Sink mobility schemes for data extraction in large scale WSNs under single or zero hop data forwarding

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***Abstract*—A mobile sink is widely considered to facilitate the data collection from energy constrained sensor fields, by having the sink come close to the sensors and conserving precious sensor node energy. The effectiveness of such a data collection approach can be measured in terms of the sensor energy conserved and the time required to collect the sensor data from the field (or, equivalently, the length of the trajectory implemented by the mobile sink).**

In this paper we explore two important dimensions in the design of mobile sink-based data collection schemes. One dimension refers to how close to the sensor nodes the sink moves to, to collect the data, which impacts on the transmission energy expenditure by the sensor node. The other dimension refers to the way the sink moves through the sensor field, to collect the data, which impacts on the delay in collecting the data. To capture the first dimension, the 0-hop and 1-hop data collection schemes are considered and studied; at the same time, two "extreme" approaches to the sink mobility process are considered: a (topology unaware) random walk-based sink mobility scheme and a (topology aware, optimal) deterministic sink mobility scheme. Through the analytic and simulative study presented in this paper, an understanding of the level of the trade-offs involved between the energy spent by the sensor nodes and the delay in completing the data collection process is obtained.

I. Introduction

Wireless Sensor Networks (WSNs) are typically large ensembles of hundreds or thousands of tiny nodes intercommunicating with the purpose of extracting useful information from the field via their on board sensors. Typically, the nodes of the sensor network are pre-programmed to form a connected network upon deployment such that essential network functionality is enabled, like query sending, query replying and other information propagation. After deployment, the network's main responsibility is to extract sensing data from the field and to communicate those to the end user. Due to the energy limitations and the potentially large geographical coverage of the WSN, collecting the data produced can be challenging.

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There has been research in the community towards energy-efficient data collection schemes. The various data harvesting approaches for large scale WSNs proposed in the literature can be categorized roughly into three classes: (a) approaches based on multi-hop forwarding of data within the sensor network; (b) approaches employing a hierarchy and clustering, passing the data forwarding responsibility to (the typically more powerful) cluster heads; (c) approaches employing a mobile sink that moves to the nodes and collects data via low cost, proximity based communication protocols. Combinations of these approaches have also been proposed, such as employing jointly node clustering and sink mobility or multi-hop data forwarding and sink mobility.

As multi-hop forwarding is considered to be energy-inefficient for a WSN, various variations to these approaches have been proposed to reduce the energy consumption. Probabilistic forwarding schemes combine energy efficiency and fault-tolerance, although they tend to spend a lot of energy in the case of dense networks [2], [14]. Adaptive, randomized algorithms are employed in order to balance the energy consumption of the sensor devices [10], [16], as very frequently sensor nodes are unequally burdened by the data forwarding process. Enhanced relay routing techniques are also employed in an effort to jointly consider factors such as load balancing, data redundancy and schedule patterns in the data forwarding decisions, [3]. There is an inherent deficiency in the multi-hop forwarding approaches, due to the fact that all traffic is to be routed eventually through the sensor nodes located in the vicinity of the static sink. This drawback can be somewhat mitigated by introducing additional sinks in the WSN so that the heavy load is distributed to the nodes around the multiple sinks.

Clustering has been proposed as a technique for increasing throughput and reducing energy consumption and latency [7] in WSNs. Sensors organize into clusters and the elected clusterheads undertake most of the burden of the data harvesting task. Although clustering is useful in organizing sensors in large WSNs there is an energy cost paid in the process of setting up and coordinating the structure, especially in the case where decentralized solutions are employed for clustering.

A widely considered approach for collecting the data from a sensor field at a low energy burden on the sensor nodes, is based on the sink mobility paradigm. According to this, a mobile agent (or sink) is commissioned with the task of collecting the data from the WSN by physically visiting the proximity of the sensor nodes and thus reducing the energy expenditure of the sensor nodes for forwarding the data towards the end user.

