A new model for deployment coverage and connectivity of Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSN) is an emerging technology to instrument the environment and collect detailed data for a better understanding and improved models to monitor or control an observed phenomenon. Coverage of the phenomenon area with a given number of WSN nodes is an important topic in deployments, e.g., collecting scientific monitoring data on a glacier [1]. Unreliable communication over the wireless channel complicates communication protocols and results in low data yield [2]. While finding an optimal placement for the deployment of nodes is a crucial task, it is a complex problem due to several independent objectives and constraints for sensing coverage, connectivity and cost. This paper presents novel models for the deployment of a WSN and proposes constraints and objectives to formulate the optimization problem.**

I. Introduction

Monitoring a phenomenon requires coverage for a given environment to allow for accurate analysis and modeling with the extracted information. However, accurate sensors and current wireless sensor nodes are expensive equipment and cannot be deployed extensively. Extracting data from an instrumented environment on distributed nodes requires collection of the data to gathering points. Comprehensive evaluation and analysis is performed outside the wireless sensor network. Due to the remote location and limited storage space on the distributed nodes, data has to be periodically sent to one or more sink nodes, which may forward the data to a secondary network (e.g. TCP/IP) via a gateway. Data collection requires the protocol stack to establish routes, where the data packets from nodes, which cannot directly communicate with a sink, are forwarded by intermediate nodes along a routing tree. This multi-hop routing needs to provide reliable data transport in order to allow for an acceptable data yield, defined by the ratio of arrived packets at the sink(s) to sent packets from all monitoring nodes. The routing tree is based on neighborhood information of individual nodes, relying on quality metrics of the communication channel in between these neighbor nodes. Hence, the quality of a routing path is dependent on the quality of individual node-to-node channels and the length of the overall paths.

The placement of nodes for a WSN deployment in a target environment, while considering multiple constraints and objectives is an NP-hard problem [11]. This results in complex trade-offs for cost and connectivity. To the best of our knowledge, there has been no previous work addressing this crucial problem in combination with realistic models for the unreliable wireless communication.

This technical report provides:

- a new model for a WSN deployment including realistic representation of the communication,
- a novel radio model by integrating the concept of transitional regions and radio irregularity,
- a detailed representation of sensing and WSN costs of a deployment,
- objectives and constraints for exploration of optimal WSN deployments based on the aforementioned models,

The technical report is structured as follows. Section II presents related work concerning deployment for coverage and connectivity of wireless sensor networks and previously proposed radio models. Section III discusses the model to represent an actual deployment of a wireless sensor network in a given environment. Section IV shows the objectives and constraints concerning the quality of a given WSN deployment. Section V summarizes the technical report.

II. Related Work

A. Coverage and connectivity in WSN deployments

A comprehensive overview of coverage and deployment and related work is presented by Karl et *a*l. in [12]. Relevant related work for this report is presented in the following.

Dhillon et *a*l. present in [6] an algorithm to improve the deployment coverage. They present case studies which display improved coverage by comparing to a random deployment. They focus on cases were the coverage threshold is high. [4] describes a unified approach for analyzing sensor coverage by using a generalization of Voronoi diagrams. They provide algorithms to determine coverage quality with worst case runtime estimations for different sensor models and coverage criteria in 2-D or 3-D. Both papers do not consider deployment connectivity and the according trade-offs.

In [5] Wang et *a*l. present the integration of communication and sensing coverage. However their communication is limited to a simplistic homogeneous euclidean distance model. Their work focuses on a given dense deployment, where the communication protocol may send nodes to sleep, while maintaining a sufficient coverage quality of the region.

In [8], the authors prove the asymptotic optimality of a stripe-based deployment pattern for different ratios of sensing range to communication range. They extend the ideas of [9] and [10] by proving the optimality over a broad range of sensing to communication range ratios. They also compare typically used deployment patterns and determine the optimal one in terms of required nodes to achieve coverage and connectivity. However, their sensing and communication models are limited to regular disks. [5] and [8] are based on assumptions, which have been addressed in the work of Kotz et *a*l.. The authors describe in [17] shortcomings of such models of a node and its environment, which is overly simplistic. None of the work considers reliability of communication considering redundant routing paths and the complex trade-off concerning deployment costs.

[11] presents a polynomial-time, data-driven algorithm using non-parametric probabilistic models called Gaussian Processes for coverage and communication. The Gaussian Processes are based on actual data from an initial deployment site. This is used to predict sensing quality and communication cost. The authors perceive coverage not in terms of a complete covering of the phenomenon space, but a covering of informative places, which takes into account correlation between sensor data.

