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Discrepancy and Multipath Routing in Wireless Sensor Networks

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Abstract

This work addresses the problem of balancing the spatial distribution of the routing-load among the nodes in a given sensor network, in multipath settings. It has been conjectured in a number of works that in dense networks, the field-based multipath routing paradigms such as electrostatic fields, uniformly distribute the traffic load throughout the $2D$ space of deployment. However, when the distribution of the nodes deployment is not uniform, two major shortcomings of such approaches become apparent: (1) paths-merging due to decrease in available neighbors; and (2) paths-merging tendency near the physical boundary of the network. Together, these two effects significantly distort the initial energy distribution of the network. We postulate that an important parameter that needs to be taken into consideration when designing routing algorithms is the *discrepancy* of the nodes distribution. Motivated by this, we propose a novel multipath routing approach that enables a better load balancing, in the sense of reducing the spatial deviation of the energy consumption, when a single or multiple sources are transmitting data towards a given sink. Our experiments demonstrate that, in addition to improving the discrepancy of the network-wide energy distribution, our techniques also prolong the network lifetime.

Keywords: Wireless Sensor Networks, Multipath Routing, Discrepancy.

Discrepancy and Multipath Routing in Wireless Sensor Networks

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This work addresses the problem of balancing the spatial distribution of the routing-load among the nodes in a given sensor network, in multipath settings. It has been conjectured in a number of works that in dense networks, the field-based multipath routing paradigms such as electrostatic fields, uniformly distribute the traffic load throughout the $2D$ space of deployment. However, when the distribution of the nodes deployment is not uniform, two major shortcomings of such approaches become apparent: (1) paths-merging due to decrease in available neighbors; and (2) paths-merging tendency near the physical boundary of the network. Together, these two effects significantly distort the initial energy distribution of the network. We postulate that an important parameter that needs to be taken into consideration when designing routing algorithms is the *discrepancy* of the nodes distribution. Motivated by this, we propose a novel multipath routing approach that enables a better load balancing, in the sense of reducing the spatial deviation of the energy consumption, when a single or multiple sources are transmitting data towards a given sink. Our experiments demonstrate that, in addition to improving the discrepancy of the network-wide energy distribution, our techniques also prolong the network lifetime.

1 Introduction

The problem of routing in wireless sensor networks (WSN) has received a considerable attention [3] and, in particular, the problem of multipath routing has been of interest for two complementary goals: (1) Increasing the reliability of the delivery and aggregates computation [23]; and (2) Balancing the load among the nodes [11, 22, 29, 39]. When it comes to load-balancing, which is the focus of this work, the multipath paradigm alleviates the problem inherent to single-path routing – uneven utilization of the energy reserves which, as an important consequence, affects the lifetime of WSNs [8].

For a given sink, the two basic kinds of multipath routing scenarios are: (1) single-source; and (2) multiple-sources [4, 16, 17, 25, 27, 30, 36], In addition to the energy consumptions due to packets forwarding, in multiple-sources settings, an important energy consumption factor are the MAC collisions due to the spatio-temporal intersection of paths from different sources. In this context, the field-based routing [17, 27] has been identified as an efficient energy balancing mechanism for both single and multiple source scenarios. The essence of field-based routing is that the sink is assigned a negative charge, while the sources are assigned positive charges, and multiple routes are based on individual gradients of the field, providing a wider range for paths, thereby reducing collisions. With all the importance and potential benefits of the field-based

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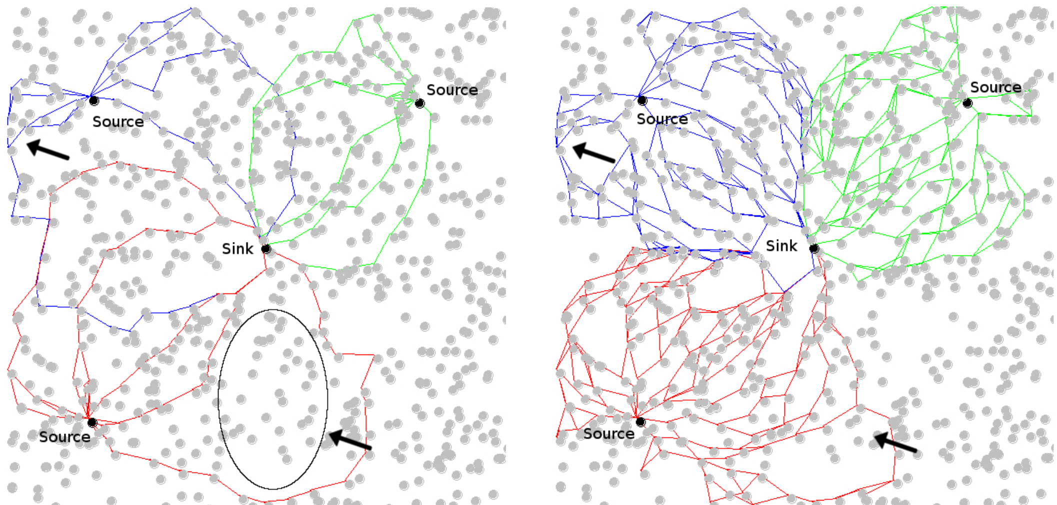


(a) using EFR (b) Proposed approach (DA-MPR)

Figure 1: Paths merging in multipath routing

routing paradigm, we observe two serious drawbacks: (1) The paths around the boundary of the network tend to merge, significantly reducing the extent of load-balancing; (2) While there is a potentially infinite number of gradient-based routes, the number actually available paths is limited by the neighboring nodes. As an illustration, Figure 1(a) shows how the EFR-based routing completely fails to utilize portions of the network (e.g., the ellipse-bound area), and causes paths-merging (e.g., the boundary) – both of which are reduced in the settings in Figure 1(b).

We postulate that, in order to improve the load-balancing, in addition to the typical parameters such as density, connectivity, etc. multipath routing algorithms need to take into account another relevant parameter of the WNS – the *discrepancy* of the nodes distribution. Intuitively, the discrepancy of a given point-set is a measure that characterizes how much the distribution of the elements of that set deviates from the uniform distribution.

At the heart of the motivation for this work is an observation regarding the adaptability of the multipath algorithms to the changes of the locations distribution in different parts of the network. Namely, if a given algorithm fails to take into account (and exploit) such changes, while the existing multiple routes may naturally have to merge in certain areas, that particular algorithm will fail to spatially expand and/or increase the number of paths in other areas, thereby amplifying the path-merging effects. Hence, the main hypothesis of this work is that if the multipath routing algorithm has some adaptability in the sense of spatial distribution around the forwarding nodes, then it may improve some vital parameters of the network, like its distribution of energy-reserves and its lifetime. Towards that end, the main contribution of this work consists of: (1) a novel forwarding algorithm that is discrepancy-aware in the sense that whenever the changes in the spatial distribution permit it, the forwarding nodes will adaptively select the next hop for transmitting, in a manner that reduces the effects of the (prior) paths merging; (2) a novel routing protocol that encompasses the forwarding ideas both in the interior and along the boundary of a given network, and incorporates them in a multiple-sources settings. Our experiments demonstrate that the proposed methodologies yield significantly better load-balancing by improving the spatial distribution of the energy consumption (resp. reserves) by over 50% when compared to the traditional field-based routing and, in addition, provide an improvement of the network lifetime (between 10% – 40%), depending on the network settings.

