RUGGED: RoUting on finGerprint Gradients in sEnsor Networks*

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Abstract

Every physical event produces a fingerprint in the environment which results a natural information gradient in the proximity of the phenomenon. Moreover, many physical phenomena follow diffusion laws. In this paper, we propose a novel scheme to effectively exploit the natural information gradient to route a query in a sensor network. Our scheme uses multiple path exploration, and controls the instantiation of paths by simulated annealing. Unlike other information-driven protocols, our scheme eliminates the overhead of preparing and maintaining the gradient information repository. We apply our scheme to study three different problems: (1) single-value query, (2) global maxima search, and (3) multiple events detection. Simulation results have demonstrated that the routing protocol, based on our proposed scheme, is highly energy efficient and achieves over 98% success rate to route around sensor holes, even in the presence of environmental noise and malfunctioning sensor nodes. We also illustrate that our scheme is well suited for a broad-range of applications; e.g., time gradient based target tracking.

1 Introduction

A distributed sensor network (DSN) consists of sensor nodes with limited energy source, sensor devices, short-range radio and on-board processing capability. Sensing capability of the attached sensing devices and their small size, make these sensor nodes highly suitable for monitoring physical phenomena. Sensor networks are most widely used for habitat and environmental monitoring[9][10][11]. More specifically, advances in the MEMS technology make it possible to develop sensors to detect and/or measure most of the usual physical phenomena like temperature, light, sound, radiation, humidity, chemical contamination, nitrate level in the water etc. Every physical event leaves some fingerprints in the environment in terms of the event's effect; e.g., fire increases temperature, chemical spilling increases contamination, nuclear leakage increases radiation. Moreover, most of the physical phenomena follow diffusion property[18][19] with distance, i.e., $f(d) \propto \frac{1}{d^{\alpha}}$, where d is the distance from the point having maximum effect of the event, $f(d)$ is the magnitude of the event's effect and α is the diffusion parameter depending on the type of effect; e.g., for light $\alpha = 2$, heat $\alpha \simeq 1$. As an example, if some location's temperature is 100^oC then, nearby locations temperature should be correlated with that based on the distance. Thus the property of physical phenomena implicity creates a distributed information repository about the event's effect. Furthermore, the information gradient concept is not limited to physical phenomena. For example, by recording the time stamp about a moving object when it passed by a sensor node, DSN can establish time gradient towards the object's current location. So, *routing protocols for DSN can exploit this natural, freely available information gradient as an important attribute to forward the query efficiently towards the source*.

Characteristics of the sensor nodes, i.e., limited battery life, energy expensive wireless communication, high probability of failure or malfunction and unstructured nature of the DSN, make routing in the DSN a challenging problem. Traditional routing protocols of the DSN are based mostly on flooding (*Directed Diffusion*[1]) or random-walk (*Rumor routing*[4], *ACQUIRE*[5], etc.). These approaches, however, do not utilize the domain-specific knowledge, i.e., the event's fingerprint gradient about the monitored phenomenon. In this paper, we effectively exploit the fingerprint gradient to design a scheme for efficient routing in sensor networks from sink to source.

Previous data-centric routing protocols those are based on information gradient[6][7][12][14], use a proactive phase to prepare distributed or cluster based gradient information repository towards a target or an event. To adapt dynamic behavior of DSN, periodic update of the information repository

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is required. To route a query from sink to source, most of these protocols use greedy routing algorithms based on information gradient. To prepare the gradient information repository and routing query, protocols do not utilize the well established law of physical events. Moreover, the query proceeds toward the source through a single path, which usually get trapped at the local maxima or minima, or reach a dead-end due to imperfect sensor device and/or environmental noise. On the other hand, generating unlimited multiple paths resembles flooding.

In this paper, we propose a scheme for using the fingerprint gradient of the event's effect to avoid the proactive phase of preparing the distributed gradient information repository and a novel energy efficient, fully distributed and reactive routing protocol based on that information gradient. Our protocol effectively exploits the laws of physical events for routing decision. Also it overcomes the limitations of usual information-driven routing protocols due to local maxima or minima using *simulated annealing* concepts in a distributed manner and establishes an effective balance between single path and multiple path exploration to discover routes. To design and test the protocol, we consider a somewhat realistic model of the environment consists of flat information region and environmental noise in addition to the region having noisy information gradient about the event's effect. We also provide several potential applications for utilizing information gradients including (but not limited to) target tracking using time gradients, event boundary detection, predicting spread of phenomenon (e.g., chemical contamination), determining earth quark patterns, among others. An overview of such applications is discussed in this document. On-going and future research will investigate application details. Here we keep our focus on the static sensor networks which are used mainly for environmental monitoring.