B. Radio model

In [13], Zuniga et *a*l.present an analysis of packet reception rates in low-power wireless links. In particular, the authors present an analysis of asymmetry in wireless links, which has a higher probability when there is a positive correlation between output power and noise floor of the radio. The authors also present a model for the different regions in wireless communication, namely the connected region, where connectivity is almost perfect, the transitional or gray region, where reception is very dynamic and the disconnected region where communication is not possible. While the expected packet reception rate decreases with distance, a significant variance in the transitional region requires a stochastic perception of the term connected by defining probability thresholds for low/high probability of low/high packet reception rates [1]. They present the transitional region coefficient, which is the coefficient of the transitional to the connected region. The transitional region coefficient is independent of noise floor and output power. Their models are used in current WSN communication characterizations [14].

In [15], statistical models for the relation between location (distance) and communication (reception rate) are presented. The authors discuss three resulting models and compare them to the simple unit disk graph (UDG) approach. The data depicts the considerable differences from stochastic models like the probabilistic graph to a UDG approach.

[16] presents the Radio Irregularity Model (RIM) to account for radio irregularities in WSN. This is mainly due to anisotropic path losses caused by the non-uniformity of the environment, and heterogeneous sending powers, mainly due to device differences caused by manufacturing variations. They present the effect of this model on protocol layers, such as MAC, routing, localization and topology control. They introduce three different parameters: The degree of irregularity (DOI) models the anisotropy by describing the maximum path loss percentage variation per unit degree change in the direction of propagation and the according variation with incremental changes. The Variance of Sending Power (VSP) and the Variance of DOI values (VDOI) account for the heterogeneity of nodes.

[17] describes some common misconceptions about wireless networks: The technical report presents axioms, which are typically used in theoretical sensor network papers. While these are assumptions facilitating the wireless sensor node model, they are not sufficiently accurate to describe real depoyments. In particular, they mention unit disc graphs, isotropic media and symmetric communication used in previous work concerning deployment coverage and connectivity.

Combining realistic, detailed radio models for nodes with multi-objective optimization and exploring the complex trade-offs, has not been addressed in previous work. The following chapters describe our approach in closing this gap.

III. Deployment Model

In order to model the deployment of a wireless sensor node, its sensing coverage has to be determined, i.e., the ability of the sensors in the instrumented environment to capture an accurate and detailed representation of the observed phenomena. The connectivity, i.e., the quality of communication channels in between individual nodes is vital to allow for sensor data retrieval. Additionally, the cost associated with a given deployment has to be considered.

In the following subsections, we present a deployment model, which includes a representation of the individual nodes of the WSN and the environment, which is instrumented with sensor nodes.

A. Node Model

In this work, a WSN of homogeneous wireless sensor nodes is assumed, as found in most WSN installations. Although some WSN architectures rely on a tiered network, there is still homogeneity in the tiers. We leave the modeling of tiered networks as future work. Homogeneity only refers to the same type of node device running the same software. Differences, e.g., due to manufacturing variations are included in our model. As an example, the radio model includes considerations for variations in the radio hardware.

The model of a node includes a description of its position, a description of its radio characteristics, i.e., its radio model, the sensing model of attached sensor and the cost of the node including the cost for its attached sensors. Nodes may have different sensors attached. Nodes without sensor, so called relay nodes, are not used for instrumentation, but only for data transport.

[1]The disconnected region typically has a packet reception rate threshold (PRR) larger than 0, since links with low PRR incur too much communication losses to be of any practical use.

The radio model is derived from the work of Zuniga et *a*l.[13] and the work of Zhou et *a*l.[16] as presented above.

For each node $k \in \{1, \dots, n\}$, the following is included in the model:

- its position as 2-dimensional coordinates (x_k, y_k),
- A radio model to describe transitional regions in wireless sensor node communication. The packet reception rate is computed in detail as a function of the distance d between the nodes as follows, cf. [18]. The signal to noise ratio (SNR) is defined as

$$\gamma(d) := P_t - PL(d_0) - 10\eta \log_{10}\left(\frac{d}{d_0}\right) + \mathcal{N}(0,\sigma) - P_n$$

