IMPROVING THE DATA COLLECTION RATE IN WIRELESS SENSOR NETWORKS BY USING THE MOBILE RELAYS

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Abstract:-In wireless sensor networks (WSNs), it is difficult to achieve a large data collection rate because sensors usually have limited energy and communication resources. Such an issue is becoming increasingly more challenging with the emerging of information-intensive applications that require high data collection rate. To address this issue, in this paper, we investigate the throughput capacity of WSNs, where multiple mobile relays are deployed to collect data from static sensors and forward them to a static sink.

To facilitate the discussion, we propose a new mobile-relay-assisted data collection (MRADC) model. Based on this model, we analyze the achievable throughput capacity of large-scale WSNs using a constructive approach, which can achieve a certain throughput by choosing appropriate mobility parameters. Our analysis illustrates that, if the number of relays is less than a threshold, then the throughput capacity can be linearly increased with more relays. On the other hand, if the number is greater than the threshold, then the throughput capacity becomes a constant, and the capacity gain over a static WSN depends on two factors: 1) the transmission range and 2) the impact of interference. To verify our analysis, we conduct extensive simulation experiments, which validate the selection of mobility parameters and demonstrate the same throughput behaviors obtained by analysis.

I. INTRODUCTION

WIRELESS sensor networks (WSNs) are an important technology that can enhance our capability of monitoring and interacting with the physical world. A typical WSN consists of a static sink (base station) and many static sensors, where each sensor is battery powered. Usually, after collecting data from the environment, a sensor sends the data to the sink using multi hop transmissions. Although such a scheme has been widely deployed and can enable low data-rate applications, it is difficulty to support high-data-rate applications because each sensor has limited radio resources and energy supply.

To improve the performance of data collection, several approaches have been proposed, Including data fusion, heterogeneous architecture, and use of mobile devices. With data fusion, correlated data obtained by neighboring sensors can be compressed before being forwarded to the sink. In heterogeneous architecture, powerful sensors with larger energy capacity and stronger communications capability are deployed to reduce the energy consumption of regular sensors and to increase the data collection rate.

Using mobile devices, data can be relayed from a sensor to the sink using less number of hops. In this paper, we will investigate the performance of data collection in WSNs with mobile devices.

In the literature, different types of mobile devices have been introduced, including mobile sensors, mobile sinks, and mobile relays. A mobile sensor is enabled with both mobility and sensing ability. A mobile sink, similar to the static sink, is the final destination of data collected by sensors. A mobile relay stores data for ascertain duration and will forward these data to a sink at a later time. In this paper, we will focus on mobile relay assisted data collection model (MRADC) in WSNs. Starting from, many MRADC models have been developed and investigated. These studies can be classified according to their objectives: 1) to improve connectivity in sparse WSNs. 2) to reduce the latency of each packet 3) to maximize the total amount of data gathered during the lifetime of a WSN, to enhance the energy efficiency (and, thus, prolong the lifetime of a WSN. Despite the importance of these objectives, we note that there is lack of theoretical understanding on the throughput capacity of WSNs with the MRADC model, where the throughput capacity is defined as the maximal achievable data collection rate from each sensor. In fact, most existing work assume that the data rate from each sensor is fixed. To address this issue, in this work, we will analyze the throughput capacity of large-scale WSNs with mobile relays. To the best of our knowledge, this paper is the first work to construct the achievable throughput capacity of WSNs with mobile relays. To facilitate the investigation, we propose a novel MRADC model, in which one static sink, n static sensors, and k mobile relays are deployed in the network area. We first group then sensors into k + 1 clusters ($c_0, c_1, c_2 \ldots\ldots\ldots\ldots, c_k$). In cluster C_0, sensors transmissions without the help of mobile relays. For each cluster c_i(i>0),a mobile relay is assigned, and this relay periodically travels between two specified locations. The first location is chosen such that the mobile relay can forward stored data to the sink in one hop. The second location is inside c_i, at which the mobile relay can collect data from cache nodes that are sensors within one hop to the second location. Moreover, the cache nodes can store data from other sensors when they are not forwarding data to the mobile relay.