There has been a substantial amount of work employing the mobile sink paradigm. In [9], the authors discuss several interesting mobility issues and implement and evaluate a small sensor network with one mobile entity that moves back and forth on a straight line to facilitate the data collection. This idea is further extended by employing multiple sinks moving in parallel and following linear trajectories and an algorithm for load balancing the data collection process [8]. Mobile collectors undertaking the task of routing the sensor data away from the sensors has been proposed in [8], [15]. Authors exploit mobile entities (called data mules) with random walk mobility or moving along parallel straight lines in the field; data mules pick up the data and drop them off at a wired access point, resulting in substantial energy savings for the sensors. In case of sensor networks deployed in urban areas, public transportation (with predictable moving path and timing), such as buses and trains, can act as mobile base stations [1]. To achieve a more flexible data gathering trajectory for the mobile collector, [12] proposed a moving path planning algorithm by finding some turning points on the straight lines, which is adaptive to the sensor distribution and can effectively avoid obstacles on the path. In [13] an alternative single-hop data gathering scheme was proposed aiming at inducing uniform energy consumption to the nodes, in which a mobile collector is optimized to stop at certain locations to gather data from the sensors in the proximity via single-hop transmissions.

Our work adopts the single mobile sink-based WSN data collection paradigm and investigates the effectiveness of various data collection approaches that employ this paradigm. The main objective is to explore the efficiencies that can be gained by exploiting sensor field knowledge and designing the sink trajectory through the field (deterministic sink movement), in comparison to a sink trajectory induced by a (more or less pure) random sink movement in the field, whose performance is also investigated. Thus, this paper attempts to shed some light into the inherent gains that can be gained from a deterministic versus a random sink mobility pattern. In addition, the paper attempts to explore the gains and costs associated with sink mobility variants that induce basic 1-hop transmission's energy expenditure or (almost) zero energy expenditure on the sensors.

More specifically, two broad classes of mobile sink-based WSN data collection schemes are considered in this paper, depending on the desired level of energy expenditure by the sensor nodes. According to the first one, it is assumed that the basic 1-hop communication capability of the sensor nodes (available for communicating with the 1-hop neighbours) will be utilized (and the corresponding energy will be spent) in order to forward data to the sink. That is, the mobile sink can collect the sensor data as soon as it physically moves to within a 1-hop transmission range of the sensor node, incurring energy expenditure of the order of that of a 1-hop communication with neighbouring nodes; this scheme (described in detail later) will be referred to as the 1-hop data collection scheme. Under the second scheme considered, the sensor nodes will not engage the basic 1-hop communication capability with their 1-hop neighbours to forward data to the sink to conserve energy. Instead, they will forward the data to the sink via a low-power proximity based wireless protocol (such as bluetooth or infrared communication) or even via a wired connection if that is possible. Consequently, the sink will be possible to collect the data only after moving arbitrarily close to the sensor nodes, incurring an (almost) zero energy expenditure (or, practically, much less than that under the 1-hop data collection scheme); this scheme (described in detail later) will be referred to as the 0-hop data collection scheme, with the understanding that an almost zero hop forwarding of data is meant to imply substantially lower energy consumption by the sensor node, compared to the other scheme.

In view of the previous it is clear that the 1-hop and 0-hop data collection schemes also specify how far or close to the sensor nodes the mobile sink will need to come in order to collect the data, which shapes the length of the trajectory of the sink. In principle, one would expect that the mobile sink would follow a longer trajectory under the 0-hop data collection scheme than under the 1-hop one, as the sink would need to come closer to each and every sensor node.

In addition to (and more importantly than) the closeness of the coming of the sink to the sensor node, what would shape more the length of the trajectory of the mobile sink before collecting all data from the WSN is the ”schedule” for visiting the various regions and broad neighborhoods of the WSN. If there exists knowledge about the location of the sensor nodes within the WSN, then a good (or even optimal in some sense) ”schedule” for visiting the various regions of the fields could be determined. Otherwise, the sink would probably have to follow a more or less random wondering in the field, possibly exploiting the history of the trajectory and avoiding revisiting the same regions. Motivated by the above considerations, in this paper we also consider two variants of the 1-hop and the 0-hop data collection schemes: the deterministic and the random sink movement. The deterministic sink movement variant will assume increased knowledge of the sensor field and is expected to complete the data collection process faster (by implementing a shorter trajectory) than the random sink movement variant which is based on much less or no knowledge about the sensor field.