. The packet reception rate (PRR) follows as:

$$PRR(d) := (1 - \frac{1}{2}e^{-\frac{\gamma(d)}{2}\cdot\frac{1}{0.64}})^{8f}$$

where $P_t, PL(d_0), d_0, \sigma, P_n, f$ are constants. η is dependent on the degree of irregularity (see below), which is a function of the angle. It follows that:

$$\eta = \eta(DOI) = \eta_0 \cdot K_i,$$

where K_i is the path loss coefficient in the direction of the transmission,

- a degree of irregularity (DOI), describing the anisotropy of radio communication due to the anisotropic medium and hardware variances, which is used to adjust the path loss η. DOI is defined as the maximum path loss percentage variation per unit degree change in the direction of the radio propagation. In [16] K_i ($i \in \mathbb{N}$) is defined as a coefficient to represent the difference in path loss in different directions [2]:

$$K_i := \begin{cases} 1, & \text{if } i = 0 \\ K_{i-1} \pm Rand * DOI, & \text{if } 0 < i < 360, \\ & \text{where} \\ & K_0 - K_{359} \leq DOI \end{cases}$$

For the use in our node model, the authors propose the following algorithm to determine DOI:

```
K[0:359] = (1,1,1,1,...)
  for i in 0 to 359 do:
   random = uniform(-1,1)
   K[(i+360-2) mod 360]+= 0.4*random*DOI
   K[(i+360-1) mod 360]+= 0.8*random*DOI
   K[(i+360  ) mod 360]+= 1.0*random*DOI
   K[(i+360+1) mod 360]+= 0.8*random*DOI
   K[(i+360+2) mod 360]+= 0.4*random*DOI
```

where uniform(a,b) is a function that returns a random number from a uniform distribution in the interval $[a, b]$.

- a elliptic sensing region per sensor type, defined by the sensing radius r_{sense},
- a covariance matrix C_{cutoff} defining the shape of the sensing area.

[2]Although not mentioned in the original paper, there needs to be the requirement, that $K_i \leq 0$. This is not reflected in the pseudo-code of the algorithm below.

Table I
MODEL PARAMETERS

Variable	Value
P_t	-7 dBm
$PL(d_0)$	-55 dBm
η	4.7
σ	4.6
f	50
P_n	-105 dBm
d_0	1m
DOI	0.02

- cost of a given deployment. The basic approach is to associate cost with each wireless sensor node. Additionally, cost may be different for nodes, as some nodes do not sense. Sensor nodes may be equipped with different sensors. Therefore, nodes can be modeled as the sum of the node cost plus the cost of the attached sensors. The granularity of the cost model depends on the importance of cost and the cost of the sensing devices.

Table I presents the parameters for our model as taken from the work in [18] and [16][3].

B. Environment Model

The environment model represents the area A in which a certain phenomenon is to be observed. Each deployment features one or more sinks, which are the roots of a routing tree. A sinks s_l, with $l \in \{1, \dots, m\}$ is represented by its position as 2-dimensional coordinates (x_{s_l}, y_{s_l}).

Additionally, a weight function $sc(\mathbf{x}) : A \to \mathbb{N}_0$ models preferences in node placement for particular areas. A scientist emphasizes her interest in a specific point by a larger weight function value $sc(\mathbf{x_k})$. This means that at least $sc(\mathbf{x_k})$ should be placed within the sensing region of point $\mathbf{x_k}$.

To this end, the environment model features:

- the position of one or more sinks s with their corresponding 2-dimensional position (x_{s_k}, y_{s_k}),
- a discretized representation of the considered area by single points $P_{env} \in G$ on a grid $G \subseteq A$,
- a function for a given sensor type $sc(P_{env}) : G \to \mathbb{N}_0$, denominating how many sensors have to cover each grid point P_{env}.

IV. OPTIMIZATION

Based on the described deployment model, an optimization problem may be formulated based on constraints and objectives for a given deployment. This section describes a possible formulation with three objectives based on the deployment model presented in Section III.

A. Constraints

Deployments, which do not satisfy the following constraint are regarded as infeasible: Each grid point P_{env} has to be covered by a certain number $sc(P_{env})$ of sensors of a given type.

[3]In [16], DOI values for long antenna MICA2 and MICAZ nodes range between 0.015 and 0.03.

This is a minimal set of constraints, which may need to be extended. WSN installations only allowing for the use of a specific number of a particular sensing device need to add additional constraints. A non-partitioned network may also be formulated as a constraint. The authors rather opted for adding this as part of an objective function by considering the worst path in a given network (cf. IV-B3).

B. Optimization Criteria

WSN deployments need to guarantee sensor coverage and the possibility to extract the data from the network for remote analysis. Such a deployment may be very different in terms of cost and the reliability of the communication of nodes in the network. Both aspects need to be formalized as objectives.