Based on the proposed MRADC model, we investigate the throughput capacity of large-scale WSNs using a constructive approach, which can achieve a certain throughput by choosing appropriate mobility parameters, such as the traveling speed, traveling distance, and other timing parameters. Our analysis illustrates that, if *k* is less than threshold *k*, then the throughput capacity can be linearly increased with the increase in *k*. On the other hand, if $k > \hat{k}$, then the throughput capacity is a constant, and the capacity gain over a static WSN depends on two factors:

1) the transmission range and 2) the impact of interference. To verify our analysis, we conduct extensive simulation experiments, which validate the selection of mobility parameters in the constructive approach and 6demonstrate the same throughput behaviors obtained by analysis.

II. DATA COLLECTION MODEL

In this section, we first briefly review existing work on MRADC models. We then introduce our MRADC model.

A*. *Existing MRADC Models As we have mentioned in the first section, there are many existing MRADC models in the literature. In general, these models can be classified according to the following three main aspects: The first aspect is the number of mobile relays. In this case, the models in assume that there is only one mobile relay. The second feature is the mobility model of the mobile relays. For this issue, an early study in is based on the random walk model, whereas most recent studies are based on controlled mobility because controlled mobility can improve the performance of data collection, in terms of energy consumption, delay of packets, etc. The third feature is the routing of data packets.

In this regard, there are three existing approaches. In data from the static sensor are forwarded to a mobile relay in one hop, and stored data in a mobile relay are delivered to the sink later in one hop. In data from the static sensor are transmitted to a mobile relay in one hop, and stored data in the mobile relays are sent to the sink later using multi hop transmission. In data are first forwarded to cache nodes using multi hop routing. The data are delivered to a static sink in one hop. In this paper, we develop a general MRADC model where we consider multiple mobile relays with controlled mobility, and we utilize different routing schemes for sensors located in different regions (i.e.c_0 and $c_i \le k$ in Fig. 1), which will be explained next.

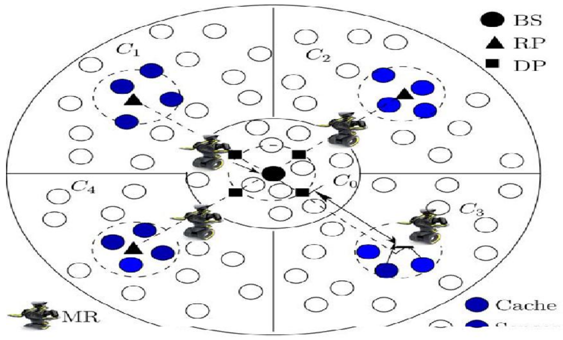

FIG:1.System model of MRADC with k = 4

In our MRADC model, we consider one static sink, *n* static sensors, and *k* mobile relays. Sensors are first grouped into *k* +1 clusters($c_0, c_1, c_2 \ldots\ldots\ldots\ldots c_k$).Cluster c_0,is located around the sink, and sensors in $c_0$send their data to the sink using multi hop transmissions without mobile relay. For any other cluster $c_i(0<i<k)$ a mobile relay is assigned, and this relay can travel between two specified locations i.e., a *rendezvous point* (RP) that is inside c_i and a *dump point* (DP) that is one hop away from the sink. To collect data in c_i, sensors first send their data to *cache nodes*, which are sensors within one hop to the RP. The cache nodes can send data to the mobile relay when it stops at the RP. Finally, the mobile relay can deliver data to the sink when it stops at the DP. Fig. 1 shows an example for the MRADC scenario with *k* = 4.To simplify the mobility of the mobile relay, we consider that a mobile relay travels between the RP and the DP with a constant period *T*. Consequently, we can define four states of a mobile relay within each period *T*.

1) Traveling state: In this state, the mobile relay is traveling between RP and the DP. The duration of this state depends on the average traveling speed of a relay and the distance between the RP and the DP.

2)waiting state*:* When the mobile relay arrives at an RP, it may wait until the cache nodes collect a sufficient amount of data from other sensors. The duration of this phase is *Tw*.

3) Harvesting state: In this phase, a mobile relay stops at the RP and is receiving data from the cache nodes. The duration of this state is Th.