The rest of the paper is organized as follows. Section 2 discusses related work on routing in sensor networks. Section 3 discusses the environment and noise models. Our protocol is described in section 4. Section 5 describes the simulation model. Approaches to solve three different problems, using of the proposed protocol, and results are presented in section 6. Other potential applications are discussed in section 7. Finally section 8, concludes the paper and discusses future work.

2 Related work

Several approaches have been proposed for routing in sensor networks. Directed Diffusion[1][2], is one of the first data-centric query dissemination protocol that is particularly useful for long lived data flow or continuous queries. In this scheme, a node's interest for named data is initially distributed through the network via flooding to find the sources of relevant data. Diffusion results in high quality paths and well-suited for long continuous queries. Initial flooding overhead is amortized by the duration of long flows. The work in [3] attempts to adapt directed diffusion according to specific applications.

Several protocols[4][5][8][13][17] have been designed based on Random walk. Asymptotically, random-walk shows good performance. But in practice, it causes high latency and without directionality and/or proper value of TTL, it may fail to discover resource. In [13], Servetto and Barrenechea have shown that multiple random-walks help to improve load balancing and to minimize critical point of failure and latency with increased communication cost.

One of the major differences between our information gradient based approach and flooding and/or random-walk based approaches is that our scheme uses sensor's measurement, about the event's effect, for routing decision. In this context our protocol is information driven, utilizes natural information gradients available as the signature of the mentioned phenomena.

Chu, Hausseker and Zhao propose Information Driven Sensor Querying(IDSQ) and Constrained Anisotropic Routing (CADR) mechanisms[6], especially for localization and target tracking. IDSQ is a proactive sensor selection strategy for correlated information based on a criterion which combines information gain and communication cost. Dynamic environment and low query rate may cause extra overhead due to frequent exchange of information between neighbors and cluster leader. CADR is a greedy algorithm which routes a query to its optimal destination by following the local gradients to maximize the information gain through the sensor network. It may suffer from getting trapped at local maxima or minima.

The recent work by Liu, Zhao and Petrovic [7] proposes min-hop routing algorithm to overcome the limitation of CADR about handling local maxima and minima. It uses a multiple step look-ahead approach in which initial network discovery phase determines the minimum look-ahead horizon so that the path planning phase can avoid network irregularity. The algorithm improves the success rate of routing the message with additional search cost. Also the increase in the neighborhood size causes more communications between the cluster leaders and their neighbors.

Another information driven routing protocol is GRAdient Broadcast (GRAB) [14] which introduces virtual gradient by building a cost field towards a particular node and then routes queries across a limited size mesh towards that node. Initial overhead for flooding the network can be amortized by routing queries reliably along the shortest path.

In [12], a navigation protocol is proposed to guide along the safest path using a distributed repository of information about the area covered by the sensor network. The network can adapt to sensor failure or addition of new nodes by continuous updates of the distributed information content. Both

building and updating of the information repository causes significant communication overhead.
Also our work has some similarities to techniques proposed in [15] and [16] for routing in ad-hoc networks using mobility diffusion to disseminate the destination location information. However, cost-model and mobility issue of ad-hoc networks make it inapplicable for static sensor networks.
Our scheme routes the query using a fully distributed decision making procedure by effectively exploiting the natural gradient information repository, which is the consequence of the fingerprint gradient of physical phenomenon being monitored and follows well established physical laws. Multiple path exploration to discover the route or the event and control the instantiation of multiple paths, using a probabilistic function based on simulated annealing concept, is another key difference with existing information-driven protocols. The ability to query for multiple sources (Sec.6.3) and use time gradient for target tracking (Sec.7) are important features of our scheme. We target applications in which queries are generally triggered to identify the origin of an event after its occurrence and its effect follows diffusion laws. For example, fire event, earth quake, chemical contamination etc. We will discuss more specific applications in Sec.7. Our scheme works without the location information. However, location information, when available, can make our protocol more energy efficient and robust.

3 Environment Model

We now describe the environment model used in this paper. The following three components are considered in attempt to properly model the environmental effects, and to design and analyze the performance of our protocol.

- **Area covered by event's effect:** When an event occurs, diffusion of its effect is a function of distance, d and time, t, i.e., $f(d,t) \propto \frac{t}{d^{\alpha}}$. Now, considering sensors reading at particular time instance, say t_1, diffusion can be expressed as a function of distance only, i.e., $f(d) \propto \frac{1}{d^{\alpha}}$. Theoretically, the tail of the diffusion of the event's effect is infinite; but in the real life, sensors are unable to detect or measure the effect of an event below a certain threshold. So, after a certain distance from the event's location, it is not possible to measure the event's effect using the small sensors of DSN. Zero reading of the sensors of these region creates a *flat information* region where information gradient is unavailable.