1) Sensor Cost (f_1): One focus is to minimize the cost of placing additional nodes. The authors opted for associating an equal node cost with each sensor node. A further distinction to consider differently equipped sensor nodes, e.g., relay nodes, which do not sense at all, remains as future work.

2) Connection Reliability (f_2, f_3): A vital criterion is the reliability of the N_{red} most reliable paths between a node i and a sink s. We refer to a single sink for the following discussion, however an extension to a multi-sink network is straight-forward.

Using the node model and the environmental model as described above, a directed, weighted graph representation of the deployment is constructed: To this end, each wireless sensor node corresponds to a vertex and the edges indicate a direct communication path between nodes. In particular, the edge weights reflect the packet reception rate at the destination node. Edges are directed to account for the asymmetry in wireless communication as included in the radio model.

For each node i, we determine the most reliable path to the sink s and compute its corresponding reliability $p_{i,1}$. This is determined for all nodes by Dijkstra's algorithm using the sink as the source. Not that the current work is for single sink networks, the extension to multi-sink networks is left as future work After computing the most reliable path, we determine the most reliable redundant path, by deleting all relaying nodes from the network for each individual node. Assume, we consider a node in a 10 node network with nodes $N = (n_1, n_2, ...n_{10})$ and a sink. The most reliable path for node n_{10} may be to n_8, which relays to n_5, which relays to the sink. Now redundant paths are computed. We construct a new graph without the relaying nodes n_8 and n_5. Deleting these nodes from the graph represents a node failure, e.g., due to drained batteries. We compute the most reliable path for the reduced graph (containing 8 nodes) as before. In the following, the term redundancy level is used to describe the redundant paths from individual nodes. Thus redundant paths form all nodes, which are computed as discussed above, i.e., after the deleting the nodes of the initial path, have redundancy level 1.

We iteratively determine redundant paths accordingly. This has to be computed for each node individually. This procedure yields corresponding path reliabilities $p_{i,j}, j \in \{2, \ldots, N_{red}\}$ until N_{red} paths are found or a path no longer exists (if less than N_{red} are found, all missing paths are assigned a probability of zero).

3) Definitions: The following objective functions present a formal description of the optimization criteria.

$$
\begin{aligned}
f_1 &= n \\
f_2 &= \frac{1}{W} \cdot \frac{1}{n} \sum_{j=1}^{N_{red}} w_j \sum_{i=0}^{n} (p_{best,j} - p_{i,j}) \\
f_3 &= \frac{1}{W} \cdot \sum_{j=1}^{N_{red}} w_j \cdot (1 - p_{worst,j}) \\
\textit{with } w_j &\in [0, 1] \\
\textit{with } W &= \sum_{j=1}^{N_{red}} w_j \\
f_2, f_3 &\in [0, 1]
\end{aligned}
$$

where $p_{best,j}$ is the path with the highest probability for a given redundancy level j and $p_{worst,j}$ the one with the smallest probability for redundancy level j.

f_1 describes the number of nodes to be used and therefore the cost of the network. f_2 describes the weighted sum over the deviations of the probabilities of the individual routing paths to the best routing path (with the highest probability) for all redundancy levels, in order to generate routing paths with equally distributed probabilities for all nodes for all redundancy levels. f_3 describes the weighted sum over the counter probabilities for all redundancy levels. While f_2 optimizes the average path probability, f_3 optimizes the path with the absolute worst probability. f_2 and f_3 are normalized with the accumulated redundancy weights w_j. All objective functions are to be minimized.

V. Summary and Outlook

This technical report presents a new model for the deployment coverage and connectivity of wireless sensor networks. It proposes a novel radio model by integrating established models of the transitional region and the directional irregularity in wireless communication for WSNs. It provides models for the nodes and environment for determining its sensor coverage, connectivity and its cost. The authors present objectives and constraints for a deployment, which are determined with the proposed models. For future work, we plan to extend the model for increased modeling accuracy and capabilities. One of the major extensions is the inclusion of obstructions for each the communication and the sensing, which is especially useful for modeling indoor scenarios. Furthermore, the cost model may be extended for relay nodes and different sensor types, e.g. differentiate between audio, video and temperature sensors. Another extension is the consideration of multiple sensor node types, e.g., low-performance, low-cost and "microserver"-type nodes composing a tiered network. Finally, we are targeting to adapt our optimization formulation for multi-sink and tiered networks concerning routing path probabilities.

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