II. Study of the 1-hop data collection scheme

In this section the 1-hop data collection scheme is considered under which the minimum level of energy expenditure by the sensor nodes is that corresponding to 1-hop transmission in the WSN. The objective of the study here is to explore the length of the trajectory required in order for the mobile sink to collect all sensor data with high probability, under a random walk based sink mobility model (requiring no knowledge of the sensor field) and an (optimal) pre-calculated deterministic sink trajectory. The length of the trajectory can be useful in estimating the delay in collecting the data from the sensor field.

In this paper the WSN is modelled as a random geometric graph, which is widely adopted for this purpose. According to this model, N network nodes are laid on a 2-dimensional plane with uniformly distributed, random locations. The set of nodes V is then complemented with a set of edges E such that for any two nodes $u, v \in V$ there will exist a link $(u, v) \in E$ iff $||u - v|| \leq r_c$, where r_c is the connectivity radius of each node. Let $G(N, r_c)$ denote such a random geometric graph. It is assumed that sensor nodes form a connected network with basic connectivity as described by the wireless connectivity criterion in [6]. The associated transmission radius of a node $u \in V$ is linked (asymptotically) to the number of nodes N according to $r_c(N) = \Theta(\sqrt{logN/N})$ to guarantee basic connectivity, when N nodes are laid uniformly at random on the unit square.

A. Random Walk-based 1-hop data collection scheme

A light sink mobility scheme, requiring no (or only local) topology information and exhibiting good scalability and robustness (against network topology changes) properties would be one based on the random walk paradigm and it is presented in this section. Under this scheme the mobile sink collects the data from the sensor field by implementing a random walk (to be described below) through the WSN. The sink initiates its movement from a randomly selected sensor node which is within r_c distance from the sink and collects the data from that (declared as visited) node. To make the data collection process more efficient we assume that all sensor nodes are aware of the data of their neighboring nodes (which they collect during a hello phase exchange) and, thus, can be relayed to the sink together with their own. Notice that the additional overhead is minimal and that the energy expenditure is still of the order of 1-hop transmission.

To help guide the sink through the field it is assumed that the sink receives also local information associated with the neighbors of the visited node consisted of the set of neighbors and their respective locations. Based on this information the sink selects uniformly at random from the list of all 2-hop neighbors of the visited node to move towards; notice that the 1-hop neighbors of a visited node are not considered as the next nodes to visit, since their data are already collected and there would be substantial redundancy in the data to be collected from such a visit. Upon arriving at a location within r_c distance from the selected node, the aforementioned procedure is repeated and the sink collects the data from the visited node and its neighbors and is also provided the set of 2-hop neighbors of the visited node and their respective locations. The above process of visiting a node constitutes one step of the underlying algorithm under the random walk-based (RW-based) 1-hop data collection scheme. Fig. 1 illustrates a realization of the movement of the mobile sink under the RW-based sink mobility scheme. As the sink movement is probabilistic in nature, it is likely that already visited nodes are revisited in the future ([17]). These revisits impact negatively on both the energy consumption of the sensor nodes and the physical distance spanned (or delay suffered) by the mobile sink. Nevertheless, the sink can operate in an autonomous, decentralized manner based only on local information at the vicinity of each node.