- **Erroneous reading of malfunctioning sensors:** Real life sensors are not perfect and subject to malfunction due to obstacle or sensor/node failures. So, some of the sensors erroneous reading may cause irregular pattern, i.e., local maxima or minima in the information gradient of the event's effect. To model the environment for our protocol, we consider malfunctioning sensors are uniformly distributed in the DSN and each malfunctioning sensor is assigned a random reading. An analytical technique is presented in the Appendix to filter such arbitrary readings of isolated malfunctioning sensor nodes. Also simulation results of Sec.6.2 demonstrates the effectiveness of the filter. To analyze the performance of our protocol in the presence of sensor error, we vary the percentage of malfunctioning sensors between 0 to 20%.

- **Environmental noise:** Condition of the surrounding environment, such as direction of airflow or fluid, humidity, etc., of sensors and the event is responsible for this type of noise. Although its effect is less where gradient information level about the event's effect is high, it gradually increases towards the low gradient zone. Due to this noise, sensor's reading can increase or decrease by a certain amount. We model this noise as follows,

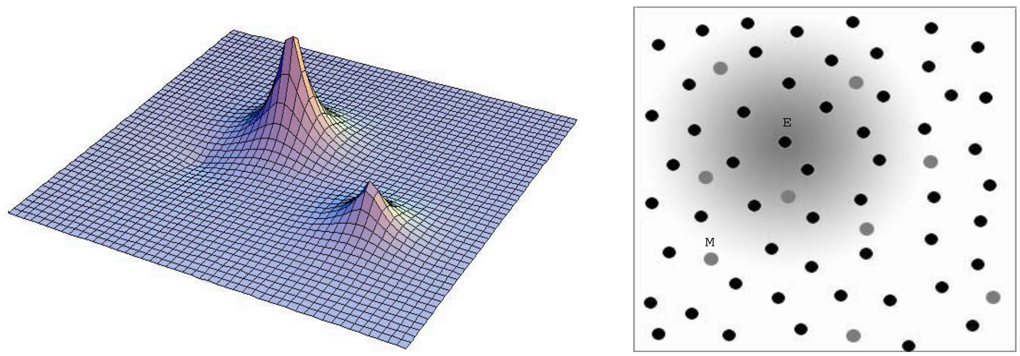
  $$f(d_i) = f^*(d_i) \pm f_{EN}(f^*(d_i)),$$
  $$f_{EN}(f^*(d_i)) \propto (f_{max} - f^*(d_i))$$

  where,
  d_i = distance of the location from peak information point (i.e., the event)
  $f(d_i)$ = gradient information of the location with environmental noise,
  f_{max} = peak information,
  $f^*(d_i)$ = gradient information of the location without environmental noise.
  The proportional constant is considered 0.03 to model the environmental for our protocol, i.e., 3% environmental noise is consider.

Thus our environmental model (Fig.1) consists of flat (i.e. zero) information region and gradient information region. Environmental noise is present only in the gradient information region, while malfunctioning sensors are uniformly distributed in both regions.

4 Protocol

With the intuition of natural information gradient discussed in Sec.1 and the environment model presented in Sec.3, our basic information-driven routing protocol is designed. It is assumed that to prevent looping, each querier generates unique sequence number for the query it sends. Based on the environment model, each query can have two different modes - (1) flat region mode and (2) gradient region mode. Initially, a query starts with flat region mode. It switches to gradient region mode as soon as it finds the gradient information about the event's effect. Thus, the query packet needs fields for the query ID and the query mode in addition to other information.



(a) (b)

Figure 1. Environment model: (a) Events are at the peaks and its effect reduces with distance. (b) Event is located at "E". Radial gradient of color represents the event's effect. Black dots denote good sensor nodes and gray dots (e.g., "M") denote malfunctioning sensor nodes. Nodes in the white region are flat information region nodes.

A query may be initiated from any arbitrary node. Upon receiving the query, the querier sets the query mode to flat region mode and forwards the query to its neighbors with its gradient information level about the queried event. Then, each neighbor independently decides whether to forward the query based on the algorithm described below.

- In the *flat information region*, if the query mode is flat, node uses flooding to forward the query towards the gradient information region (Fig.2(a)). Otherwise, a node uses probabilistic forwarding described next. The query does not switch to the gradient mode unless gradient information is found. Hence, in the absence of event(s), gradient information will be zero (in the ideal condition) and the protocol will only use this flooding approach.

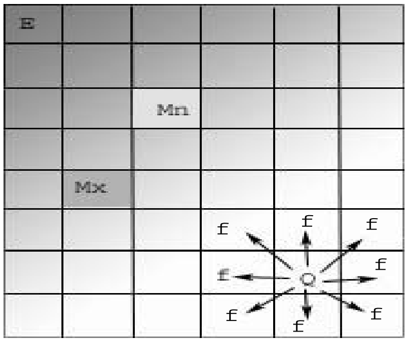
- In the *gradient information region*, a node uses greedy forwarding approach. If a node is able to improve the information level, it forwards the query to its neighbors for further improvement (Fig.2(b) and 2(d)). Otherwise, the node performs probabilistic forwarding, described next. Note that, this greedy forwarding approach is different from classical greedy forwarding algorithms which either choose the best neighbor or a set of best neighbors based on collected information of neighbors like information level, close to destination etc. In our greedy forwarding approach underlying concept is, if a node's reading is more than that of its parent node along the forwarding path, then the forwarding path through the node may reach to nodes having higher readings.

