Maximizing Network Throughput with Minimal Remote Data Transfer Cost in Unreliable Wireless Sensor Networks

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ABSTRACT

In this paper we consider the use of a link-unreliable wireless sensor network for remote monitoring, where the monitoring center is geographically located far away from the region of the deployed sensor network. The sensing data is transferred to the monitoring center by the third party communication service, which incurs service cost. We first formulate a novel optimization problem of maximizing the network throughput with minimal service cost, which is shown to be NP-hard. We then develop approximation algorithms. We finally evaluate the performance of the proposed algorithms by simulations. Experimental results demonstrate that the solutions delivered by proposed algorithms are fractional to the optimum.

Categories and Subject Descriptors

C.2.2 [**Computer-Communication Network**]: Network Protocols; G.1.6 [**Numerical Analysis**]: Optimization

Keywords

Unreliable data transmission, load-balanced forest, combinatorial optimization problem

1. INTRODUCTION

In this paper we consider a renewable wireless sensor network (WSNs) [1] with unreliable wireless links deployed in a remote region to monitor phenomena of interest, where the monitoring center is geographically located far away from the monitored region [2]. The transfer of sensing data from the deployed WSN to the monitoring center is carried by the third party communication service, such as 3G/4G networks or satellite telecommunication. The accumulative volume of data received by the center within a specified period is referred to as the *network throughput* and the cost incurred by the use of the third party service is referred to as the *service cost*. Our objective is to maximize the network throughput of the deployed unreliable sensor network, while minimizing the service cost of transferring data to the monitoring center.

Deploying wireless sensor networks for environmental monitoring has been extensively studied in the past, and most existing studies in literature focused on optimizing network performance by assuming (i) the base station and the sensors are located in the same region; and (ii) wireless communication in the sensor network is reliable. In contrast, we here deal with an essentially different application scenario where (i) the data monitoring center is geographically located far away from the region of the sensor network, and the sensing data needs to be forwarded to the center via a third party network which does incur service cost, and (ii) wireless communication in the sensor network are not reliable, which means that data loss is unavoidable during its transfer. Load-balancing adopted in this paper was extensively studied in the past [3, 4]. However, the load-balancing studied here is different from previous studies in that the loads at tree roots are allowed to exceed their capacities, and the load of each tree root is determined by not only the number of its descendants but also the end-to-end reliability of each routing path between a node and the root. Thus, traditional solutions are not applicable, and new algorithms need to be developed.

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2. PRELIMINARIES

2.1 System model

We consider a heterogeneous, unreliable wireless sensor network $G = (V \cup GW, E)$, where V is the set of sensors, GW is the set of gateways equipped with 3G/4G radios, and E is the set of links. There is a link between two sensors or a sensor and a gateway if they are within the transmission range of each other. $n = |V|$ and $K = |GW|$. We assume that both sensors and gateways are stationary and their locations are known a *priori*, where gateways are deployed in some strategic locations in the monitoring region. The data generation rate of all sensors is identical, denoted by r. We consider a long-term periodic environmental monitoring application scenario, in which sensors have low data generation rates and the generated data is transmitted to the gateways through multi-hop relays. Thus, data burst and bandwidth capacity constraint are not the major issues for such an application. Denote by R the transmission range of each sensor. As wireless communication is unreliable, denote by p_e the *reliability* of link $e \in E$ with $0 \leq p_e \leq 1$. We assume that the sensing data generated from each sensor will be sent to one of the gateways through the routing tree rooted at the gateway. The collected data by the gateways will then be forwarded to the remote monitoring center, through a long-distance communication service provided by a third party company.

The accumulative volume of data received by the K gateways within a specified monitoring period τ is defined as the *network throughput*. Let T_i be the tree rooted at gateway $g_i \in GW$ and $V(T_i)$ the set of sensor nodes in T_i, $1 \le i \le K$. All sensors are to be included in the K trees, i.e., $\bigcup_{1\le i\le K} V(T_i) = V$. Let $e_1, e_2, \dots, e_l$ be the link sequence of a routing path $P(v, g_i)$ in T_i from a sensor node $v \in V(T_i)$ to gateway g_i. Denote by p_{v,g_i} *the end-to-end reliability* of $P(v, g_i)$ between v and g_i, then $p_{v,g_i} = \prod_{i=1}^{l} p_{e_i}$. Let $L(g_i)$ be the amount of data received by gateway g_i through tree T_i within the period of τ, referred to as *the load* of gateway g_i, then $L(g_i) = \sum_{v\in V(T_i)}(p_{v,g_i} \cdot \tau \cdot r)$. The network throughput thus is

$$D^{(\tau)} = \sum_{i=1}^{K} L(g_i). \tag{1}$$

The cost of transferring the collected data from the gateways to the remote monitoring center for a monitoring period of τ is referred to as *the service cost*. In this paper, we adopt a popular data plan provided by telecommunication companies, where a fixed cost C_f for a data quota Q at each gateway is charged within the period of τ, and the extra charge will be applied with a *penalty* rate c_p for every MB of exceeding data over the data quota, assuming that the penalty rate is much higher than the fixed cost rate c_f for data quota Q, i.e., $c_p > c_f = \frac{C_f}{Q}$. Let C_p be the penalty cost of a data quota Q, i.e., $C_p = c_p \cdot Q$, then $C_p > C_f$. The service cost on each individual gateway depends on not only the volume of collected data but also the chosen data plan. Denote by C the service cost for the period of τ,

$$C = K \cdot C_f + \sum_{i=1}^{K} \max\{0, (L(g_i) - Q) \cdot c_p\}. \tag{2}$$

2.2 Problem definition

Given an unreliable sensor network $G(V \cup GW, E)$, a specified monitoring period of τ, and a data plan that has a fixed cost C_f for a data quota Q and a penalty rate c_p, *the maximizing network throughput with minimal service cost* (MTMC) problem is to find a forest $\mathcal{F} = \{T_i \mid T_i$ is a routing tree rooted at gateway $g_i \in GW$, $1 \le i \le K\}$ in G spanning all sensor nodes such that the accumulative volume of data received by the K gateways $D^{(\tau)}$ in Eq. (1) is maximized while the service cost of transferring $D^{(\tau)}$ to the remote monitoring center is minimized.

