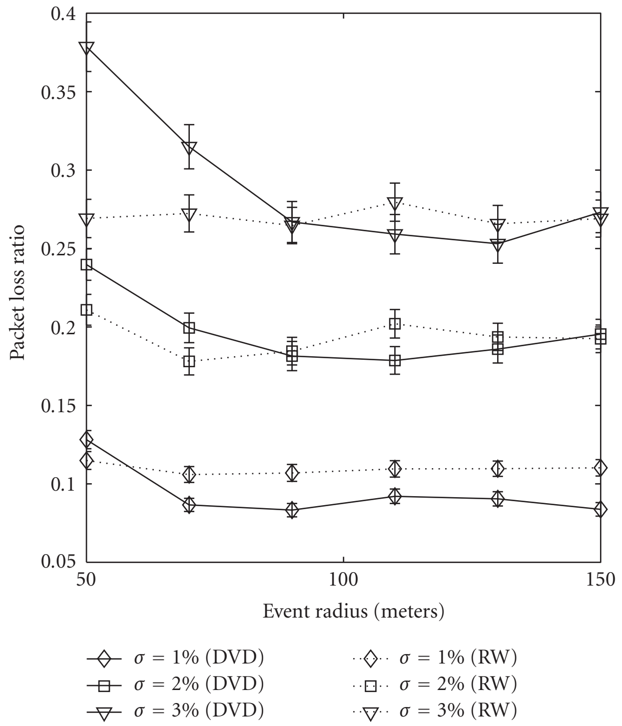


Figure 20: Sensitivity of Packet loss for DVD and RW.

100 s. For simulation results, 50 different seeds were chosen to evaluate average performances. Confidence intervals of 95% are further evaluated to study the robustness of the average performances.

6.1. Perturbation Analysis. In practice, location, velocity and distance from CoE will rarely be measured exactly. Thus, it is necessary to analyze the effect of error in location, velocity and distance from CoE. Towards this end, we consider the following Gaussian perturbation model. If γ in general represents either, location, velocity or distance from CoE, then the measured γ (γ_m) for node i, is represented as: $\gamma_m(i) = \gamma_a(i) + \sigma\beta(i)\gamma_a(i)$, where $\gamma_a(i)$ is the actual value of γ, σ is the perturbation fraction and $\beta(i)$ is a zero-mean Gaussian random variable with unit variance. For simplicity, we assume the same value of σ for location, velocity and distance from CoE perturbations. On the other hand, β is node and parameter-specific. We assume that cell phones are equipped with GPS and velocities are computed from consecutive location measurements. The performances of DVD, RW, and *Centralized* schemes are compared in terms of localization error, packet loss, delay and energy dissipated based on this given perturbation model.

The lower localization error of CoE in DVD than in RW (Figure 19) is due to more number of packets arriving at the BS from the event region (Section 5.2), which improves the Least Squares estimation (for $\sigma > 0$) or trilateration (for $\sigma = 0$) accuracy. A similar trend is observed for all σ and R_e as shown in Figure 19.

Packet loss ratio has been defined as the *Number of packets dropped while relaying/Total Number of packets to be relayed*. Figure 20 shows a comparable packet loss performance of both protocols. The packet loss ratio of RW remains constant for all event radii. The packet loss ratio of DVD drops with increase in event radius as the number of packets to be relayed is enhanced significantly with increase in event radius (Figure 18).

The average number of hops are obtained considering only those packets that reach the BS successfully. Both DVD and RW, as σ increases, packets relayed over more number of hops are likely to be dropped. This lowers the average number of hops. DVD has a lower average number of hops than RW, as seen in Figure 21. This is because, the relay node chosen as the node with minimum waiting time at each hop in DVD, is more likely to be closer to the BS than the relay node chosen by RW, as seen in Figures 15 and 16 and explained in Section 5.1.

In both DVD and RW, the energy dissipated in the network increases with event radius (Figure 22). However, due to more number of packets to be relayed in DVD (Figure 18), the energy dissipated is higher than in RW. Also, the number of hops in RW is more than in DVD, resulting in higher energy efficiency. In both cases, the energy dissipated decreases with increase in perturbation as fewer number of packets get effectively relayed in the network, due to higher packet loss.