The rest of this paper is organized as follows. Section 2 recollects the necessary background and Section 3 presents our *Discrepancy Adaptive Field Persistent* forwarding (DA-FP) algorithm used by the relay-nodes, subsequently used in Section 4 in which we present our *Discrepancy Adaptive Multipole Routing* (DA-MPR) protocol. Section 4 presents our experimental observations and in Section 5 we position our work with the related literature. Section 6 concludes the paper and outlines directions for future work. In the Appendix of this report, we present the `java` source code of our implementation of 2D-deployment generator for various

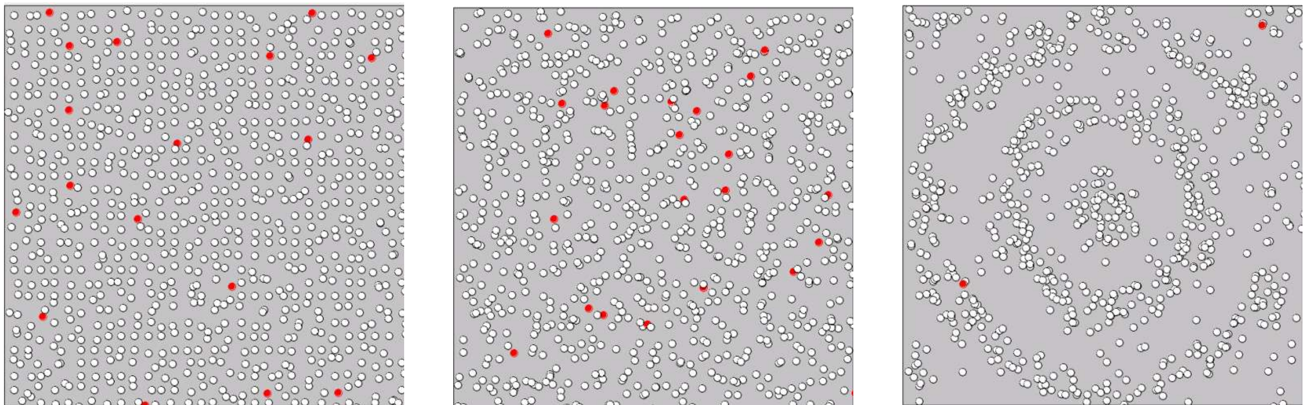


Figure 2: Discrepancy of Nodes Distributions

values of the nodes-locations discrepancy [14].

2 Preliminaries

We now present the basics of the network model considered in this work, after which we refresh some concepts of electrostatic fields and discuss the concept of geometric discrepancy.
We consider a multi-hop WSN covering a region of interest, represented by a simplified but widely accepted model, where each node n_i has a unique ID and a fixed physical location represented as a coordinate in the reference system. Nodes are assumed to have the capability of determining their locations at run-time, either by means of a location hardware (e.g., a GPS), or by implementing a location discovery algorithm [10, 26]. In addition, each node has information about the position and state of its one-hop neighbors, and we also assume that nodes know the boundaries of the network (either by pre-loading this information, or by using an appropriate protocol, e.g., [7]) and that they are cooperative [33] i.e., they will not maliciously refuse to forward packets. For the initial interactions between source(s) and sink we utilize greedy geographic routing [19] (cf. Section 4).

2.1 Electrostatics Basics

A discrete distribution of N static particle charges q_i with respective positions $\mathbf{r}_i \in \mathbb{R}^2$ produces an electrostatic field $\mathbf{E}$, typically represented as a set of smooth i.e. *field lines* with constant magnitude, (i.e., gradient) which describe the field at a given point. The electrostatic potential ϕ_E at point $\mathbf{r} \in \mathbb{R}^2$ is given by:

$$\phi_E(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \sum_{i=1}^{N} sgn(i) \frac{|q_i|}{|\mathbf{r}_i - \mathbf{r}|} \tag{1}$$

where $\mathbf{r}_i$ $(1 \le i \le N)$ are the locations of the charges, corresponding to the positions of the sink and source nodes, and ϵ_0 is the vacuum permittivity. If i is the sink, then $sgn(i) = -1$, and $sgn(i) = 1$ otherwise. The curve along which a given node n_k searches for the next hop is determined based on the electric field at $\mathbf{r}_k \in \mathbb{R}^2$ which, using Equation 1, is given by:

$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \sum_{i=1}^{N} sgn(i) \frac{|q_i|}{|\mathbf{r}_i - \mathbf{r}|^3} (\mathbf{r}_i - \mathbf{r}) \tag{2}$$

2.2 Discrepancy of a Point Set

Given a d-dimensional unit cube $C^d = [0, 1)^d$, the discrepancy of an n-point set $S \subset C^d$ measures how much the distribution of the elements of S deviates from the uniform one [24]. We note that, unlike $d = 1$, in the cases of $d \geq 2$, there may be different criteria of uniformity (e.g., vertices of a square grid vs. equilateral triangles in 2D) and sets that have a good discrepancy for one distribution, may have a bad discrepancy for another. Let $d = 2$ and let *A(R)* denote the area of an axis-parallel rectangle R. The discrepancy of S from the uniform distribution, on R is defined as

$$D(S, R) = nA(R) - |S \cap R| \tag{3}$$

Letting $\mathcal{R}_2$ denote the collection of all the axis-parallel rectangles, the *discrepancy* of S *over* $\mathcal{R}_2$ is defined as:

$$D(S, \mathcal{R}_2) = \sup_{R \in \mathcal{R}_2} |D(S, R)| \tag{4}$$

Letting $\mathcal{R}_2$ denote the collection of all the axis-parallel rectangles, the *discrepancy* of $\mathcal{S}$ over $\mathcal{R}\in$, and the discrepancy-function of all the n-point sets, are respectively defined as:

$$D(\mathcal{S}, \mathcal{R}_2) = \sup_{R \in \mathcal{R}_2} |D(\mathcal{S}, R)| \tag{5}$$

$$D(n, \mathcal{R}_2) = \inf_{\mathcal{S} \subseteq [0,1]^2, |\mathcal{S}|=n} D(\mathcal{S}, \mathcal{R}_2) \tag{6}$$

In one-dimensional case ($d = 1$), the discrepancy of an infinite sequence $u = [u_1, \ldots, u_n](\subset [0, 1])$, denoted $\Delta(u, n)$ is defined as the supremum of $|n(b - a) - |\{u_1, \ldots, u_n\} \cup [a, b)||$, taken over all intervals $[a, b)$. It can be demonstrated (cf. [24]) that for any 1D sequence u, a 2D n-point set S can be constructed such that $\Delta(u, n) \leq 2D(S, \mathcal{R}_2)$.

In general, for an n-point set $\mathcal{S}$ and another set M, the discrepancy of $\mathcal{S}$ with respect to M can be defined as $D(\mathcal{S}, M) = |n \cdot A(M \cup [0, 1]^2) - |\mathcal{S} \cup M||$ and, similarly to equation **??**, taking a sup-remum over all the sets from a given collection $\mathcal{M}$, a discrepancy function can be defined as $D(n, \mathcal{M}) = \inf D(\mathcal{S}, \mathcal{M})$.

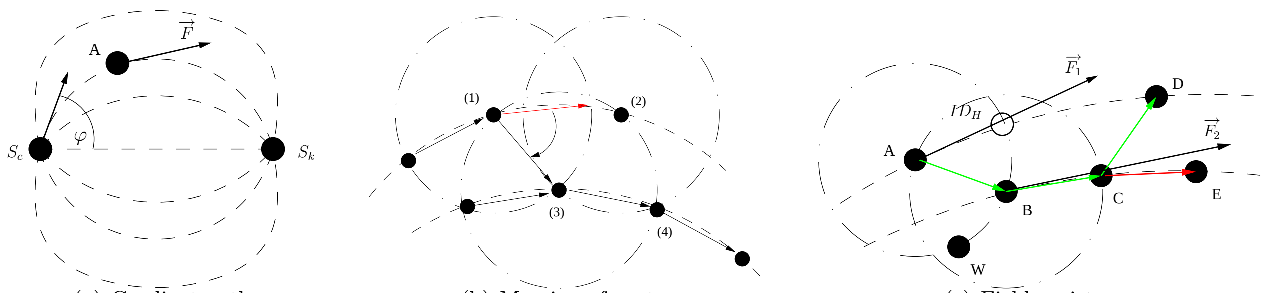
A plethora of application domains have relied upon results from the discrepancy theory – numerical integration [6], computer graphics and pattern recognition (super-sampling) [**?**], complexity theory are but few examples – and methods have been proposed for computing a discrepancy, as well as ensuring upper/lower bounds on generated sets [6, 9, 32]. However, to the best of our knowledge, this apparatus has note yet been fully utilized in WSN settings and, in that sense, we are taking a first step towards exploiting it in multipath routing settings.

3 Exploiting Spatial Distribution in Forwarding

We now proceed with explaining in greater detail the forwarding algorithms that are used by the nodes as a heuristic to guide the selection of the next-hop from among the set of available neighbors. As we mentioned, our aim is to "force" the routing nodes to spread (in a spatial sense) the number of possible route, thereby adapting the shape of the multiple routes to the changes in the spatial distribution. Subsequently, we present our approach that improves the existing solutions for balancing the energy-consumption when routing near the boundary of the network (cf. [17, 27]).