4) Dumping state: In this phase, a mobile relay stays at the DP and is send stored data to the sink. The duration of this phase is Td.

It shall be noted that *T* is not the constraint of packet delay, which is the time duration for a packet to travel from its source to the sink. In this paper, we mainly focus on the throughput capacity, and we will not investigate the packet delay of the MRADC model.

III. ANALYTICAL FRAMEWORK

In this section, we develop an analytical framework to investigate the throughput capacity of large-scale WSNs with MRADC. We first address the system models, including the transmission model, the network model, and other assumptions.

We then discuss the approach to construct the achievable throughput capacity.

A. System Models

*1) **Transmission Model**:* In this paper, we consider a particular protocol model.1 Specifically, following we let r be the one-hop transmission range, and let $(1+\Delta)r$ be the interference range. Then, a transmission from node $n_i$to node $n_j$is successful if and only if

$|n_i–n_j| \le r$------------------ *(1)*
$|n_q− nj| \ge (1+\Delta)r$---------------*(2)*

Where n_q represents any node that is simultaneously sending. In this paper, we assume that r is a constant and that the successful transmission data rate is fixed to W bits per second, which is also a constant.

***2) Network Model**:* In our network model, we consider that n ($n\to\infty$) static sensors are deployed in a unit circle area (the radius of which is 1/where n represents any node that is simultaneously sending. In this paper, we assume that r is a constant and that the successful transmission data rate is fixed to W bits per second, which is also a constant.

Note that we choose a unit circle area to simplify the analysis; in reality, sensors can be deployed in an arbitrary region. We further divide the unit circle area into two parts, i.e., the *central circle* with radius $r0$ and a *ring*. Sensors located in the central circle are grouped into cluster $C0$. Since $n\to\infty$, with high probability, the number of nodes in $C0$ is$N_0= \pi r^2$. The ring area is partitioned into k sectors with the same shape, as shown in Fig. 1. Sensors in the same sector are grouped into a cluster. The number of nodes in each ring cluster$\surd\pi$) randomly following a Poisson point process. A static sink is located at the center of the circle. Note that we choose a unit circle area to simplify the analysis; in reality, sensors can be deployed in an arbitrary region. We further divide the unit circle area into two parts, i.e., the *central circle* with radius r_0 and a *ring*. Sensors located in the central circle are grouped into cluster C_0. Since $n\to\infty$, with high probability, the number of nodes in C_0 is $N_0= \pi r2n$.The ring area is partitioned into k sectors with the same shape, as shown in Fig. 1. Sensors in the same sector are grouped into a cluster. The number of nodes in each ring cluster is the same $Ni = (1/k)(n –N_0)$ ($i>0$).

We also consider that all DPs are on a circle whose center is the sink and whose radius is r. Similarly, all RPs are on a circle whose center is the sink and whose radius is $r + l$. More over,the DP and the RP of the same relay are on a line that includes the center of the circle. Therefore, the traveling distance of each mobile relay is l. To collect data from sensors, we apply the *time-division multiple access* (TDMA) schedule in for communications between sensors. To avoid interference between mobile relays and sensors, the locations of the RP and DP must satisfy the following conditions. 1) The distance between a DP and the edge of the central circle is greater than $(\Delta + 1)r$. In this manner, the transmission from a mobile relay to the sink does not interfere with the communications in ring clusters. We can then derive a requirement for r_0:

Where $\delta = 2+\Delta$is used to simplify the notations.

2) An RP must be located within a ring sector, and the distance between the RP and the border of its sector is greater than δr. In this manner, the transmission from any cache node to the mobile relay does not interfere with the communication in other clusters. With such a design, we can obtain the following conditions.

*3) **Other Assumptions**:* To simplify our discussion, we make the following assumptions, many of which are common for investigating the performance of large-scale wireless networks.

1) We assume that r is small enough so that we can construct $k + 1$ clusters according to our previous discussions.

2) We assume that each node (sensor or mobile relay) is equipped with a half-duplex transceiver, which means that it cannot simultaneously send and receive. Since the transmission data rate is fixed to W, we have $Td = Th$.

3) We also assume that all nodes transmit data on the same frequency. Moreover, TDMA is used for medium access.