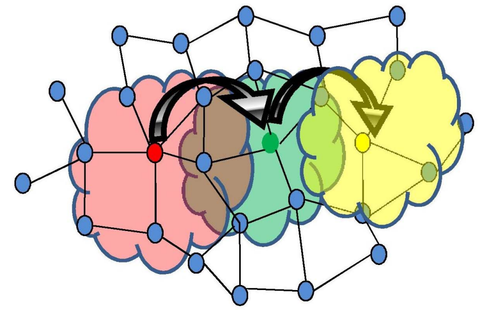

Fig. 1. The RW-based 1-hop data collection

B. Deterministic 1-hop data collection scheme

A significant shortening of the length of the trajectory of the mobile sink can be achieved by carefully devising an algorithm to (deterministically) guide the passage of the mobile sink through a set of sub-areas of the unit square sensor field and collect the data of the sensors that reside within each sub-area (by making them transmit their data in a single hop to the sink). An efficient algorithm for data retrieval through a single mobile sink passing over the sensor field can be devised when combining the work of [4] and [5] as described below.

It has been proven in Lemma 1 of [4] that a random geometric graph $G(N, r_c)$ drawn on the unit square can be partitioned into squares of length $A(N) = \sqrt{2logN/N}$ such that every square contains at least one node w.h.p. (with high probability). Such a partitioning of the sensor field is considered in our deterministic scheme as well to ensure that each square sub-area contains at least one sensor node, thus the step/stop of the mobile sink at the square sub-areas will make sense. Given the partitioning of the unit size sensor field into a grid with side size $A(N)$ we base our algorithm on the existence of Hamiltonian paths on grids, as proposed in [5]. Hence there is a route of the mobile sink that traverses all square sub-areas once. Considering such a Hamiltonian path starting (without loss of generality) from the square at the upper left corner of the grid and ending at the square at the lower right corner of the grid (see Fig. 2) we use the Hamiltonian snake to devise our algorithm for the deterministic data collection scheme.

The sink (assuming full knowledge of the geography of the square partitioning of the field) moves sequentially (based on the snake-like trajectory) from the centre of a square to

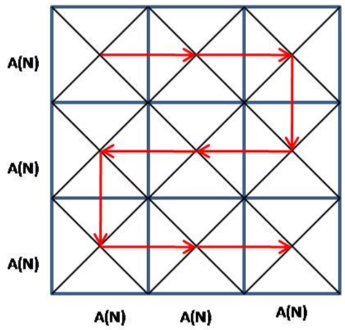

Fig. 2. Determinist 1-hop data collection scheme

the centre of the next one in line. From the centre of a square where it is located at some point, the sink forms the quadruple (x_l, y_l, x_u, y_u) of the lower and upper bounds of the coordinates of the current square and collects data from the sensors within a 1-hop transmission range; as explained later, all sensor nodes in the square are within 1-hop transmission from the centre of the square by construction. The sink then calculates the geographic coordinates of the centre of the neighboring square, according to the snake Hamiltonian path. Our metric for measuring the length of the sink trajectory is based on the number of steps/stops/locations during the execution of the algorithm and can be evaluated directly based on the grid partitioning of the sensor area. In particular, the number of steps/stops of the Hamiltonian path corresponds to the number of square sub-areas of the field, which can be directly evaluated as $B = \frac{1}{A^2(N)} = \frac{N}{2logN}$.

A critical quantity for the 1-hop transmission scheme is the transmission range r_c of the sensor nodes, as it shapes the energy expenditure by the sensor nodes. Notice that the transmission range must satisfy the condition $r_c \geq \sqrt{logN/N}$ to ensure basic network connectivity, w.h.p. In addition to this, r_c should be clearly related to the size of the square areas present under the deterministic data collection scheme, in such a way that the mobile sink visiting (the centre of) a square, be within the transmission range of all the nodes in that square and collect all sensor data during that move/step/stop. In order for this to happen, r_c should be no less than half the size of the diagonal D of each square of side size $A(N)$, or, $r_c = \frac{1}{2}D = \frac{\sqrt{2}}{2}A(N) = \sqrt{logN/N}$, which is precisely the basic network connectivity condition. Consequently, under basic network connectivity conditions ($r_c \geq \sqrt{logN/N}$), the Hamiltonian snake-based deterministic data collection scheme can collect the sensor data at an energy cost of no more than 1-hop data forwarding within the network, and this is always possible when the sink is located at the centre of the square.