- The type of irregular patterns possible in the gradient information region, due to erroneous sensors reading as discussed in Sec.3, can be sharp drop or rise of information level about the queried event. To overcome such local and isolated maxima or information hole, the protocol uses a probabilistic forwarding (Fig.2(c)) which is a function based on simulated annealing concept. As a parameter, the function takes the hop-count(x) in the gradient information region. That is, the probabilistic function, $f_p(x) = \frac{1}{x^a}$ where, 'a' depends on the diffusion parameter, α and controls the reachability of the protocol. As we will discuss, the performance is a function of the interplay between 'α' and 'a'. This will be discussed in Sec.6.

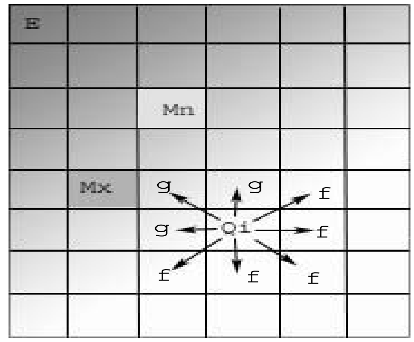
Nodes use the reverse path as a basic mechanism to send the reply of the resolved query to the querier. However, depending on the type of query, the reply mechanism may be optimized to suppress unpromising responses; more discussed in Sec.6.2. Initially the protocol instantiates multiple paths to discover source(s); but, in the absence of multiple sources most of the paths will terminate after few hops. Note that our algorithm does "NOT" require neighbor "Hello" messages (i.e., a node processing the query is not assumed to know all its neighbors readings). This has proven to save significant overhead over using "Hello" message.

5 Simulation Model

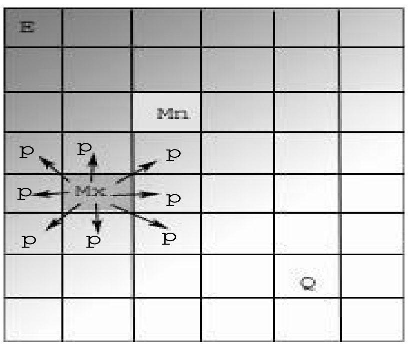
Simulations were carried out to validate and characterize the performance of the proposed information gradient based routing protocol. The objective of the simulation model is not only to analyze the performance of our routing protocol, but also to study how to exploit the natural information gradient effectively.
In the simulation, two different sensor layouts are used. The first layout is a regular 100×100 grid of 10000 sensor nodes



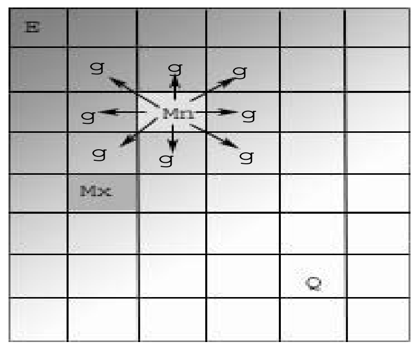
(a) 'Q' forwards query to its neighbors. All '*f*' nodes are in the flat information region, so they use flooding again.



(b) All '*g*' nodes are in gradient information region, so they switch the query mode to gradient mode and must forward again.



(c) All neighbors(*p*) of M_x have less information, so they will probabilistically forward the query to their neighbors.



(d) All neighbors(*g*) of M_n have more information, so they will forward the query to their neighbors.

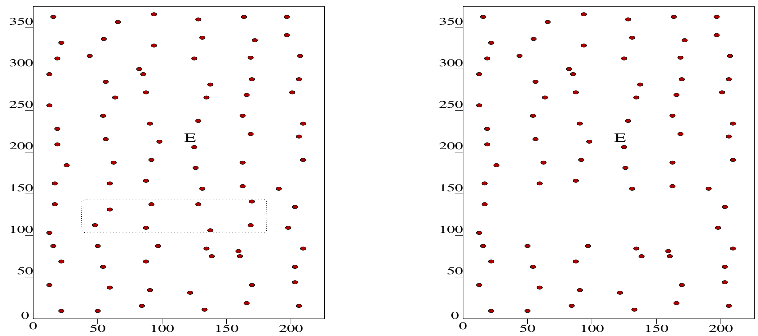
Figure 2. Routing protocol: Event is at 'E' and querier 'Q' located in the flat information region. Effect of 'E' follows diffusion law. M_x is local maxima and M_n is local minima.

and each node has eight neighbors. The second layout is a uniform random grid (Fig.3(a)) used in [7] to simulate a sensor field of dimension $225 \times 375 m^2$ with sensors having $50m$ communication radius. It is generated from a regular 15×6 grid of 90 sensor nodes by perturbing the grid points with independent Gaussian noise(0,25). For single-value query (Sec.6.1), to test the success rate of our routing protocol in the presence of sensor holes, we remove grid points from row 5-6 and columns 2-5 before perturbing the grid points (Fig.3(b)). In addition to sensor layouts, the environment is modelled using its three components described in Sec.3. For all simulations, parameter α, of the phenomenon diffusion function is set to 0.8.