4) We assume that the traveling speed of any mobile relay is a constant v meters per second.

5) Since we are interested in the fundamental capability of the network, we do not apply data fusion in any of the node.

Analytical Approach

In this section, we first define the throughput capacity and explain the main idea of our approach. We then elaborate on the throughput bounds based on the proposed MRADC model. Finally, we discuss the physical constraints that define the search space in which we can find the maximal achievable throughput. existing studies , we define the *throughput capacity U* as the maximal data rate, at which every sensor can send data to the sink. The main idea of our analytical approach can be summarized as follows.

1) We note that the throughput capacity is limited by the data collection capability in different states of the mobile relay.

Therefore, we first develop three throughput bound function that aims to maximize the minimum of the three bounds.

2) To obtain the throughput capacity, we also need to consider the impact of the physical constraints for implementing the MRADC model, including

interference, timing, scheduling, and mobility of nodes. These physical constraints define a search space, in which we can maximize the throughput capacity.

3) With the objective function previously mentioned and all the constraints, we can see that finding the throughput capacity becomes an optimization problem, which will be solved in the next section.

IV. THROUGHPUT CAPACITY OF A WIRELESS SENSOR NETWORK WITH THE PROPOSED MOBILE DELAY-ASSISTED DATA COLLECTION MODEL

In this section, we will analyze the throughput capacity of a WSN with respect to k, under our MRADC model. Specifically, we first further analyze the throughput bounds introduced in the last section, in which we will define new parameters that can help to derive the throughput capacity. Based on the analysis, we will prove the achievable throughput capacity with respect to k. Finally, we summarize the parameters to implement the MRADC model, such as the location of the RP and the traveling speed.

A. Further Analysis for the Throughput Bounds

To facilitate further discussions, we define two parameters.

1) We define $\rho = l/v\_T$, which is the proportion of time *in T* that each mobile relay travels from the RP to the DP (or from the DP to the RP).

2) We denote $\psi = k((1/2) - \rho)$, which is an auxiliary parameter for obtaining the throughput capacity.

With the aforementioned parameters, we can rewrite the three throughput bounds with triplet ($k, \rho, A0$) as

$$U_s(k,\rho,A_0) = \frac{W}{n}\left(1 + k\rho - \frac{k}{2}\right)\delta^2 A_0$$

$$U_i(k,\rho,A_0) = \frac{W}{n}\frac{\frac{k}{2}+k\rho}{\delta^2(1-A_0)}$$

$$U_h(k,\rho,A_0) = \frac{W}{n}\frac{\frac{k}{2}-k\rho}{1-A_0}.$$

Moreover, we can also define

$$U'_s(\psi,A_0) = \frac{W}{n}\frac{(1-\psi)}{\delta^2 A_0}$$

$$U'_h(\psi,A_0) = \frac{W}{n}\frac{\psi}{1-A_0}.$$

To guarantee $Us(k, \rho, A0) \geq 0$ and $Uh(k, \rho, A0) \geq 0$, we have

$$\frac{1}{2} \geq \rho \geq \max\left\{0, \frac{1}{2} - \frac{1}{k}\right\}$$

which specifies the optimization space of the throughput capacity, in which we can also derive

$$0 \leq \psi \leq 1$$

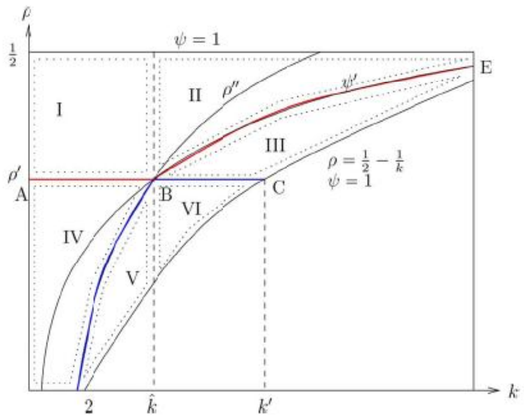

Fig. 2. Optimization space for the throughput capacity

V. SIMULATION RESULTS

In this section, we develop simulations to evaluate the performance of our MRADC model and to verify our theoretical analysis. We first introduce the simulation settings and our methodology. We then analyze the maximum throughput capacity under a given number of mobile relays k.