End-to-end delay has been computed only for data that successfully reaches the BS. The average delay is lower in DVD than in RW due to fewer number of hops (Figure 21)

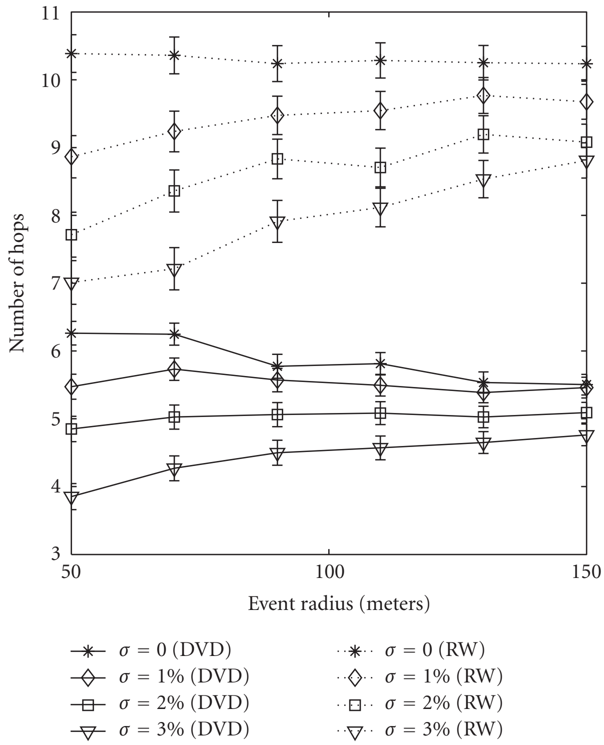


Figure 21: Sensitivity of Average number of hops for DVD and RW.

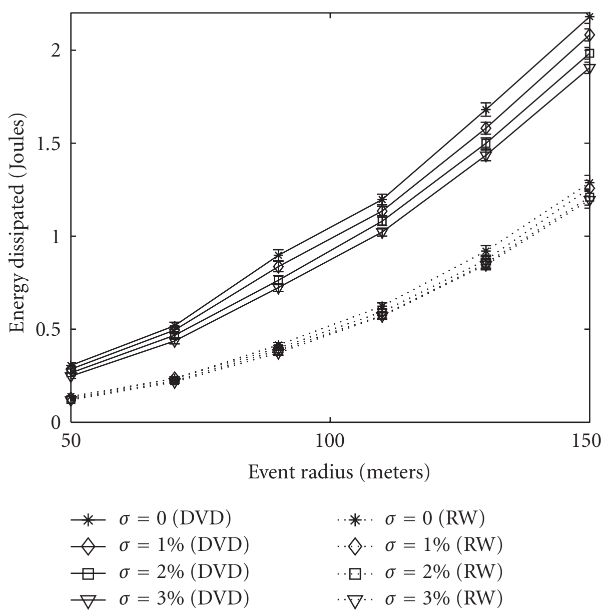


Figure 22: Sensitivity of Energy dissipated in the network for DVD and RW.

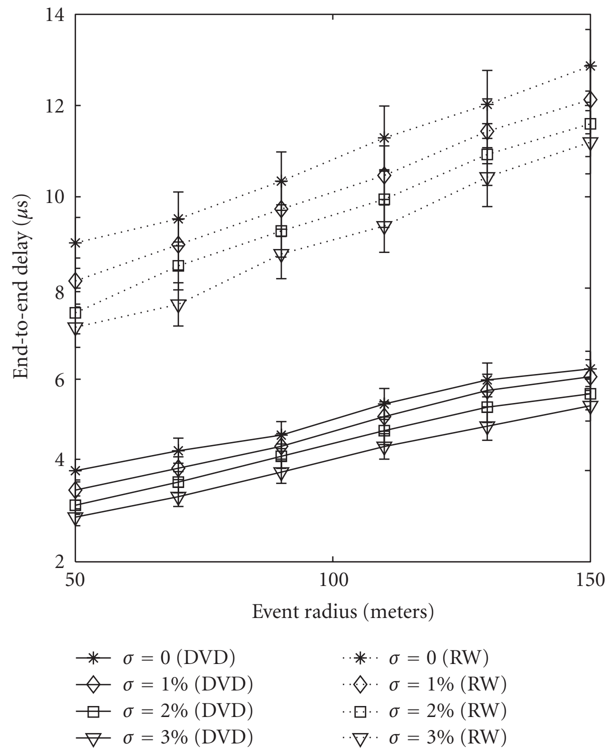


Figure 23: Sensitivity of end-to-end delay for DVD and RW.

and lower waiting times (Section 4). Both for DVD and RW, delay decreases with increase in perturbation (Figure 23). This is because, packet losses are higher and packets located farther from the BS do not get relayed successfully.