Evaluation of the routing algorithm is done in terms of average energy dissipation and success rate, i.e., reachability. To compute energy dissipation, we consider total number of transmissions required to forward and reply the query. Performance of our routing algorithm is compared with flooding and expanding ring search (ERS), which uses additive increase of ring size. Effectiveness of the information gradient is analyzed by varying the first two components of the environment model, i.e., the percentage of flat information region nodes and the percentage of uniformly distributed malfunctioning nodes. Also we pay attention to tune the parameter '*a*' of the probabilistic function described in Sec.4, to find optimal trade-off between energy dissipation and improve reachability of our proposed routing protocol.

6 Performance Evaluation

Three different problems are studied and analyzed using the information gradient based scheme. These are (1) Single-



(a) (b)

Figure 3. Sensor layout: (a) uniform random grid. Sensors within dotted rectangle are removed to create sensor hole, (b) uniform random grid with sensor hole. "E" denotes the location of the event.

value query, (2) global maxima search, and (3) multiple event detection.

6.1 Single-value Query

This type of query searches for a specific value and has a single response. Here, we assume that only one node has the response. And the response is about an event, where the effect follows a diffusion law and creates the information gradient. Also the event source is assumed to be stationary. For example, search for a source of chemical leakage, where information gradient is a fingerprint of the chemical contaminant. So, the routing algorithm needs to find the source. Here the source uses reverse path to send the reply to the querier.

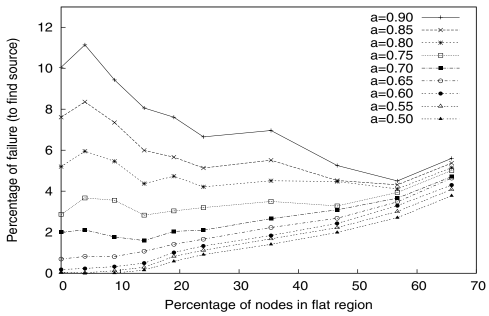
For single-value query, the event is simulated at location (74,49) of the first sensor layout and the querier can be any of the remaining nodes. In Figure 4(a) and 4(b), for 15% malfunctioning nodes, we vary the number of nodes in the flat information region from 0-66% to show the change of query failure rate and average energy dissipation respectively for different values of 'a' of the probabilistic forwarding function (Sec.4). With the increase of the flat information region nodes, flooding overhead becomes dominant. The protocol creates multiple paths, so the failure rate decreases but at the same time the energy dissipation increases. But the malfunctioning nodes (Sec.3) cause the protocol to switch to the gradient mode erroneously; so, the failure rate increases for more than 57% flat information region nodes.

In Figure 5(a) and 5(b), for 36% flat information region nodes, the number of malfunctioning nodes are varied. With increase of malfunctioning nodes, the protocol switches from the flat region mode to the gradient region mode rapidly, which reduces the flooding overhead, but increases the failure rates especially for higher value of 'a'. It is important to notice from Figures.4 and 5 that for higher value of 'a', the probabilistic forwarding function, $f_p(x) = \frac{1}{x^a}$ (Sec.2) drops sharply and the protocol explores less number of nodes. As a result, the failure rate increases and the average energy dissipation decreases. For $a < \alpha$, the probabilistic function drops slowly and allows to follow the diffusion pattern due to α by more probabilistic forward. Thus, values of $a < \alpha$ but close to α give the optimal trade-off between the energy dissipation and the reachability. In simulations, though α is 0.8, but due to simulated environmental noise, it is found from Figures.4 and 5 that $a = 0.65$ is the optimal for the simulated scenario. Further, in Figure.6, the average energy dissipation of our algorithm is compared with that of the flooding-based querying (FBQ) and the expanding ring search (ERS) algorithms using the same configuration of the layout. Our routing protocol reduces the energy dissipation by 47-80% over FBQ, while the flat information region nodes of 66% or less. Also in the presence of 47% or less flat information region nodes, our protocol reduces the energy dissipation by 18-50% over ERS.

