

# Work-in-Progress: Efficient Heuristics for Low Radiation Paths in Wireless Sensor Networks\*

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**Abstract**—We call radiation at a point of a wireless network the total amount of electromagnetic quantity (energy or power density) the point is exposed to. The impact of radiation can be high and we believe it is worth studying and control; towards radiation aware wireless networking we take (for the first time in the study of this aspect) a distributed computing, algorithmic approach.

We exemplify this line of research by focusing on sensor networks, studying the minimum radiation path problem of finding the lowest radiation trajectory of a person moving from a source to a destination point in the network region. For this problem, we sketch the main ideas behind a linear program that can provide a tight approximation of the optimal solution, and then we discuss three heuristics that can lead to low radiation paths. We also plan to investigate the impact of diverse node mobility to the heuristics' performance.

## I. INTRODUCTION

Imagine a person moving in a smart building with abundant heterogeneous wireless networking (such as WiFi, Blue-tooth, ZigBee and Cellular), carrying wearable, on-body or even implanted wireless devices (such as smart phones, medical equipment and tiny smart sensors). We call “radiation” at a target elementary surface the total amount of electromagnetic quantity (in terms of energy or power density) it is exposed to. The additive/correlated impact of electromagnetic radiation not only to the human itself but also to any carried sensitive nano-scale devices and vital equipment can be important; even if this impact can be considered controversial we believe it is worth studying and control.

In particular, we note that almost all wireless devices operate in frequencies of the non-ionizing spectrum for the transmission and reception of their signals. The impact of non-ionizing frequencies on humans is distinguished in thermal and non-thermal effects. It is true that safety levels for humans have been based on thermal effects of electromagnetic radiation. Yet, many scientists worry for non-thermal effects, since they can occur far below the established safety levels of radiation. In that field, mechanisms are still being investigated and there is not yet a well accepted link between some of the aforementioned effects and the radiation levels or radiation form. Several recent epidemiological studies in different areas as well as multidisciplinary experiments suggest that the radiation

aspect is important and worth further studying (for a partial list, see e.g. [1], [2], [3]).

What also troubles scientists is that, while it is not clear how non-thermal effects occur, the radiation environment around human is being continuously enriched. This is enhanced by the fact that lately novel on-body or implanted wireless sensors and remotely controlled in-body medical devices are being introduced. Even if they operate at very low levels, nobody can really answer yet if there is an additive effect or what is the highest number of nodes/sensors a human can carry or what is the total “low level” electromagnetic power he/she can handle. While there are general standards that sensors need to satisfy, there are no measurements for radiation levels or any consideration on radiation levels when multiple sensors are being introduced. As has been explained above there is no causal link between the non-thermal effects and the radiating sources. Also, radiation can (potentially) influence nano-scale electronic devices. Because of all reasons above, even low levels of radiation are worth to investigate and control.

In this paper, we begin the investigation of the aspect of electromagnetic radiation in modern and future heterogeneous wireless networks. In our long term vision, the network will be able to spatially quantify radiation and human presence and accordingly self-configure to automatically and dynamically reduce radiation, while maintaining satisfactory operation and performance. We exemplify our approach by focusing on wireless sensor networks; we are aware of the fact that the radiation of tiny wireless sensors is not very high but start this line of research with this network type as a first proof of concept for a broader, heterogeneous wireless network setting. Our broader goal is to come up with radiation awareness in an adaptive, distributed manner, by providing design principles and studying key algorithmic and networking aspects of radiation aware wireless networking. In this work, we study the minimum radiation path problem of finding low radiation trajectories in a wireless sensor network. For this problem, we provide a linear program for the optimum, as well as efficient heuristics. We also plan to study the impact of mobility.

A different, interesting problem is assuming a very general radiation field and deploy a sensor network as a measurement and guidance tool. We also note that known adaptive power control methods address similar issues but our methods manage radiation explicitly.