3.1 Discrepancy-Adaptive Routing via Field-Persistency

The essence of the field-base routing (e.g., EFR [27]) is in the behavior of the relay-nodes in between the source and the sink: each relay-node forwards the packets attempting to follow a given gradient field. When a particular node n_i receives a packet, it can readily determine the gradient of the field that it belongs to, based on the: (1) Location and charge of the source(s); (2) Location and charge of the sink; and (3) Its own location. The magnitude of the force exerted on each point along an iso-contour is *constant* – e.g., in Figure 3(a), $\overline{F}$ at location A is uniquely determined by the value of the angle φ selected by S_c.



(a) Gradient path (b) Merging of routes (c) Field-peristency

Figure 3: Discrepany-Aware Field Persistent Routing. (a) Source selects an initial angle φ (b) Path merging in sparser areas. (c)Un-merging previously merged paths.

Figure 3(c) presents a zoomed-in portion of the Figure 3(a), and we use it to illustrate the basic difference between our methodology, which we call *Discrepancy-Aware Field-Persistent* forwarding (DA-FP), and the original EFR [27]. Consider the sensor node A in Figure 3(c), and assume that currently it needs to forward a packet towards the sink. The ideal next-hop node that it would select (illustrated with location ID_H), would be the one located at the intersection of the circle bounding its communication range, and the gradient curve to which A belongs, determined by $\|\overline{F}_1\|$. Since there is no node at that location, according to the EFR policy, the node A will select its neighbor B as the next-hop because: (1) it is furthest away towards the sink; and (2) it is closest to the original route[1] of the iso-contour determined by $\|\overline{F_1}\|$ at A, as opposed to W.

Subsequently, the current relay-node B in 3(c), will execute the same behavioral policy, except now, using the Equation 2, it will become aware that it belongs to the iso-contour of $\overline{F}_2$, and it will select the node C from his one-hop neighbors, as the next relay-node. The main difference between our DA-FP approach and the original EFR is illustrated in the behavior of the node C in 3(c). Namely, according to the EFR, the node C will select its neighbor E as the next relay-node, whereas in our DA-FP approach, the node C will select its neighbor D as the next relay-node. The rationale is that the node D is the closest one (from among C's neighbors) to the *original iso-contour route* specified for A, which is an "ancestor" of C. To accomplish this, clearly, some extra information needs to be "embedded" in the transmitted packets and, as we outlined above, it is sufficient for every packet to "remember" the initial curve (i.e., the initial tangent-angle) that it was sent through by the source.

The immediate benefits of the DA-FP can be intuitively explained as: (1) EFR would have "forgotten" that node D is the closest node to the original iso-contour; (2) EFR would have double-loaded nodes like B, C and D – because both iso-contours ($\overline{F}_1$ and $\overline{F}_2$) would select these nodes. As presented in the previous paragraph, the overhead imposed by DA-FP is that in addition to the parameters needed for internal calculations (location and charge of sink and source(s)), each packet has to contain an extra-parameter: the "identity" of the original field-curve used by the source when selecting the first relay-node. As our experiments will demonstrate, this overhead is negligible (e.g., 1Byte per packet is sufficient to encode 256 different paths) when compared to the load-balancing benefits achieved by DA-FP. Figure 4, where darker shades indicate higher energy depletions, shows snapshots of the evolutions of the corresponding energy maps when the respective approaches are executed in a simulated environment (cf. Section 5). The illustration presents the energy-map status at different time-instances and, as can be seen, the depletion of the energy reserves is much more uniform when DA-FP is used. A formal description of the steps executed by a relay-node based on the DA-FP strategy is given by Algorithm 1.

We note that the DA-FP approach proposed here is similar in spirit to the trajectory-based forwarding (TBF) [28], except, to specify a given trajectory, the source selects one specific "outgoing angle" (cf. φ in Figure 3(a)), which the relay-nodes carry over as part of the transmission-packet. This, in turn, enables the source to implement different policies of *alternating* among routes - e.g., by discretizing the values of

[1] We note that in the original work [27], a bound is placed on the angle that the next-hop can have with respect to the tangent (i.e., the direction of $\overline{F}_1$) at A.

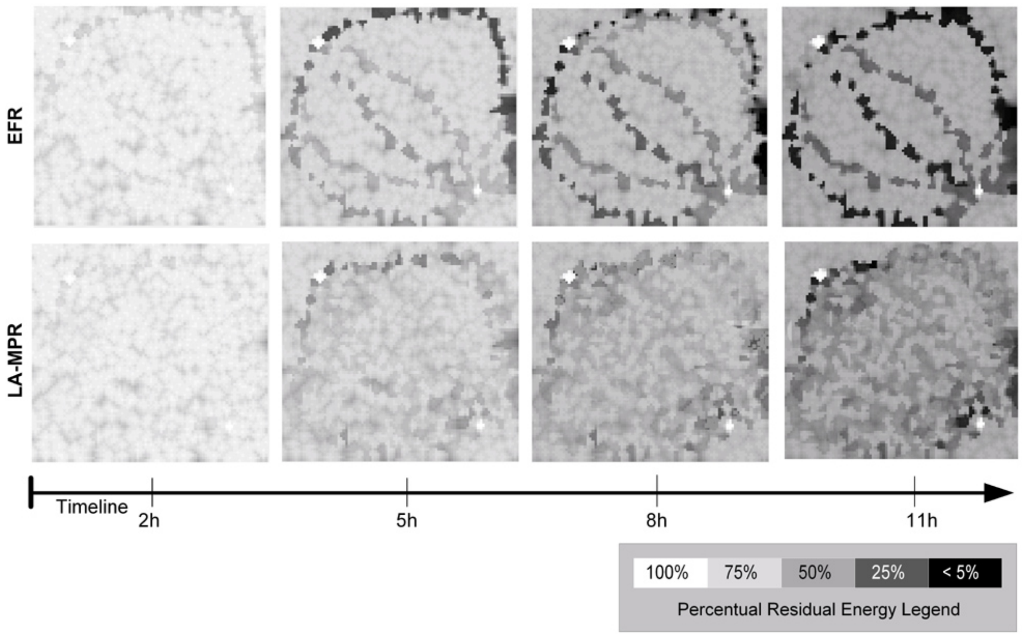


Figure 4: Comparing Energy Depletions

Algorithm 1 Relay-Nodes and DA-FP

Input:
$snk, src \in \mathbb{R}^2$: the sink and source nodes and their locations, q: their charges, φ_{init} (resp. $\overline{F}_{init}$): the initial routeID (selected by the source).
Auxiliary Variables:
$sn_{curr}.x, sn_{curr}.y$: the location of the current-relay sensor node, $NB(sn_{curr})$: the set of one-hop neighbors of sn_{curr}

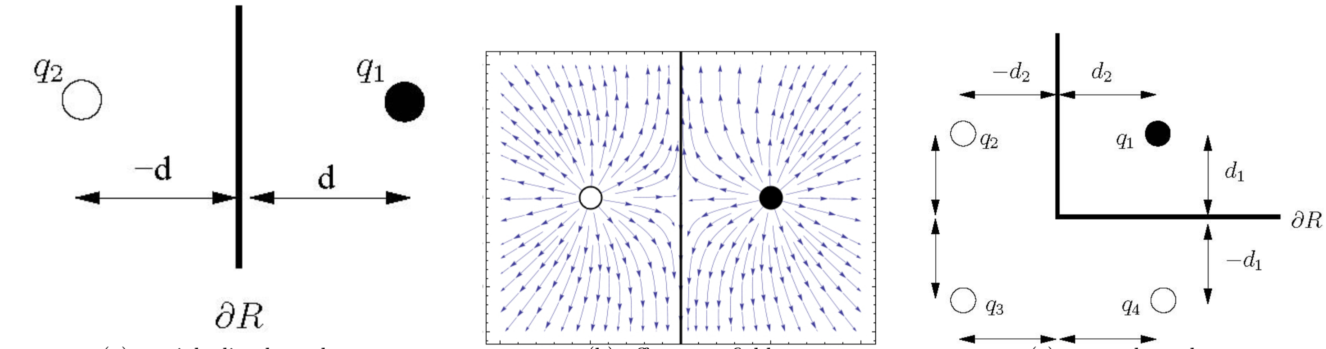
```
Using src, snk, q and own location, determine the φ_curr
Determine the sn_j ∈ NB(sn_curr) which is farthest along φ_init
Let sn_next = sn_j
if no such sn_j exists then
    Let sn_next = the node obtained by sn_curr using ERF modified so that φ_next is determined that is closest to φ_init (in case φ_init != φ_curr)
end if
```

$\varphi \in [0, 2\pi]$, the family of possible routes can be indexed, and a bound can be placed on their total number. Clearly, this entails that some nodes' locations may not belong to an actual route, however, in such cases, the nodes will be considered to belong to the closest (in terms of Euclidian distance) route. In case of a tie, we resolve it by letting the node n_i belong to the smaller of the two index-values.