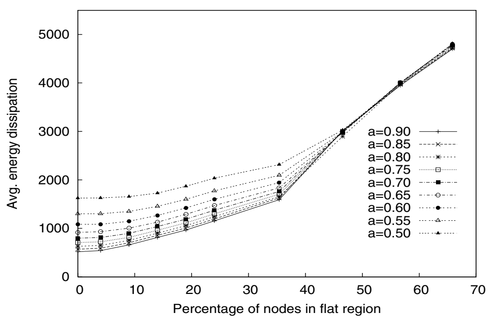
The second sensor network layout is used to test reachability in the presence of a deployment gap or hole. Target is simulated at location 'E' and queriers can be any node below the sensors hole of the sensor network layout as shown in Fig.3(b). In Figure 7, for 20% malfunctioning nodes, the flat information region nodes are varied from 20-94%. For smaller values of 'a', the success rates of our protocol to route the query around the sensors hole are above 98%, even at the presence of 55% flat region nodes.

6.2 Global Maxima Search

The query finds the maximum value of the event's effect within the sensor monitored region. This important statistic gives the current critical status about the observed phe-

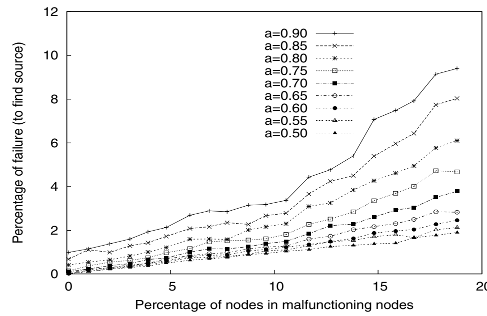


(a) Failure rate

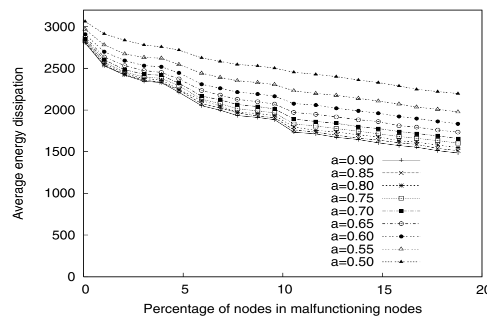


(b) Average energy dissipation

Figure 4. Effect of flat information region nodes (3% environmental noise and 15% malfunctioning nodes).



(a) Failure rate



(b) Average energy dissipation

Figure 5. Effect of malfunctioning nodes (3% environmental noise and 36% flat information region nodes).

nomenon. For FBQ and ERS algorithms, to decide about the maximum value, need to explore all nodes of the DSN. However, using the gradient information, our protocol determines the global maxima by exploring only a limited number of nodes.

Due to distributed nature of sensor network, any node with some gradient information about the observed phenomenon, can become a potential responder of the query; so the reply overhead for this type of query may become significant. Hence, we propose a reply suppression scheme in which intermediate nodes suppress non-promising replies by caching and comparing the maximum value of the responses passing through the node for the same query ID, as shown in Figure.8. In the suppression scheme, a node forwards the reply unless it receives some higher gradient information from its neighbors' broadcast replies. To make this scheme even more effective a node may use a timer (per reply) that is set before a reply is sent or forwarded, while the timer is running the node listens to other broadcast replies and suppresses unnecessary reports. The timeout is a function of the network size.

For this type of query, we use the first sensor network layout with the same configuration used for the single-value query (Sec.6.1). The failure rates to find the global maxima are similar to those of the single-value query (Figure.4(a)). In Figure.9(a) and 9(b), for 15% malfunctioning nodes, we vary the percentage of the flat information region nodes. As discussed in Sec.6.1, erroneous reading of malfunctioning nodes in the flat information region causes a query to switch to gradient region mode. Due to absence of further gradient information and sharp drop of probabilistic function for higher values of '*a*', along that path, information improvement halts after the malfunctioning node. So, the node initiates a reply towards the querier after timeout of the query. But, for lower value of '*a*', the probabilistic function drops slowly which causes more probabilistic forwarding of the query. It increases the probability to reach the gradient information region and the reply comes from actual source node. For these reasons, in both Figure.9(a) and 9(b), for 44% to 65% flat information region nodes, higher value of '*a*' shows more energy dissipation. For more than 65% flat information region nodes, the gradient information region size reduces more and the average energy dissipations for all values of '*a*' become identical. However, after using the filter to detect the malfunctioning nodes described in the Appendix, the number of

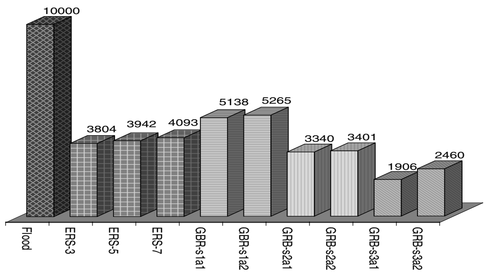


Figure 6. Comparison with FBQ, ERS, and our gradient based routing (GBR). Here ERS ring sizes are 3, 5 and 7. For GBR, *s1*,*s2* and *s3* indicate 66%,47%, and 36% flat information region nodes respectively. And *a1* and *a2* indicate '*a*' is 0.7 and 0.5 respectively.