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## II. BASIC DEFINITIONS AND PRELIMINARIES

*Radiation at a point.* Consider a sensor network where motes are deployed in a target area. Any point  $\vec{x}$  of the target area is exposed to a certain amount of electromagnetic quantity (in terms of energy or power density) that is generated by the motes. We call this quantity *radiation at point  $\vec{x}$*  and we assume it is given by the formula

$$R(\vec{x}) \stackrel{\text{def}}{=} \sum_{v \in V} \frac{r^2}{(1 + \text{dist}(\vec{x}, v))^2} \quad (1)$$

where  $V$  is the set of motes (or vertices) of the network,  $r$  is the wireless transmission range of the motes and  $\text{dist}(\vec{x}, v)$  is the Euclidean distance between point  $\vec{x}$  and mote  $v$ . In other words, the total radiation at a point is the sum of radiation created by all nodes “close” to the point. The above formula assumes that radiation is additive, it is proportional to the square of transmission range of the motes and inversely proportional to the square of the distance.

This radiation definition is currently the standard one among experts in electromagnetic radiation; still, a detailed, multi-disciplinary empirical study (including real measurements of the radiation field around a wireless node) could lead to a more accurate (and even quite different) radiation formula. We note however that the algorithms presented here are not restricted by this choice of function.

*Radiation of a path.* Let now  $\mathcal{P}$  be a continuous path in the target area (i.e. not necessarily a path on the nodes of the network). We define the *radiation that an entity moving along path  $\mathcal{P}$  receives* as  $R(\mathcal{P}) \stackrel{\text{def}}{=} \int_{\mathcal{P}} R(\vec{x}) d\vec{x}$ . Instead of computing this integral, we can approximate it by the following summation: Let  $\mathcal{P}_0, \dots, \mathcal{P}_m$  be a partition of  $\mathcal{P}$  into  $m$  parts of equal (small) length  $d = \frac{\|\mathcal{P}\|}{m}$ . Let also  $\vec{x}_i, 0 \leq i \leq m-1$  be the leftmost point of part  $\mathcal{P}_i$ . Then  $R(\mathcal{P}) \approx \sum_{i=0}^{m-1} R(\vec{x}_i)d$ . Since  $\lim_{m \rightarrow \infty} \sum_{i=0}^{m-1} R(\vec{x}_i)d = \int_{\mathcal{P}} R(\vec{x}) d\vec{x}$ , we will often use the approximation formula for the radiation of  $\mathcal{P}$  as a quite good approximation for the actual radiation of the path, provided  $d$  is small enough (i.e.  $m$  is large).

We are interested in finding exact or approximate algorithmic solutions to the following problem:

*Definition 1 (The Minimum Radiation Path Problem - MRP):* Given a Sensor Network  $G$  deployed in a target area  $\mathcal{A}$ , a starting point  $A$  and a target point  $B$ , find a path  $\mathcal{P}$  in  $\mathcal{A}$  that starts from  $A$ , ends at  $B$  and minimizes  $R(\mathcal{P})$ .

We stress the fact that the path  $\mathcal{P}$  does not necessarily include the nodes of the network. As a matter of fact, since radiation near those points is high, one should try to avoid them when moving from a point  $A$  to  $B$ . We also note that the experimental shows that, further to the total path radiation, our heuristics avoid high radiation levels throughout the path (i.e., not only the aggregate radiation is low but also the radiation at all individual path intervals).

## III. APPROXIMATING THE OFFLINE OPTIMUM SOLUTION TO MRP

Without loss of generality, assume that the target area  $\mathcal{A}$  is a square. We tessellate  $\mathcal{A}$  in  $n^2$  equal squares that are

characterized by their relative position in the tessellation, with square in position  $(1, 1)$  being the top left one. Furthermore, each square is represented by its center.

We now construct the following directed graph  $G_{n,\mathcal{A}} = (V_{n,\mathcal{A}}, E_{n,\mathcal{A}})$  as follows: The vertex set of  $G_{n,\mathcal{A}}$  is the set of all square center points  $v_{i,j}$ , namely  $V_{n,\mathcal{A}} = \{v_{i,j} : v_{i,j} \text{ is the central point of the square in position } (i, j), 1 \leq i, j \leq n, \text{ of the tessellation}\}$ .