3.2 Boundary Effects and Methods of Images

As we mentioned, the merging of initially-different routes can also happen at the geographic boundary of a given network. The so-called boundary condition problem has been solved in [17, 35] via partial differential equations, however, such solution may not be practical in WSN settings. We now present an approach based on a well known physical heuristic (*method of images*) to achieve a similar result in a simpler and distributed manner.

Let us denote ∂R as the boundary of the deployment region. Our goal is to reduce the severity of the path merging effects near the boundary. Assume that a charge q_1 is located at a distance d from the boundary (cf. Figure 5(a)). Finding a potential ϕ such that $\nabla_\nu \phi = 0$ for $\mathbf{r} \in \partial R$ will create a zero-potential effect on the boundary, thereby guiding the paths away from its border. The method of images suggests to place an additional, virtual charge q_2 at position $-d$ from the boundary segment under consideration. For $\mathbf{r} \in \partial R$,



(a) straight-line boundary (b) effect to a field (c) corner boundary

Figure 5: Method of Images: (a) A virtual charge q_2 and a zero potential at ∂R. (b) Decreasing the boundary-paths merging. (c) 3 virtual charges near corners.

Algorithm 2 Sink behaviour in DA-MPR routing protocol

Variables:
$snk \in \mathbb{R}^2$: position of sink node, $L \subset \mathbb{R}^2 \times \mathbb{R} \times \mathbb{R}$: (position, charge, duration) of active sources
Auxiliary Variables:
$src, src' \in \mathbb{R}^2$: geographic positions, $q \in \mathbb{R}$: electric charge, $t \in \mathbb{R}$: duration time, $r \in \mathbb{N}$: route identifier

```
loop
  if query injected then
    src', t, r ← parse(userQuery)
    q ← createCharge(src', snk)
    for all src ∈ π1(L) do
      sendToNet(UPDATE(src, snk, (src', q, t))
    end for
    L ← L ∪ (src', q, t)
    sendToNet(QUERY(src', snk, userQuery, r, L))
  else if message received then
    if type(message) == RREQ then
      src, r ← parse(message)
      sendToNet(ACK(src, snk, r))
    else if type(message) == DATA then
      extract sensor readings and present to user
    end if
  end if
end loop
```

we obtain

$$\phi(\mathbf{r}) = \frac{1}{4\pi\epsilon_0}\left(\frac{q_1}{|d|} + \frac{q_2}{|d|}\right) \tag{7}$$

and derive $\nabla_\nu \phi(\mathbf{r}) = 0$ for $\mathbf{r} \in \partial R$.
Knowing the geographical limits of the network (by either pre-loading it or executing an appropriate algorithm [7]), each relay node can decide *locally* whether to apply the method of images or not. If a given node is close to the border, it will include the virtual image charges in the calculation of its field vector. In the case a particular node is close to the corner of the WSN boundary, more than one virtual charges may be needed – e.g., 3 image charges are utilized for the corner in Figure 5(c). We note that the method of images leans on a uniqueness theorem for the Laplace equation, and can be applied to sufficiently regular boundaries, e.g. spheres or cylinders.

4 Multipole Routing Protocol

One of the key advantages of multipole electrostatic routing is its capability to reduce MAC collisions by forming mutually exclusive routing areas for each source (cf. Figure 1(b)). To realize such mutually exclusive areas, each source needs to have an up-to-date information about the existing charges (sources) in the network. A dissemination mechanism was suggested in [17], in which sink and source nodes advertise their locations and respective charges by flooding. This may be sound choice, assuming that the WSN is dense and

Algorithm 3 Source behaviour in DA-MPR routing protocol

Variables:
$src, snk \in \mathbb{R}^2$: geographic position, $L \subset \mathbb{R}^2 \times \mathbb{R} \times \mathbb{R}$: (position, charge, duration) of known sources, $R \subset \mathbb{N}$: acknowledged routes, $P \subset \mathbb{N}$: pending routes
Auxiliary Variables:
$p \in \mathbb{R}^2$: geographic positions, $q \in \mathbb{R}$: electric charge, $t \in \mathbb{R}$: duration time, $r \in \mathbb{N}$: route identifier, $n \in \mathbb{N}$: maximum number of routes

```
1: loop
2:   if message received then
3:     if type(message) == QUERY then
4:       L, n, snk ← parse(message)
5:       P, R ← ∅
6:       for 1 ≤ i ≤ n do
7:         r ← 360i/n
8:         P ← P ∪ r
9:         sendToNet(RREQ(snk, src, r, L))
10:      end for
11:    else if type(message) == ACK then
12:      r ← parse(message)
13:      R ← r
14:      P ← P \ r
15:    else if type(message) == UPDATE then
16:      (p, q, t) ← parse(message)
17:      L ← L ∪ (p, q, t)
18:      for all r ∈ R do
19:        P ← P ∪ r
20:        R ← R \ r
21:        sendToNet(RREQ(snk, src, r, L))
22:      end for
23:    end if
24:  else if sensor reading d available then
25:    if R ≠ ∅ then
26:      r ← selectRoute(R)
27:      sendToNet(DATA(snk, src, L, d))
28:    end if
29:  end if
30: end loop
```

the nodes' locations are uniformly distributed, since a significant fraction of sensor nodes can be expected to participate in relaying duties. However, when path-mergings occur, the flooding-based dissemination incurs costs that outweigh the benefits. To alleviate the drawbacks of flooding-based dissemination, in this section we present a light-weight, non-flooding protocol for the maintenance of electrostatic multipole fields. The detailed protocol behavior and interplay of sink and source nodes in our *Discrepancy-Adaptive Multipole Routing Protocol* (DA-MPR) is shown in Algorithms 2 and 3. In the sequel, we explain the main phases of each algorithm.

• *Source Node Joining:* Upon query injection, the sink node assigns an electric charge q to the specified source node[2]. The sink keeps track of all active sources (and their charges) in an appropriate data structure (cf. Alg. 2, lines 2-4), and unicasts: (i) the query and (ii) the knowledge about active sources, via a $QUERY$ message to the joining source node (cf. Alg. 2, l. 8-9). Upon reception of a $QUERY$ message, the joining source node resets its state, parses the user query, and starts the route discovery (cf. Alg. 3, lines 3-5).

• *Route Discovery:* A source selects outgoing angles for the specified number of routes, and creates and sends $RREQ$ messages (cf. Alg. 3, lines 6-10). The respective routes are set to pending until they get acknowledged by the sink node via an ACK message (cf. Alg. 3, lines 11-14). Upon reception of a $RREQ$ message, the sink replies to the respective source node by sending back an ACK message (cf. Alg. 2, lines 11-13).

• *Data Transmission:* As soon as a source has sucessfully discovered valid routing paths, it starts to send $DATA$ messages using those routes. Furthermore, the source node adjusts the flow rates per route based on the electrostatic field (packets are sent proportionally to the strength of the field, as suggested in [17]) (cf. Alg. 3, lines 24-29). Upon reception of a $DATA$ message, the sink node extracts the message payload and returns it to the user application (cf. Alg. 2, lines 14-16).

• *Updating:* The sink node keeps active sources informed about joining sources via $UPDATE$ messages (cf.

[2]In analogy to Coulomb's Law, the electric charge assigned to a source is reciprocally proportional to the square of the relative distance between the sink and the source. The charge of the sink is the negated sum of the sources' charges.

Alg. 2, lines 5-7). Upon reception of an $UPDATE$ message, an active source updates its knowledge about other source nodes, sets its active routes to pending, and re-runs the route discovery due to possible changes in the routing behavior of intermediate nodes (cf. Alg. 3, lines 15-23). On reception of an ACK messages the respective pending routes get re-activated. We note that an update may incur an extra overhead of two additional packets ($RREQ$ and ACK) per route for each source.