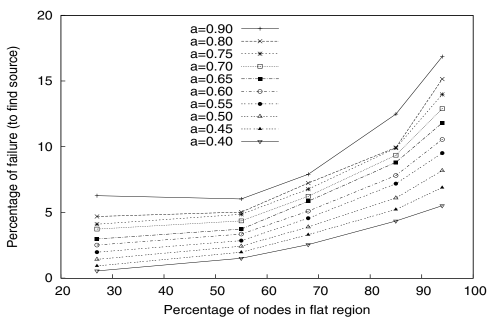
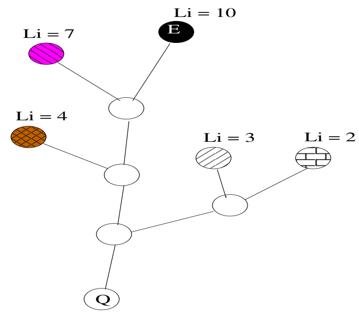
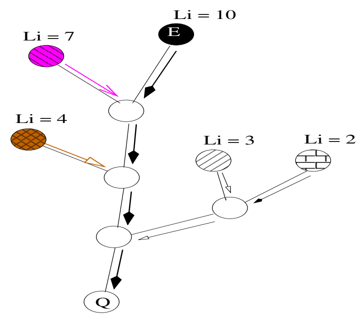


Figure 7. Query failure rate to route a query around sensors hole of the second sensor layout.



(a) Query forwarding ends at the shaded nodes.



(b) Intermediate nodes suppress the non-promising replies.

Figure 8. Optimized reply mechanism. Here, event and querier are at 'E' and 'Q' respectively. L_i is the information about the event's effect.

replies from the malfunctioning nodes is reduced dramatically. As a result, the average energy dissipation reduces significantly, as shown in Figure.9(b). We notice that for this type of query the effects of malfunctioning nodes are similar to those of the single-value query. Also, it is found that $a = 0.65$ is optimal for the simulated scenario.

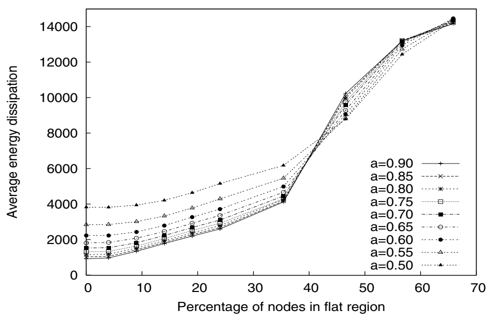
6.3 Multiple Events Detection

This type of query searches for multiple events of the same type. So sensors, within the gradient information region of multiple sources, record resultant gradient information. For example, fire incident causes multiple sources as it spreads with time. So, a sensor monitoring temperature, actually records resultant temperature at its location due to these multiple fire sources. Using multiple path exploration and the gradient information, our protocol attempts to find all the multiple sources.

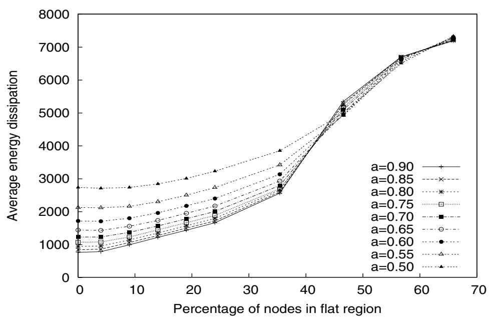
In our simulation, sources are uniformly distributed in the first sensor network layout and the querier can be any of the remaining nodes. In Figure.10(a) and 10(b), for 15% malfunctioning nodes, we vary the number of sources from 1 to 18. We notice that for less than five sources, $a = 0.4$ gives the optimal trade-off between the number of sources found and the average energy dissipation. But, with the increase of number of sources in the sensor network layout, the resultant gradient information due to multiple sources creates some plateaux regions and requires more probabilistic forwarding to forward query towards sources through that region. So lower value of '*a*' is required so that the probabilistic function drops slowly and allows more probabilistic forward. For five or more number of sources, $a = 0.35$ is found the optimal in the simulated scenario.

7 Other Potential Applications

In Sec.6, three generic types of query routing are discussed and solved using the natural information gradient based approaches. These approaches can be combined to solve several essential real life applications. Due to space limitation, here we illustrate the time gradient based target tracking only.