A. Settings

In our simulation, n = 9000 sensors are uniformly deployed in a unit circle area, the radius of which is 600 m. The transmission range is r□ (r□ $\in${20, 30} m). Since the radius of the unit circle is $1/\sqrt{\pi}$ units, wehave $r = r*/600\sqrt{\pi}$ units. To guarantee the connectivity of the network, we can choose $r*$ such that the expected number of neighbors for each node is at least 10 [22]. For the mobility of mobile nodes, we let T = 1200 s, and we let the traveling speed v be from 0.01 to 2.5 m/s.

B. Methodology

Based on the MRADC scheme previously described, we implement our simulation in the following four steps:

In Step One, we randomly deploy n nodes in the unit circle area. We then build a graph, with the maximum length of each edge being δr. With such a graph, we identify a number Nx, which is the minimum number to color all the nodes such that two adjacent nodes have different colors.

In Step Two, we specify an $r0$ in range $\delta r \leq r0 \leq 1/\sqrt{\pi} - 2\delta r$ and a ρ in range max (0, (1/2) − (1/k)) < ρ < (1/2). Following, we calculate l and the associated *v*. We can also calculate $Th = (T/2) - \rho T$ and $Ts = T - k((T/2) - \rho T)$.

In Step Three, we partition the network into two parts, i.e., a central circle with radius *r*0 and a ring. For the ring, we further create *k* sectors and specify *k* RPs based on our discussions in the previous sections. According to our MRADC model, we select all nodes that are one hop from an RP as cache nodes of the particular RP.

In Step Four, for the central cluster, we build a balanced tree, with the sink being the root of the tree using Algorithm 1 in. Similarly, for each ring cluster, we build a balanced tree for all sensors with the root being the RP using Algorithm 1 in as well.

Next, we calculate the throughput capacity of the network. For the central cluster, we have

$$\widetilde{U_s}(k,\rho,A_0) = \min_j \left\{ \frac{W(T-kT_h)}{N_0^j T N_x} \right\}$$

where *Nj* 0 is the number of sensors in the subtree of sensor *j* in cluster *C*0.

To calculate the throughput bound for cache nodes, we use

$$\widetilde{U_i}(k,\rho,A_0) = \min_{m,j} \left\{ \frac{W(T-T_h)}{N_m^j T N_x} \right\}$$

where *Njm* is the number of sensors in cluster *Cm* (*m* > 0) that are in the sub tree of sensor *j*, which is not a cache node. For the throughput bound for mobile relay, we have

$$\widetilde{U_r}(k,\rho,A_0) - \min_{0<i\le k} \left\{ \frac{WT_h}{TN_i} \right\}.$$

As we want to find the optimal *r*0 and *ρ*, we have

$$\widetilde{U}(k) = \max_{\rho,A_0}\left\{\min_i\left\{\widetilde{U_s}(k,\rho,A_0),\widetilde{U_i}(k,\rho,A_0),\widetilde{U_r}(k,\rho,A_0)\right\}\right\}$$

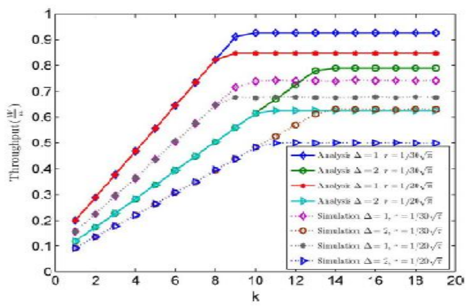

Fig. 3. *U*(*k*) and _*U*(*k*) versus *k* under different *r*'s and Δ's.

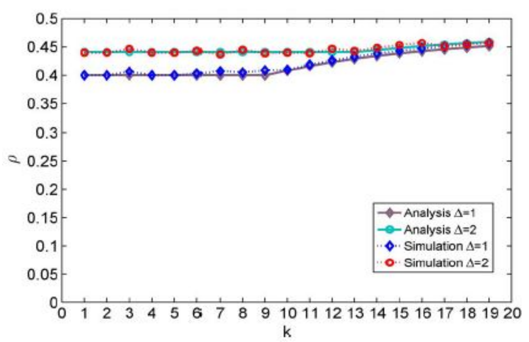

Fig. 4. Optimal *ρ* versus *k* under different Δ's, where *r* = 1⁄30√*π*.