Lastly, we note that the sink node transmits ACK, $QUERY$ and $UPDATE$ messages to the respective source nodes using a greedy geographic routing algorithm of choice. Source nodes transmit $RREQ$ and $DATA$ messages to the sink node using the routing algorithm proposed in Section 3.

5 Experimental Evaluation

The experiments were performed using our own simulator, SIDnet-SWANS [**?**, 13], which adapted and built upon the JiST-SWANS [1] simulator for sensor networks. The core objective of these experiments was to analyze the net effect of sustained routing over the lifetime of the network, taking in consideration the nodes death rate due to battery depletion as well as its direct consequence over the QoS. The experimental platform consisted of a cluster of 4 quad core Linux machines, on which the experiments ran in a continuous batch.

We tested the benefits of our proposed methodology on a simulated testbed of 750 homogeneous nodes having the following configuration: (i) 20,000 bps transmission/reception rate on the MAC802.15.4 protocol, (ii) 5 seconds time-to-sleep interval, and (iii) power consumption characteristics based on the Mica2 Motes specs [2]. To reduce the simulation time, while preserving the validity of the observations, a small fully-charged battery with an initial capacity of 35 mAh powered each node, for a projected lifespan of several tens of hours under moderate load.

We compared our proposed DA-MPR against the EFR approach [27] by varying several parameters. Firstly, we considered three different distributions of the nodes' locations (cf. Figure 2), for which the respective discrepancies' values were 0.01, 0.02, and 0.04, obtained using an implementation of the algorithm[3] in [14]. In addition, the parameter space included: (1) – *density*, in terms of the average number of 1-hop neighbors, with values 8, 12, and 24, obtained by varying the dimensions of the sensing field. The choice of these values was based on approximating the number of neighbors to ensure the connectivity in a random graph (cf. [**?**, 20]). Although 24 may be too large for practical applications, we wanted to create settings most favorable for ERF. (2) – *paths diversity*, in terms of maximum allowable alternative source-sink paths (cf. Section 3): 15, 30 and 50 paths. Before we present the summarized version of the observations, we report on some individual runs:

Figure 6 and Figure 7 illustrate the impact of the two parameters that motivated this work on the different aspects of the network's evolution.

In the sequel, we present the average of the observation of 50 runs for each parameter-vector (a total of 450 simulations), where we varied the length of the *(sink,source)* distance between 10% and 80% of the diagonal of the rectangle bounding the network, and we used up to 4 sources for a given sink.

Load-Balancing: We first present the observations regarding the benefits that DA-MPR yields on the load balancing, in terms of the deviation of the residual energy among the nodes. The top part of Figure 8 shows the impact of node's density over the degree of (im)balance of the energy reserves, As shown, under sparse network conditions (i.e., 8 one-hop neighbors on average), the DA-MPR achieves a maximum of 68% improvement in single-source, and 59% improvement in multiple-sources settings. On the other hand, the bottom part of Figure 8 illustrates shows the impact of the discrepancy on the load balancing, under medium-density conditions. The main observation is that DA-MPR is far less sensitive to deviations of particular nodes distributions than EFR, due to un-merging of the routes.

Network Lifetime: As a consequence of the better balancing of the residual energy, DA-MPR ultimately yields benefits in terms of prolonging the networks lifetime. There are different definitions of the concept of a lifetime [8] in WSN and in our experiments we focused on the following three criteria: – the time until the very first node dies; – the time until 5% of the nodes die; – the time until 10% of the nodes die.

[3] Source code given in the Appendix.

Figure 9 presents a tabular summary of the averaged values of our experimental observations (due to a lack of space, we do not report more detailed results (cf. [31]) here). The columns labelled with "+%" present the benefits of the DA-MPR in terms of percentage increase of the network's lifetime, when compared to the EFR, the performance of which is consistently inferior. In all but extremely (unrealistically) dense network scenarios, in single-source settings the benefits of DA-MPR increase with the increase of the discrepancy of the nodes distribution. In multiple sources scenarios, this trend continues to hold in the sparse networks conditions, giving consistently better performances in the other cases. Recall that the reason for considering densities of 24 neighbors per node is to cater the fact that EFR performs best in (theoretically) infinitely dense networks, but degrades significantly in sparser ones. As demonstrated, DA-MPR improves in such trends, which is a key contribution of this work. The scenarios in which the discrepancy is high (0.04) and nodes densities are relatively small (i.e. 8 one-hop neighbors) are extremes, where most of the tested deployments exhibited disconnected topologies, hence we do not report for these settings.

The last set of experiments is summarized in Figure 10, which illustrates the importance of having a broader family of routes used in alternation. As it can be seen, both EFR and DA-MPR benefits from increasing the number of admissible paths, albeit EFR improves marginally beyond the 15 routes mark as the effective number of routes EFR actually uses, due to early path-merging effects, is much lower. However, in both single and multiple source scenarios, DA-MPR reaches a "plateau" at around 30 admissible paths, beyond which no additional lifetime gains are reported.

6 Related Work

The studies of load balancing in wireless sensor networks (WSN) have had different motivations. One of them is due to the observation that shortest path (and, in general, single-path) routing algorithms unevenly deplete the energy reserves. When source-sink pairs are selected at random, the center of the network handles most of the communication costs, and as a consequence, its energy is consumed at a faster rate [21,41]. The uneven utilization of energy resources reduces the lifetime of the network and causes holes, however, it has already been demonstrated that achieving a completely balanced energy depletion in WSN settings is, in general, impossible and approaches like q-switch routing were introduced, aiming at sub-balanced energy depletion [40].

Multipath routing has been identified as an option for load balancing, but not just any multipath technique would do. In [12], the authors show that in order to be effective, multipath routing should not select the K-shortest paths but rather select paths that spread the traffic across the network. Based on this insight, several important contributions have been proposed for single-sink single-source scenarios [4, 16, 25, 30, 36]. However, these techniques have a major limitation on single-sink multiple-source scenarios: simultaneous paths between the different sources intersect each other creating severe contention in the wireless medium, imposing overhead on the MAC layer.

In the context described above, the field-based routing has been identified as a paradigm for better load balancing in single-sink multiple-source scenarios. The expanding characteristic of the electric fields allow the spreading of paths across the network, and the attraction-repulsion characteristic of the electric charges determines mutually exclusive routing areas for each source. In [27], Nguyen et al. describe a distributed, stateless, multi-path electrostatic routing scheme (EFR). Their approach demonstrates scalability, robustness, higher delivery ratio and lower overheads when compared to LAR, DREAM, GPSR and AOMDV. However, Nguyen et al. are oblivious to the problem of network boundaries, that is, paths directed towards the borders of the network merge into a single path stressing the use of energy on these nodes.

To the best of our knowledge, the impact of the discrepancy of the nodes locations distribution in WSN on the load balancing in multipath settings has not been investigated. We demonstrated that the field-based multipath routing leaves a significant proportion of the nodes without participating in the communication costs, thereby increasing the level of uneven distribution of the energy. The main novelty of our work is that we presented a routing approach which, with a negligible overhead, can exhibit a level of spatial awareness that can significantly improve the balance of the networks energy-maps.

As for the boundary problem, a centralized solution was proposed by Kalantari *et al.* in [17]. However, the solution requires a-priori information about traffic demands and node positions. By solving a set of partial differential equations, the authors obtain multiple paths without trespassing the boundaries of the network. On a similar line of work, Toumpis and Tassiulas [35] show that the optimal placement of nodes between a set of sources and sinks resembles an electrostatic field. The authors show that their method can also be used to solve boundary problems. Contrary to the centralized solutions of these works, we propose a low-overhead distributed mechanism to cope with boundary effects.

The field of (geometric) discrepancy has been extensively studied, motivated by the potential benefits in various areas [6, 9]. An attempt to introduce concepts such as compression-discrepancy and sparseness discrepancy in WSN settings is presented in [42], however, the discussion offers only centralized approach, and no impact on any particular routing strategy is considered.