The 95% confidence intervals show that DVD consistently outperforms RW in terms of localization accuracy and end-to-end delay, however with a higher energy dissipation, for all event radii and perturbation ratios. For both protocols, the confidence interval for average packet losses (Figure 20) and average localization error (Figure 19) increases with increasing σ, indicating a larger variance in performance at higher perturbations. The small values of confidence intervals for energy dissipated, delay and average number of hops validate the robustness in the average performances of both protocols.

Figure 24 shows the performance of a centralized scheme (Cellular Sensor Networks without multihop). As expected, the end-to-end delay is significantly lower than that of DVD while the localization error performance is comparable to that of DVD and slightly better at high event radii. The low end-to-end delay is due to single-hop transmission of sensed data from *event nodes* to the BS. The large number of packets generated from event region (Figure 18) is responsible for the lower localization error of the centralized scheme, especially at high event radii. Packet losses are however high in the network due to long range transmissions. This limits the localization error performance especially at lower event radii where fewer number of nodes sense the event. More importantly, there is a significant increase in energy dissipated and possible congestion due to more number of packets transmitted in single hop from the event region (Figure 18).

Considering the comparable event localization performances of the Centralized and distributed approaches as well as the heavy energy requirements imposed on cell phones by the centralized approach, a Multihop Cellular