The edge set of  $G_{n,\mathcal{A}}$  contains all arcs from any point  $v_{i,j}$  to the center points of its neighboring squares (we say that a square is a neighbor to another if they have an edge in common), namely  $E_{n,\mathcal{A}} = \{(v_{i,j}, v_{i',j'}) : (i' = i \text{ AND } j' = j \pm 1) \text{ OR } (i' = i \pm 1 \text{ AND } j' = j), \text{ for } 1 \leq i, i', j, j' \leq n\}$ .

If we assume that any path between the starting point  $A$  and the target point  $B$  is composed by intervals between the points in the center of the squares of the tessellation. By making the tessellation finer, we can get better approximations of the actual path. Therefore, the problem of finding an optimal path between points  $A$  and  $B$  is reduced to the problem of finding a minimum weight path between vertices  $A$  and  $B$  in  $G_{n,\mathcal{A}}$ , assuming that the weight each edge  $e = (e_1, e_2)$  is equal to the  $w(e) = d \cdot R(e_1)$ , where  $d$  is the length of the side of the squares in the tessellation.

In view of the above, a carefully designed linear program (or Dijkstra's Algorithm) can be used to find a desired shortest (weighted) path in  $O(|V_{n,\mathcal{A}}|^2) = O(n^4)$  running time.

## IV. HEURISTICS FOR MRP

In this section, we consider several approaches that can lead to low radiation paths for MRP. We stress out the fact that the algorithms presented are not restricted by our specific choice of function for  $R(\vec{x})$ , namely equation (1).

### A. Minimizing the total distance - Algorithm MinD

This is simply the path defined by the straight line connecting  $A$  and  $B$  and its radiation can be very high. It is only intended for comparison purposes. However, this naive approach could provide good solutions to MRP if the mobility of the nodes in the network is high, since any prediction of radiation levels will be outdated even after a short period of time.

### B. Minimizing the next step radiation - Algorithm MinR

We assume that the entity moving has knowledge of the target location  $B$ . Furthermore, given that we are at some point  $\vec{x}$ , we assume that the moving entity can compute the radiation at any point located inside  $D(\vec{x}, r)$  (which is possible if all the sensors in the larger disc  $D(\vec{x}, 2r)$  can be heard from it).

At any point  $\vec{x}$  during its movement, the entity performs the following step: Let  $S(\vec{x}, r, \phi)$  be the area of all points  $\vec{x}'$  that satisfy  $\|\vec{x} - \vec{x}'\| \leq r$  and  $\widehat{B\vec{x}\vec{x}'} \leq \frac{\phi}{2}$  (the angle  $\phi$  can be e.g.  $180^\circ$ ).

- 1) If  $B \in D(\vec{x}, r)$ , then move in a straight line to  $B$ .
- 2) Otherwise, choose uniformly at random  $k$  points inside  $S(\vec{x}, r, \phi)$  and move in a straight line to the one that has the lowest radiation ( $k$  can be e.g. 3).

The weakness of this approach seems to be that it does not take into account the total distance traveled by the entity and so the resulting path can be quite long. However, this can be reduced by choosing carefully the angle  $\phi$ .

### C. Improving the radiation/progress to destination trade-off - Algorithm MinDR

In order to overcome the disadvantage of MinR, we present the heuristic MinDR, which takes into account the distance from the target. We make the same assumptions (on knowledge of  $B$  and on the ability to calculate the radiation of points in distance  $r$ ) as for the MinR heuristic.

At any point  $\vec{x}$  during its movement, the entity performs the following step:

- 1) If  $B \in D(\vec{x}, r)$ , then move in a straight line to  $B$ .
- 2) Otherwise, choose uniformly at random  $k$  points inside  $D(\vec{x}, r)$  and move in a straight line to the point  $\vec{x}' = \arg \min_{\vec{y}} R(\vec{y}) \|\vec{y} - B\|$ .

Notice that this approach takes into account the total distance traveled by the entity, by assuming that once it goes to the new point  $\vec{x}'$ , the radiation levels encountered from that point on will more or less be similar to  $R(\vec{x}')$ . Notice also that when choosing the candidate points, it does not exclude points that tend to increase the distance from its target. As a matter of fact, it might even select one of these points if its radiation level is sufficiently low.