7 Concluding Remarks and Future Work

We addressed the problem of improving the balance of the energy-reserves in WSN in the settings of multipath routing which, as a consequence, also prolongs the network lifetime. In general, it can be expected that more paths would yield a better load-balancing, however, the popular approaches founded upon the field-based routing paradigm did not consider an important characteristic of the network – the discrepancy of the distribution of the nodes locations. We demonstrated that, in addition to the density (average number of available neighbors), this is an important factor to consider when designing multipath routing algorithms. Towards that end, we presented routing methodologies that adapt to the spatial distribution of the neighboring nodes. We also presented techniques for multipath routing in the presence of multiple sources transmitting towards a given sink, based on the method of images, which decreases the impact of the network boundary on the paths-merging effect. Our experiments demonstrated that the proposed approaches offer significant benefits when compared to the popular field-based one, such as EFR [27], both in terms of better balancing of the energy reserves, which is the main motivation for multipath routing, as well as increasing the lifetime of a given WSN.

We believe that our current results have barely scratched the surface of exploring the various benefits that the discrepancy theory can bring to the different research problems of interest to WSN. Specifically, our algorithms act in a local-best-effort manner to utilize the spatial distribution wherever possible, and we used the built-in features of the simulator [31] to obtain the values of the discrepancies in different deployment-distributions. Currently, we are working on developing energy-efficient distributed algorithms that a WSN can use to determine its own discrepancy, where the challenging question is how that information can be dynamically maintained (cf. [9]) at different levels of granularity. In this work, we assumed that the initial energy reserves were uniform across the nodes, however, an important problem is how to couple the evolution of the energy reserves with the nodes distribution and how/when to disseminate that information. A potential avenue to explore in this context is to develop abstractions similar to the multidimensional grid files from database research [38].

We also plan to investigate how some of the concepts presented in this work can be cast in other contexts in which field-based routing has been used e.g., optimal attraction regions for networks with multiple sinks [18]; timely and reliable delivery on convergecast applications [15]; routing in networks with mobile sinks [5,34,37].

Appendix

```
public class HeinrichDiscrepancy {
    /**
     * Calculates the discrepancy of a 2D point-set based on
     * the Heinrich method
     *
     * @param A - list of 2D points (x, y) \in [0, 1)
     *
     * @return - the computed discrepancy
```

```
     */
    public static double calculateDiscrepancy(List<NCS_Location2D> A) {
        int d = 2;         // dimension
        int m = A.size();

        double[] v = new double[m];

        for (int i = 0; i < m; i++) {
            v[i] = 1.0/m;
        }

        double disc = Math.pow(3, -d);

        double sum1 = 0;
        for (int i = 0; i < m ; i++) {
            sum1 += v[i] * (1 - Math.pow(A.get(i).getX(), 2))
                         * (1 - Math.pow(A.get(i).getY(), 2));
        }

        disc += - Math.pow(2, 1-d) * sum1;

        double sum2 = 0;
        for (int i = 0; i < m ; i++)
            for (int j = 0; j < m; j++) {
               sum2 += v[i] * v[j]
                            * ( 1 - Math.max(A.get(i).getX(), A.get(j).getX()))
                            * ( 1 - Math.max(A.get(i).getY(), A.get(j).getY()));
            }

        disc += sum2;

        return Math.sqrt(disc);
    }
}
```

References

[1] http://jist.ece.cornell.edu/index.html.

[2] http://www.xbow.com.

[3] K. Akkaya and M. Younis. A survey on routing protocols for wireless sensor networks. *Ad Hoc Networks*, 3(3), 2005.

[4] S.J. Baek and G. de Veciana. Spatial energy balancing through proactive multipath routing in wireless multihop networks. *IEEE/ACM Trans. Netw.*, 15(1):93–104, 2007.

[5] S.H. Chang, M. Merabti, and HM. Mokhtar. Coordinate Magnetic Routing for Mobile Sinks Wireless Sensor Networks. In *AINAW '07*, volume 1, 2007.

[6] B. Chazelle. *The Discrepancy Method: Randomness and Complexity*. 1998.

[7] J. Deogun, S. Das, H. Hamza, and S. Goddard. *An Algorithm for Boundary Discovery in Wireless Sensor Networks*, pages 343–352. 2005.

[8] I. Dietrich and F. Dressler. On the lifetime of wireless sensor networks. *TOSN*, 5(1), 2009.

[9] D.P. Dobkin, D. Eppstein, and D. P. Mitchell. Computing the discrepancy with applications to supersampling patterns. *ACM Trans. Graphics*, 15(4), 1996.

[10] L. Fang, W. Du, and P. Ning. A beacon-less location discovery scheme for wireless sensor networks. In *INFOCOM*, pages 161–171, 2005.

[11] Y. Ganjali and A. Keshavarzian. Load balancing in ad hoc networks: Single-path routing vs. multi-path routing. In *INFOCOM*, 2004.

[12] Y. Ganjali and A. Keshavarzian. Load balancing in ad hoc networks: single-path routing vs. multi-path routing. In *INFOCOM 2004*, volume 2, 2004.

[13] O. Ghica, G. Trajcevski, P. Scheuermann, Z. Bischoff, and N. Valtchanov. Sidnet-swans: A simulator and integrated development platform for sensor networks applications. *SenSys*, 2008.

[14] S. Heinrich. Efficient algorithms for computing l_2 discrepancy. *Mathematics of Computation*, 65(216), 1996.

[15] Hsing-Jung Huang, Ting-Hao Chang, Shu-Yu Hu, and Polly Huang. Magnetic diffusion: disseminating mission-critical data for dynamic sensor networks. In *MSWiM '05*, pages 134–141, New York, NY, USA, 2005. ACM.

[16] N. Jain, D.K. Madathil, and D.P. Agrawal. Energy Aware Multi-path Routing for Uniform Resource Utilization in Sensor Networks. *LNCS*, pages 473–487, 2003.

[17] M. Kalantari and M. Shayman. Routing in wireless ad hoc networks by analogy to electrostatic theory. In *Communications, 2004 IEEE International Conference on*, volume 7, pages 4028–4033 Vol.7, 2004.

[18] M. Kalantari and M. Shayman. Design optimization of multi-sink sensor networks by analogy to electrostatic theory. In *WCNC 2006. IEEE*, volume 1, pages 431–438, 2006.

[19] B. Karp and H.T. Kung. Gpsr: greedy perimeter stateless routing for wireless networks. In *MobiCom '00*, pages 243–254, New York, NY, USA, 2000. ACM Press.

[20] B. Krishnamachari, S. B. Wicker, and R. Bejar. Phase transition phenomena in wireless ad-hoc networks. In *In GLOBECOM*, 2001.

[21] S. Kwon and NB. Shroff. Paradox of Shortest Path Routing for Large Multi-Hop Wireless Networks. In *INFOCOM 2007*, pages 1001–1009, 2007.

[22] W. Luo, W. Liu, and Y. Zhang. Performance optimizatin using multipath routing in mobile ad hoc and wireless sensor networks. *Combinatorial Optimization in Communication Networks*, 2, 2005.

[23] A. Manjhi, S. Nath, and P.B. Gibbons. Tributaries and deltas: Efficient and robust aggregation in sensor networks. In *ACM International Conference on Management of Data (ACM SIGMOD)*, 2005.

[24] J. Matousek. *Geometric Discrepancy: an Illustrated Guide*. 1999.

[25] A. Mei and J. Stefa. Routing in outer space: fair traffic load in multi-hop wireless networks. In *MobiHoc '08*, pages 23–32, New York, NY, USA, 2008. ACM.

[26] R. Nagpal, H.E. Shrobe, and J. Bachrach. Organizing a global coordinate system from local information on an ad hoc sensor network. In *IPSN*, pages 333–348, 2003.

[27] N. T. Nguyen, A. Wang, P. Reiher, and G. Kuenning. Electric-field-based routing: a reliable framework for routing in MANETs. *SIGMOBILE Mob. Comput. Commun. Rev.*, 8(2):35–49, 2004.

[28] D. Niculesu and B. Nath. Trajectory based forwarding and its applications. In *MOBICOM*, 2003.

[29] G. Parissidis, V. Lenders, M. May, and B. Plattner. Multi-path routing protocols in wireless mobile and ad hoc networks: A quantitative comparison. In *NEW2AN*, 2006.

[30] L. Popa, A. Rostamizadeh, R. Karp, C. Papadimitriou, and I. Stoica. Balancing traffic load in wireless networks with curveball routing. In *MobiHoc '07*, pages 170–179, New York, NY, USA, 2007. ACM.

[31] Witheld Reference. Information Available to PC-Chairs.

[32] P. Shirley. Discrepancy as a quality measure for sample distributions. In *Eurographics*, 1991.