C. Results Analysis

In our experiments, for a given WSN setting with specified *k*, Δ, *r*, we simulate 50 randomly generated topologies. To achieve the maximum throughput capacity, we increase *r*0 with steps of 0.1*r* from *δr* to $1/\sqrt{\pi} - 2\delta r$, and we increase *ρ* with steps of 0.01 from $\max(0, (1/2) - (1/k)) + 0.01$ to $(1/2) - 0.01$.

Fig. 3 first shows both the simulation and theoretical results of throughput capacity *U*(*k*) and _*U*(*k*) versus *k* under our MRADC.We can observe the similarity between the simulation results and theoretical results. In particular, our experiments show that the simulation results are about 80% of the numerical results with the same setting. Here, we note that the simulation results are obtained when the RPs are located at the centers of ring clusters. If the RPs are placed to closest possible locations to the sink, the achievable throughput will be about 60% of the theoretical results. Fig. 3 also shows the impact of *r* and Δ. Comparing the results under different *r*'s, we can observe that the throughput capacity decreases when *r* increases. On the other hand, we find that the throughput capacity decreases when Δ increases. In Figs. 4 and 5, we compare the optimal conditions for both *r*0 and *ρ* to achieve the maximum throughput capacity in both simulation and theory. These two figures show that the simulation results are almost the same as the theoretical results, which validates the selection of optimal parameters in the theoretical analysis.

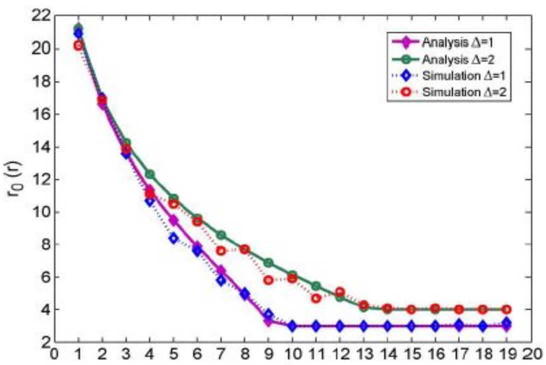

Fig. 5. Optimal *r*0 versus *k* under different Δ's, where *r* = 1⁄30√*π*.

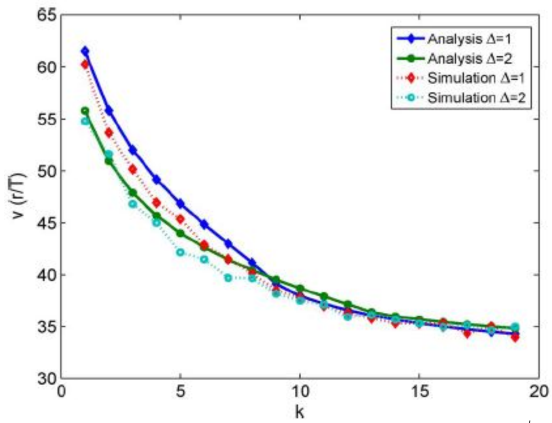

Fig. 6. Optimal *v* versus *k* under different Δ's, *r* = 1⁄30√*π*.

CONCLUSION

In this paper, we have investigated the throughput behaviors of WSNs with mobile relays. We have first proposed a new MRADC model, in which we have considered multiple relays with controlled mobility. Based on this model, we analyzed the achievable throughput capacity of large-scale WSNs using a constructive approach, which can achieve a certain throughput by choosing appropriate mobility parameters.

Our analysis illustrates that, if the number of relays is less than a threshold, then the throughput capacity can be increased with more relays. On the other hand, if the number is greater than the threshold, then the throughput capacity is a constant, and the capacity gain over a static WSN depends on two factors: 1) the transmission range and 2) the impact of interference. To verify our analysis, we have conducted extensive simulation experiments, which validate the selection of mobility parameters and demonstrate the same throughput behaviors obtained by analysis.

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