### D. A dichotomy algorithm - Algorithm MinDRD

This algorithm is in fact a composition of algorithms MinD and MinDR, since given that we are at some point  $\vec{x}$ , the algorithm considers both moves that MinD and MinDR propose and finally makes a move that is a combination of those moves according to a parameter  $\tau$  that describes its trust in them. Initially, we set  $\tau = 1$ . At every time step  $t$ , the algorithm does the following:

- 1) Let  $\vec{x}_{DR}$  be the point that is suggested by MinDR, let  $d = \|\vec{x}_{DR} - \vec{x}\|$ , and let  $\vec{x}_D$  be the point proposed by MinD (i.e. in the direction of the vector  $B - \vec{x}$ ) in euclidean distance  $d$  from  $\vec{x}$ .
- 2) The algorithm computes  $\vec{x}' = \vec{x} + \frac{d(\tau(\vec{x}_{DR} - \vec{x}) + (1 - \tau)(\vec{x}_D - \vec{x}))}{\|\tau(\vec{x}_{DR} - \vec{x}) + (1 - \tau)(\vec{x}_D - \vec{x})\|}$  as the next point. Notice that this is exactly the point in the circle of center  $\vec{x}$  and radius  $d$ , in the direction of the vector  $\tau(\vec{x}_{DR} - \vec{x}) + (1 - \tau)(\vec{x}_D - \vec{x})$ , which is the weighted sum of the suggestions of algorithms MinDR and MinD.
- 3) Finally the algorithm updates the parameter of trust to MinDR by

$$\tau' = \alpha\tau + (1 - \alpha) \min \left\{ 1, \frac{dR(\vec{x})}{\frac{d + \text{dist}(\vec{x}', B)}{d + \text{dist}(\vec{x}, B)} R(\vec{x}')} \right\}$$

where  $\alpha$  is a fixed parameter of the algorithm that we call *momentum*. Notice that  $dR(\vec{x})$  is the amount of radiation that MinDR expects to have left behind after moving for length  $d$  away from  $\vec{x}$ . Similarly,

$\frac{d}{d + \text{dist}(\vec{x}', B)} (dR(\vec{x}) + \text{dist}(\vec{x}', B) R(\vec{x}'))$  is the amount of radiation that MinDR expects to have left behind after moving for length  $d$  (i.e. after moving to  $\vec{x}'$ ) in the path  $\vec{x} \rightarrow \vec{x}' \rightarrow B$ .

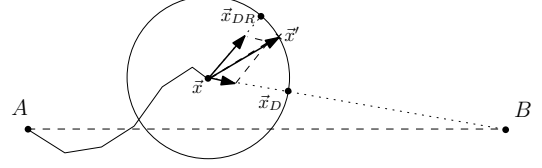


Fig. 1. A dichotomy between MinDR and MinD.

The main idea behind MinDRD is that at any point, it proposes a move according to its level of trust to the MinDR heuristic (i.e. the “belief” that once it goes to a new point  $\vec{x}'$ , the radiation levels encountered from that point on will more or less be similar to  $R(\vec{x}')$ ). More specifically, a “good” move, which verifies that the assumption of MinDR is correct, results in strengthening the trust (measured by the parameter  $\tau$ ) to MinDR. On the other hand, a “bad” move (i.e. a move that increases the cumulative radiation more than MinDR expects) weakens this trust.

### V. CONCLUSION AND FUTURE WORK

We begin to investigate radiation aware wireless networking, for the first time in the relevant research from an algorithmic perspective. We start this line of research by exemplifying in sensor networks and first define radiation at a point of a wireless sensor network region, as the total amount of electromagnetic quantity (energy or power density) the point is exposed to. We then introduce the minimum radiation path problem, i.e. finding the lowest radiation trajectory for a person moving from a source to a destination point in the network region. For this natural problem, we then present three on-line heuristics. Besides experimentally evaluating these heuristics, we intend to extend them in order to take into account diverse mobility patterns of the nodes in the network.

Other future research goals include effectively incorporating the radiation aspect in fundamental networking problems, like in data propagation, as well as suggesting on-line methods for network self-configuration, in a context-aware manner, to minimize radiation while still preserving good performance. A (multidisciplinary) experimental study with real devices could lead to a more accurate radiation definition and radiation map around a wireless device. Also, to investigate the radiation aspects in broader, heterogeneous wireless network settings.

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