[33] V. Srinivasan, P. Nuggehalli, C.-F. Chiasserini, and R. R. Rao. Cooperation in wireless ad hoc networks. In *INFOCOM*, 2003.

[34] J. Tateson and I.W. Marshall. A Novel Mechanism for Routing in Highly Mobile Ad Hoc Sensor Networks. *LNCS*, pages 204–217, 2004.

[35] S. Toumpis and L. Tassiulas. Packetostatics: deployment of massively dense sensor networks as an electrostatics problem. In *INFOCOM 2005*, volume 4, pages 2290–2301 vol. 4, 2005.

[36] G. Trajcevski, O. Ghica, and P. Scheuermann. CAR: controlled adjustment of routes and sensor networks lifetime. In *MDM 2006*, page 23, 2006.

[37] Z. Vincze, K. Fodor, R. Vida, and A. Vidacs. Electrostatic Modelling of Multiple Mobile Sinks in Wireless Sensor Networks. In *PWSN '06*, 2006.

[38] K.-Y. Whang, S.W. Kim, and G. Wietherhold. Dynamic maintenance of data distribution for selectivity estimation. *VLDB*, 3(1), 1994.

[39] S. Wu and K. Selçuk Candan. Power-aware single- and multipath geographic routing in sensor networks. *Ad Hoc Networks*, 5(7):974–997, 2007.

[40] X. Wu, G. Chen, and S.K. Das. Avoiding energy holes in wireless sensor networks with nonuniform node distribution. *IEEE Trans. Parallel and Distributed Computing*, 19(5), 2008.

[41] J. Yang and D. Zhang. An energy balancing unequal clustering protocol for wireless sensor networks. *Information Techology*, 8(1), 2009.

[42] Z. Zhenjiang. Analysis of distribution uniformity of nodes in wireless sensor networks. *High Techology Letters*, 13(1), 2007.