III. Study of the 0-hop data collection scheme

As the energy limitations of the sensor nodes are typically severe, it is highly desirable to keep the energy expenditure as low as possible in any task executed by these nodes. This way, the WSN lifetime can be prolonged and/or energy resources can be made available to other important functionalities, such as network coordination or other computation tasks.

In this section we consider a data collection approach that would reduce the energy expenditure on the sensor nodes, for communicating their data, to pretty much the absolutely minimum. That is, instead of paying the basic 1-hop communication cost (determined by the minimum transmission range to ensure network connectivity, as discussed earlier) during the data collection process, we consider data collection schemes that bring the mobile sink arbitrarily close to the sensor node and retrieve the sensor data at an almost zero wireless communication cost, as discussed earlier.

A. *Random Walk-based 0-hop data collection scheme*

Our random walk based 0-hop data collection scheme is based on a mobile sink following the random walk paradigm in visiting the proximity of - almost zero distance away from - the sensor nodes of a WSN modelled as a random geometric graph $G(N, r_c)$ with basic connectivity ($r_c = \sqrt{logN/N}$); the next node to be visited is randomly selected from the set of neighbours of the current one, without backtracking. The resulting data collection process can follow a long (in steps) trajectory (or take long time) in this case to complete (polynomial time in N), as it is shown in [11], since the graph may contain arbitrary bottlenecks, which tend to 'trap' the random walker in local neighborhoods.

B. *Deterministic 0-hop data collection scheme*

As with the random walk-based 0-hop data collection scheme discussed above, the deterministic 0-hop data collection scheme described here aims at minimizing the burden on the sensor nodes by moving the sink arbitrarily close to the sensor node. The determinism introduced here, aims at speeding up the data collection process (in comparison to the random walk-based 0-hop data collection scheme), by exploiting knowledge of the topology and using an efficient algorithm for visiting the various sub-areas of the sensor field.

Contrary to the deterministic 1-hop data collection scheme in which the square partitioning of the field facilitated the data collection by moving the sink to 1 (centre) point in each square, the sink will need to visit each and every sensor node (close to zero distance away from them) in order to collect the sensor data at almost zero energy expenditure for the sensor node. Thus, it seems that the square partitioning is not particularly useful, at least in helping implement "bulk" (from a single sink position) sensor data collections.

The direct analogue to the deterministic 1-hop data collection scheme would be to devise an algorithm that determines the minimum length trajectory of a mobile sink in visiting all the randomly placed sensor nodes in the field. This is the well-known travelling salesman's problem which is not tractable for large N.

Our 0-hop data collection scheme is a heuristic scheme that is based on the following two design goals or observations.

The first one has to do with recent work on random walks with jumps that has shown that by taking the random walk

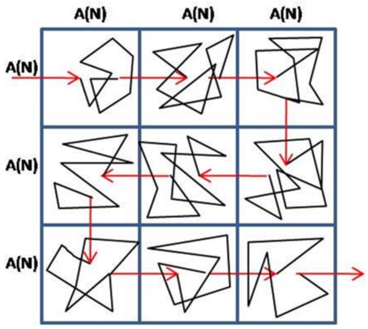

Fig. 3. Deterministic 0-hop data collection scheme

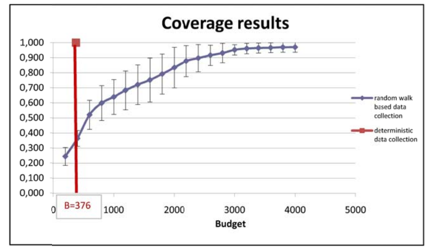

Fig. 4. Coverage results for random walk-based and deterministic 1-hop data collection schemes

agent away from a region and moving it to a remote one (implementing a jump) can substantially improve the efficiency of the random walk process in covering a set of nodes forming a random geometric graph ([17]). Consequently, by inserting jumps to the random walk-based 0-hop data collection scheme, some improvement in the sink trajectory could be expected.