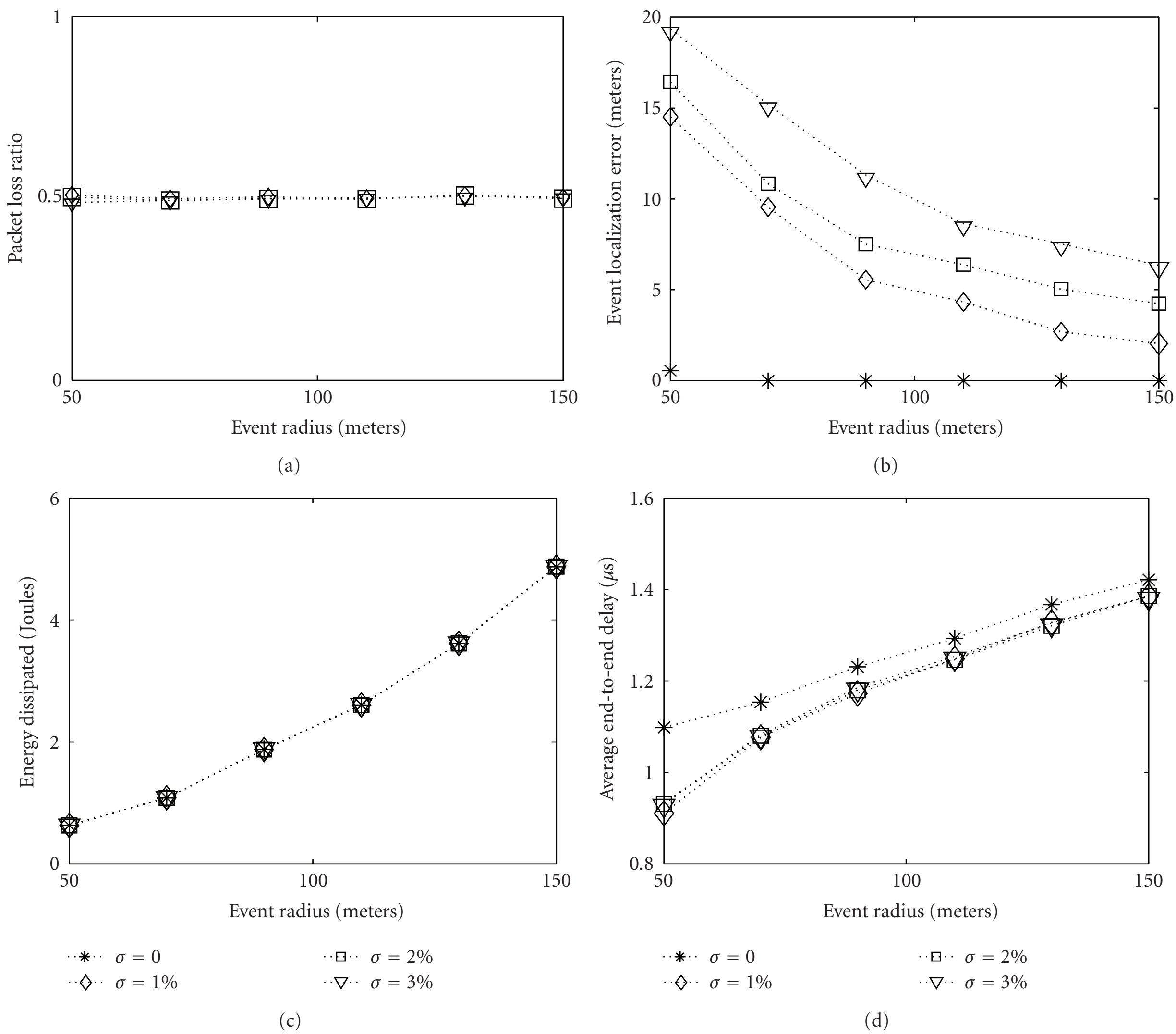


FIGURE 24: Sensitivity Analysis of Packet loss ratio, Event Localization error, Energy dissipation, and average End-to-end delay for Centralized data aggregation.

Sensor Network (MCSN) with a distributed approach would be favorable compared to the Centralized approach. With respect to the existing RW protocol, the distributed waiting time based DVD protocol is more appealing due to its better event localization and delay performance for the moving event localization application of an MCSN.

7. Some Recent Works in Cellular Sensor Networks

Urban, mobile, participatory, or people-centric sensing is being widely popularized as a technology which can bring about changes in people's lives in a direct and profound manner, [1, 2, 27, 28]. There are a large number of research and development, academic and governmental partnerships, that are attempting to make *urban sensing* using *Cellular Sensor Networks*, a tool for social change. Here, we have attempted to include as many references as we can on *Cellular Sensor Networks*. For instance, in Accra, Ghana, pollution data was captured, throughout the day by GPS-supported Carbon monoxide sensor kits carried by taxi drivers and students [29–31]. Ten other cases where cell phones contribute to assistance in the areas of public health, security and environmental conservation have been presented in [29]. The *Urban Sensing* group at *UCLA*, [32], works on a large number of areas like public health, community cultural expression and well-being, environmental monitoring and urban planning. The *Mobile Millennium* project uses positioning data from GPS-enabled cell phones mounted on vehicles, to get real-time traffic information [5]. In [33], a system, UbiFit garden, has been developed for people to monitor lifestyle and to encourage physical activity. In [4], projects ranging from personal sensing systems to sensing terrain are under research, while [34] studies the real-time movement patterns in Rome. Various underlying issues in the development of *Cellular Sensor Networks* are discussed in literature. The Campaignr framework, [35], was proposed for accessing the data from the sensors in a robust way, yet hiding the complexities underlying embedded mobile phone environment. Tackling security-related issues is considered in [36], while [37] proposes a continuous query-processing system for intermittently connected mobile sensor networks. Handling of spatio-temporal queries efficiently from the sensors is described in [38]. Data inferencing using cooperative techniques to overcome device heterogeneity is considered in [39].

8. Concluding Remarks

The main contribution of the paper is the Distributed Velocity-Dependent (DVD) waiting time based protocol for Multihop Cellular Sensor Networks (MCSNs). DVD exploits the Random Waypoint (RWP) distribution of cell phone users and is considered here for a moving event localization application. In this paper, the time-stationary probability density function (pdf) of waiting time in DVD has been derived. An analysis of the spatial distribution of waiting time, coupled with the inferences drawn from the pdf of the waiting time, validate the simulation results. Extensive simulations, carried out with perturbations in location, velocity and measured intensity, show that with or without perturbations, the proposed DVD protocol performs better than RW in terms of event localization and delay. Further, DVD based MCSN has a comparable event localization performance and significantly lower energy dissipation than the existing Centralized Cellular Sensor Network. We shall be considering the problem of localizing multiple events and overlap of event regions for possible extension of the proposed protocol.

Acknowledgments

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