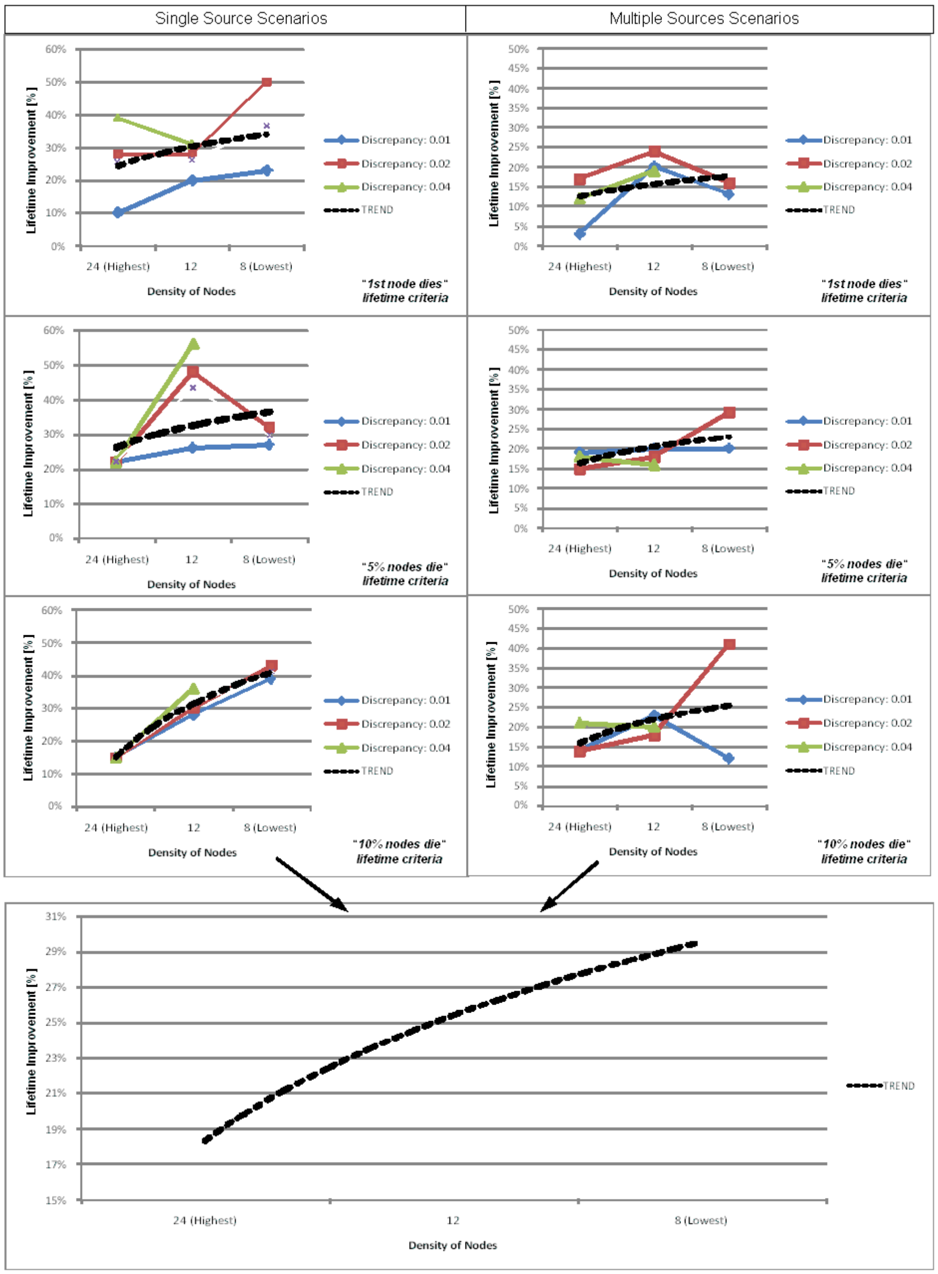


Figure 6: The impact of the density

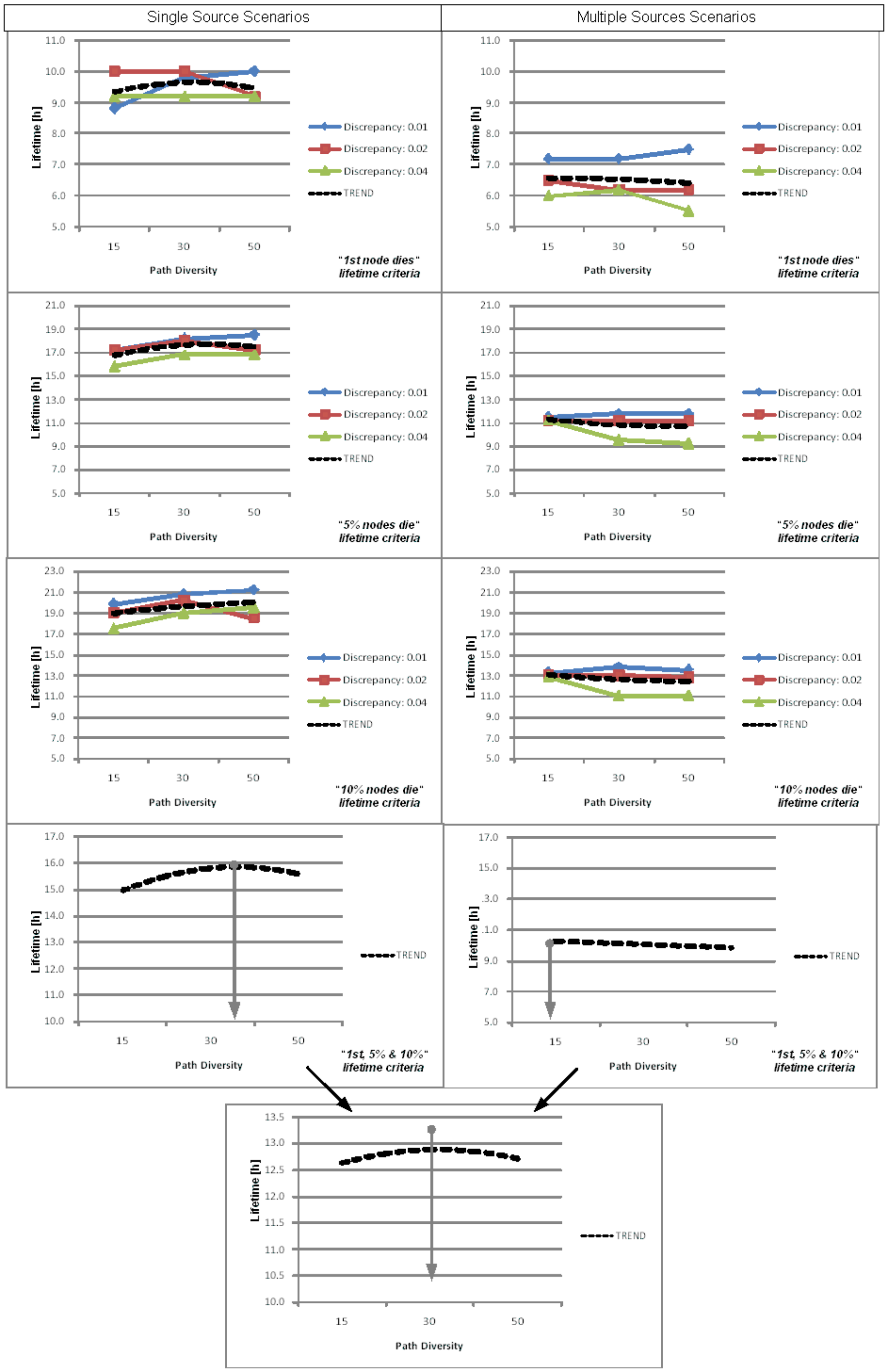


Figure 7: The impact of the path-diversity (discrepancy awareness)

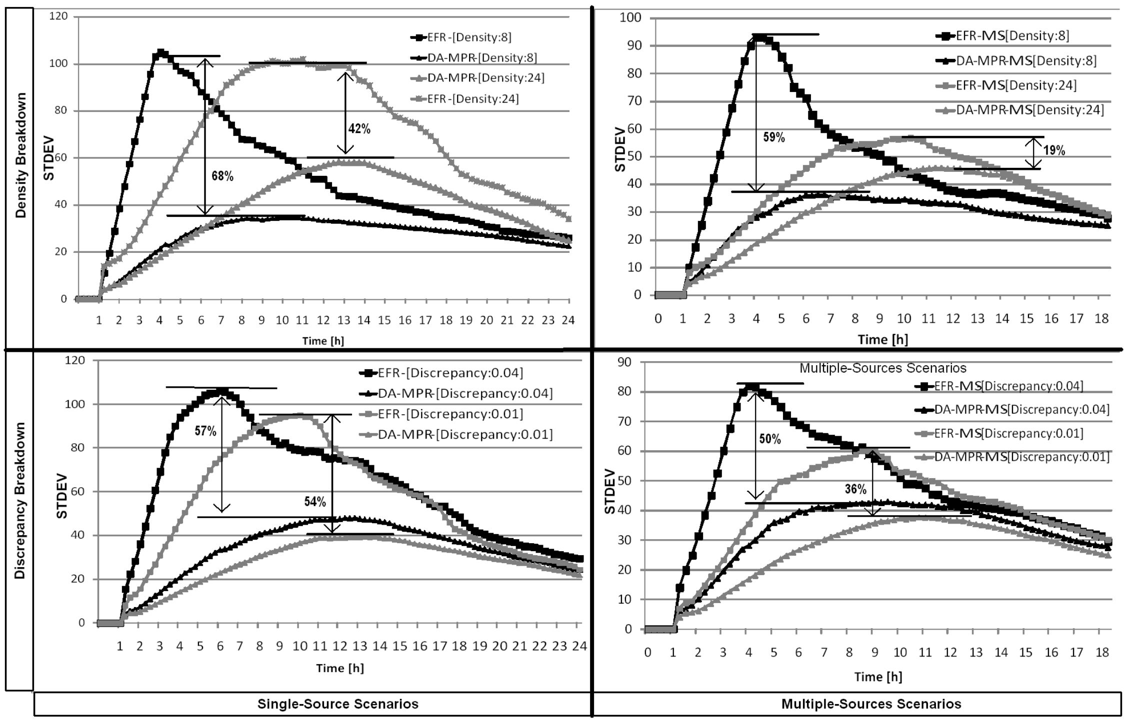


Figure 8: Load-balance: Density (top) and Discrepancy (bottom)

		Path Diversity	30								
		Nodes' density	24			12			8		
	Discrepancy	Lifetime Criteria	EFR	DA-MPR	+%	EFR	DA-MPR	+%	EFR	DA-MPR	+%
Single Source	**0.01**	1st	10.2	11.2	**10%**	8.2	9.8	**20%**	7.5	9.2	**23%**
		5%	16.2	19.8	**22%**	14.5	18.2	**26%**	12	15.2	**27%**
		10%	19.8	22.8	**15%**	16.2	20.8	**28%**	13.8	19.2	**39%**
	0.02	1st	9.5	12.2	**28%**	7.5	9.6	**28%**	4.8	7.2	**50%**
		5%	16.2	19.8	**22%**	12.2	18	**48%**	10	13.2	**32%**
		10%	19.8	22.8	**15%**	15.5	20.2	**30%**	12.2	17.5	**43%**
	0.04	1st	8.8	12.2	**39%**	7	9.2	**31%**	-	-	-
		5%	16.2	19.8	**22%**	10.8	16.8	**56%**	-	-	-
		10%	19.8	22.8	**15%**	14	19	**36%**	-	-	-
Multiple Sources	**0.01**	1st	7.8	8	**3%**	6	7.2	**20%**	5.5	6.2	**13%**
		5%	11.8	14	**19%**	9.8	11.8	**20%**	8.5	10.2	**20%**
		10%	14	16	**14%**	11.2	13.8	**23%**	10.5	11.8	**12%**
	0.02	1st	7	8.2	**17%**	5	6.2	**24%**	4.5	5.2	**16%**
		5%	12	13.8	**15%**	9.5	11.2	**18%**	7	9	**29%**
		10%	14	16	**14%**	11	13	**18%**	7.8	11	**41%**
	0.04	1st	5.8	6.5	**12%**	5.2	6.2	**19%**	-	-	-
		5%	11	13	**18%**	8.2	9.5	**16%**	-	-	-
		10%	12.8	15.5	**21%**	9.2	11	**20%**	-	-	-

Figure 9: Impact of Density

		Nodes' density	12								
		Path Diversity	**15**			**30**			**50**		
	Discrepancy	Lifetime Criteria	EFR	DA-MPR	+%	EFR	DA-MPR	+%	EFR	DA-MPR	+%
Single Source	**0.01**	1st	7.8	8.8	**13%**	8.2	9.8	**20%**	7.8	10	**28%**
		5%	14	17.2	**23%**	14.5	18.2	**26%**	13.2	18.5	**40%**
		10%	16.2	19.8	**22%**	16.2	20.8	**28%**	16.2	21.2	**31%**
	0.02	1st	7.5	10	**33%**	7.5	10	**33%**	7.5	9.2	**23%**
		5%	13	17.2	**32%**	12.2	18	**48%**	11.8	17.2	**46%**
		10%	15.8	19	**20%**	15.5	20.2	**30%**	15	18.5	**23%**
	0.04	1st	6.8	9.2	**35%**	7	9.2	**31%**	7	9.2	**31%**
		5%	10.8	15.8	**46%**	10.8	16.8	**56%**	11	16.8	**53%**
		10%	14.2	17.5	**23%**	14	19	**36%**	14.2	19.5	**37%**
Multiple Sources	**0.01**	1st	6.5	7.2	**11%**	6	7.2	**20%**	6.8	7.5	**10%**
		5%	9.8	11.5	**17%**	9.8	11.8	**20%**	9.2	11.8	**28%**
		10%	11.2	13.2	**18%**	11.2	13.8	**23%**	11.2	13.5	**21%**
	0.02	1st	5.8	6.5	**12%**	5	6.2	**24%**	5.8	6.2	**7%**
		5%	10	11.2	**12%**	9.5	11.2	**18%**	9.8	11.2	**14%**
		10%	11.2	13	**16%**	11	13	**18%**	11.2	12.8	**14%**
	0.04	1st	5	6	**20%**	5.2	6.2	**19%**	5	5.5	**10%**
		5%	8.2	11.2	**37%**	8.2	9.5	**16%**	8.2	9.2	**12%**
		10%	9.2	12.8	**39%**	9.2	11	**20%**	9.2	11	**20%**

Figure 10: Impact of Number of Paths