The second one has to do with the (optimal) partitioning of the WSN into squares (see earlier), which could be employed to define different network regions that the random walker could be jumped into in a sequential and deterministic manner, after spending some time implementing a (pure) random walk in each one of them.

Based on the above observations or design goals, the deterministic 0-hop data collection scheme is introduced here, as an efficient heuristic to speed up the random walk-based 0-hop data collection scheme, without the need to cope with the complexity of solving (and assuming the necessary topological knowledge) of the travelling salesman problem. As illustrated in Fig. 3 the deterministic 0-hop data collection scheme employs a random walk with deterministic jumps that exploit the partitioning introduced earlier. Upon visiting of each square sub-area of side length $A(N)$ the mobile sink is programmed to perform a simple random walk without backtracking over the sub-set of sensor nodes residing within the square sub-area. The amount of steps/stops/locations that the mobile sink executes within each square sub-area before leaving that square is a controlled parameter that is set so that the total number of steps/stops spent during the data collection process be equal to a set value H that is referred to as the available budget for the sink movement; this budget is split equally among all square sub-areas. Consequently the sub-budget H_s associated with the random walk movement of the sink within each square sub-area is given by $H_s = \lfloor \frac{H}{B} \rfloor$, where B is the number of square sub-areas for the grid partitioning (defined earlier).

IV. Simulations and Results

The random walk-based 1-hop data collection scheme and both the random walk and deterministic 0-hop data collection schemes were simulated using the Omnet++ simulation environment. The simulation results presented refer to the achieved coverage degree in a large-scale WSN for various values of the available budget H (i.e., total number of movements/steps/stops allowed for the mobile sink) during the data collection process. The results on the coverage degree for the deterministic 1-hop data collection scheme are obtained from the analysis presented in earlier sections.

The networking model adopted for a WSN in all results shown in this paper is essentially the same, based on a random geometric graph $G(N, r_c)$ with $N = 10000$ nodes and $r_c = 0.3645$ (basic connectivity of the graph) laid on a unit square area with uniformly distributed random variables x_u, y_u for the locations of a node $u \in V$. These settings are used for the random walk based data collection schemes, whereas a slight modification is essential for the deterministic data collection schemes due to the associated partitioning of the unit square area. In order for the number of squares B to be an integer, one has to use truncation and determine the value of B from $B = \lfloor \frac{1}{A^2(N)} \rfloor$. Doing the backwards calculation for the total number of nodes in the network leads to a slightly higher value of N which is $N_{det} = 10152$.

A. Results for the 1-hop data collection schemes

The simulations results are presented in Fig. 4 for the random walk-based 1-hop data collection scheme. The simulated network comprises of $N = 10000$ nodes and the achieved coverage is plotted in the Figure. It can be observed that a budget equal to about 1/3 of the number of sensor nodes present in the WSN is needed to collect all the sensor data under the 1-hop data collection scheme. The associated energy requirements under the 1-hop data collection are low, given that we have considered basic network connectivity (that is, the minimum transmission range possible).

The performance of the deterministic 1-hop data collection scheme can be evaluated by invoking the analysis presented in earlier sections. Complete coverage (100%) can be achieved by having the mobile sink stop at each and every square box it encounters over the Hamiltonian snake-like path. Based on the analysis presented and, after the truncation of the decimals for the value of B, the resulting required budget is $B = 376$. By comparing this value against the results plotted in Fig. 4, one can easily notice the significant improvement in performance by the deterministic 1-hop based data collection scheme. The random walk-based 1-hop data collection scheme does not achieve coverage larger than 30% for budgets of the same order (300-400). In view of the fact that a step