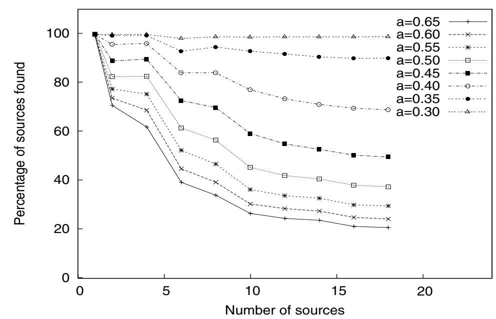


(a) Average energy dissipation *without* filter to avoid malfunctioning nodes.

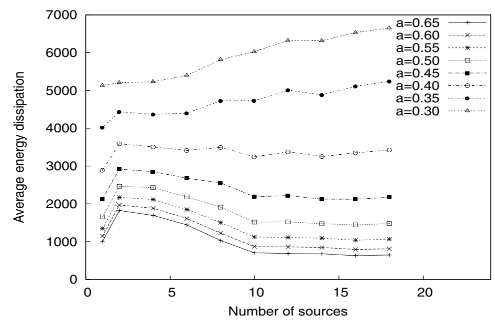


(b) Average energy dissipation *with* filter.

Figure 9. For global maxima search, effect of flat information region nodes, while environmental noise is 3% and malfunctioning nodes are 15%. Notice that y-scale of (a) and (b) are 0-14000 and 0-8000 respectively.



(a) Percentage of sources found vs number of sources.



(b) Average energy dissipation.

Figure 10. Multiple events detection, while environmental noise is 3% and malfunctioning nodes are 15%.

7.1 Target Tracking

In a tracking scenario, consider targets as point sources of signals and the signal amplitude attenuates with distance according to diffusion law. Here, each sensor node requires its location information to report the target's current position. This is not required for routing decision.

Now, as the target enters and moves, sensors within the signal range of the target record the local time stamp when the target has been sensed. At each time instance, multiple sensors may detect the same target. To precisely determine the location, each of these sensor nodes initiates query for maximum signal strength similar of global maxima search (Sec.6.2), within the small gradient region of signal, created due to the point source, i.e., the target. Here a higher value of 'a' is required so that the probabilistic function (Sec.4) drops sharply and limits unnecessary forwarding. Also the query alerts the nodes immediately outside the gradient region, about the possible movement of the target. Furthermore, from the recorded local time stamp for the target, sensor nodes can create time gradients in terms of number of clock ticks has been passed after sensing the target which decreases along the direction of the moving target. Now routing a query for the finding the minimum value of such clock ticks, is essentially following the target. Since, the sensor node close to current position of the target has the minimum value of clock ticks after sensing the target at that instance.

8 Conclusion and Future Work

In this paper, we presented a scheme to route on fingerprint gradients in sensor networks. The main contributions of this paper are

1. The proposed novel scheme to exploit the natural information gradient repository, which is a consequence of the fingerprint gradients of the event's effect.

2. The novel reactive, fully distributed routing protocol for sensor network, based on that information gradient repository.

Unlike other information-driven protocols for sensor network, our scheme eliminates the overhead of preparing and maintaining the information gradient repository. Three different problems were studied using our scheme and the performance of the routing protocol for each problem, was demonstrated by simulations. Overall energy dissipation of the protocol was found significantly low compared to FBQ and ERS. Also its success rate to route around sensors hole, was found to be over 98%.
Multiple path exploration and control the instantiation of paths by simulated annealing, make our protocol well suited for broad range of applications including time gradient based target tracking, event boundary detection. One possible future research direction is to develop protocols for target tracking and target counting using our proposed scheme. Also we have found that the parameter '*a*' of the probabilistic function depends on the diffusion parameter α. So, another important future work will be to establish analytical relationship between '*a*' and α to further reduce the energy dissipation.

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Appendix

Filtering Erroneous Readings of Malfunctioning Sensors:

Consider two sensor nodes S_1 and S_2 and they are neighbor of each other.
Let, distance of S_1 and S_2 from the event's location are d and $d+1$ hops respectively, as grid topology is used.
Due to event's effect, reading of S_1 and S_2 are R_1 and R_2 respectively, and we get,

$R_1 = \frac{C}{d^\alpha}$, and
$R_2 = \frac{C}{(d+1)^\alpha}$, respectively.
Here, C is proportional constant.

Hence, $\frac{R_1}{R_2} = \frac{(d+1)^\alpha}{d^\alpha} = (1+\frac{1}{d})^\alpha \approx 1 + \frac{\alpha}{d}$, where $|\frac{1}{d}| < 1$
Therefore, if sensor reading follows diffusion law, then

$\frac{R_1}{R_2} \approx 1 + \frac{\alpha}{d}$

In our simulation study, $\alpha = 0.8$.
Hence, $\frac{R_1}{R_2} \approx 1 + \frac{\alpha}{d} < 2.0$ is used as a reasonable simple filter to detect malfunctioning nodes.