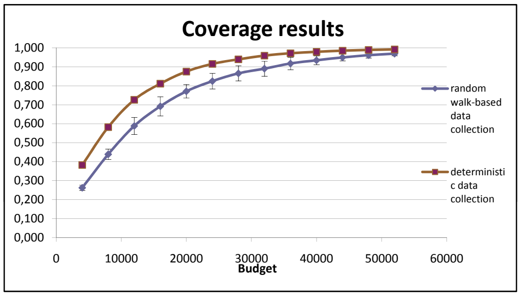

Fig. 5. Coverage results for random walk-based and deterministic 0-hop data collection schemes

under the deterministic 1-hop based data collection scheme corresponds to a physical distance of $A(N) = \sqrt{2logN/N} = O(\sqrt{2logN/N}) = O(r_c)$ and a step under the deterministic 1-hop based data collection scheme is typically greater than r_c and less than $2r_c$, again $O(r_c)$, it is evident that a lower number of steps required by the deterministic 1-hop based data collection scheme also implies a shorter trajectory for the mobile sink and, thus, a shorter delay in collecting the sensor data.

B. Results for the 0-hop data collection schemes

Fig. 5 presents simulation results under both the random walk-based and deterministic 0-hop data collection schemes. It can be clearly observed that the budget required to achieve a similar coverage is drastically larger than that under the corresponding 1-hop based data collection schemes. The budget requirements under these schemes are in the order of tens of thousands (10000-40000), whereas the corresponding budget requirements under the 1-hop based data collection schemes are in the orders of thousands of steps/stops/locations (1000-4000).

From Fig. 5 it can be concluded that the random walk-based 0-hop data collection scheme yields lower coverage for the same budget, compared to the deterministic 0-hop data collection scheme. The observed performance under the random walk-based scheme is the typical one expected for the network coverage by a random walker without backtracking moving arbitrarily within a connected network modelled as a random geometric graph. One can see that partial cover can be achieved in $O(N)$ number of steps/stops/locations, whereas complete coverage is more difficult to achieve and requires, $O(NlogN)$ in the best case scenario or polynomial in N for other cases. These findings have been confirmed independently for random geometric gaphs in [18].

The second plot seen in Fig. 5 presents results under the deterministic 0-hop data collection scheme. The presence of discrete regions (squares) in the sensor field, and the ability of the mobile sink to leave the currently (mostly expected to have been already) explored square and start a "new" short random walk without backtracking in the next square (as dictated by the snake-like Hamiltonian path) is beneficial for the achieved coverage, especially in the low budget region of the plot (partial network coverage). To illustrate the potential benefits obtained by introducing the deterministic 0-hop scheme, notice that, the required budget for 95% cover of the network is about $H = 28000$ under that scheme, versus $H = 50000$, under the random walk-based 0-hop data collection scheme; that is, a 44% reduction in the required budget (or distance spanned by the sink, or, delay in achieving the specific data collection target). This improvement in budget requirements is gained at the price of the increased complexity of the deterministic 0-hop data collection scheme compared to the random walk-based 0-hop data collection scheme.

V. CONCLUSIONS

This paper considers the single mobile sink-based WSN data collection paradigm and investigates the effectiveness of various data collection approaches. The efficiencies that can be gained by exploiting sensor field knowledge and designing the sink trajectory through the field (deterministic sink movement), in comparison to a sink trajectory induced by a (more or less pure) random sink movement in the field are investigated through the presented study. In addition, the paper explores the gains and costs associated with sink mobility variants that induce basic 1-hop transmission's energy expenditure or (almost) zero energy expenditure on the sensors.

Based on the study and the results presented, it is shown in the paper that the 1-hop data collection schemes achieve good cover of the sensor field (i.e., collect a good portion of the data) with a relatively low mobility budget (i.e. number of steps/stops/locations to be visited). This is particularly true under the deterministic 1-hop data collection scheme that clearly and drastically outperforms the random walk-based 1-hop data collection scheme. The 0-hop data collection schemes, which are capable of collecting the sensed data at almost zero expended energy on behalf of the sensor network, induce substantially higher delay in collecting the data, compared to their 1-hop counterparts, as it is clearly shown in the results section.

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