THEOREM 1. *The decision version of MTMC problem is NP-complete.*

PROOF. This claim is proved by reducing a NP-complete problem, the subset sum problem, to the MTMC problem. Details are omitted, due to space limitation. □

3. ALGORITHM FOR UNIFORM LINK RELIABILITY

In this section we consider the MTMC problem in a sensor network where each link has a uniform link reliability p with $0 < p \le 1$, for which we devise a novel approximation algorithm that can achieve the maximum network throughput while the service cost is bounded.

Given the network $G(V \cup GW, E)$, we construct another network $G' = (V \cup GW \cup \{s'\}, E')$ as follows. A virtual sink s' and an edge between s' and each gateway node $g \in GW$ are added to G', i.e., $E' = E \cup \{(g_i, s') \mid g_i \in GW\}$. Let T^{BFS} be a Breadth-First search tree in G' rooted at the virtual sink s' with the depth h, where the virtual sink s' is in layer 0 and all gateway nodes are in layer 1 of T^{BFS}. Let V_l be the set of nodes of T^{BFS} in layer l for all l with $0 \le l \le h$. Then, the nodes in $V \cup GW$ is partitioned into h disjoint subsets $V_1, V_2, \dots, V_h$ such that $V_1 = GW$, $\cup_{l=2}^{h} V_l = V$, and $V_i \cap V_j = \emptyset$ if $i \ne j$ and $1 \le i, j \le h$. Note that $l-1$ is the minimum number of hops in G from $v \in V_l$ to its nearest gateway in GW, with $2 \le l \le h$. For each node $v \in V_l$, its contribution to the network throughput for a period of τ is identical and at its maximum, which is $d_l = d^v_{max} = p^{l-1} \cdot (\tau \cdot r)$. The maximum network throughput thus is $D_{max} = \sum_{l=2}^{h} \sum_{v\in V_l} p^{l-1} \cdot (\tau \cdot r) = \sum_{l=2}^{h}(|V_l| \cdot p^{l-1} \cdot \tau \cdot r)$.

3.1 Load-balanced forest

We first iteratively construct a forest $\mathcal{F}$ consisting of K routing trees rooted at K gateways such that the load among the gateways is well balanced while the maximum network throughput is maintained. Within each iteration, a level expansion of each tree is conducted. Let $\mathcal{F}_l$ be the forest spanning the nodes in the first l layers. Initially, $\mathcal{F}_1$ spans all gateways $g_1, g_2, \dots, g_K \in GW$ and the load of each gateway $L(g_i)$ is 0, for all i with $1 \le i \le K$. Assuming that forest $\mathcal{F}_l$ has been built, we now expand the forest to $\mathcal{F}_{l+1}$ by including the nodes in V_{l+1} with the objective that the maximum load among the K gateways in $\mathcal{F}_{l+1}$ is minimized. To this end, we adopt a similar strategy as the one in [4]. The algorithm of constructing a load-balanced forest is referred to as `Load_Balanced_Forest`, or `LBF` for short.

3.2 Dynamic load readjustment

Having the forest of load-balanced routing trees, we then readjust the load among the gateways dynamically to further reduce the service cost. To balance the load among the K gateways, we consider the following cases. If the loads of all gateways are no greater than or no less than the data quota Q, we do nothing because the service cost is already the minimum one. Otherwise, the cost can be improved through readjusting the load among the K gateways through a series of *edge swapping* that replaces a tree edge by a non-tree edge while keeping network throughput unchanged. To this end, we only consider edge swapping in the same neighboring layer to reduce the service cost.

Given the load-balanced trees in forest $\mathcal{F}$, the dynamic load readjustment algorithm examines the tree edges in the forest from the lower layer to the higher layer. Let $E_{l,l+1} = (V_l \times V_{l+1}) \cap E$ be the edge set between two neighboring layers l and $l+1$ for all l with $1 \le l \le h-1$. Let $e_1 = (u, v) \in E_{l,l+1}$ be a tree edge considered at this moment and nodes v and u are in layers l and $l+1$, respectively. Let $L(u)$ be the volume of data collected at node u in T_i from all its descendant nodes in the subtree rooted at u, and the volume of data received at the gateway derived from node u is $p^l \cdot L(u)$. We remove this tree edge and add another non-tree edge $e_2 = (u, v') \in E_{l,l+1}$ to form a new forest if this leads to a less service cost. Assume that nodes v and v' are in trees

T_i and T_j rooted at gateways g_i and g_j. Perform swapping only if the following conditions are met: (i) T_i and T_j are not the same tree, (ii) $L(g_i) > Q$ while $L(g_j) < Q$, and (iii) $L(g_i) - p^l \cdot L(u) > L(g_j)$. This procedure continues until all tree edges have been examined. We refer to this dynamic load readjustment procedure as algorithm `Refine_Cost`.

3.3 Algorithm

Algorithm `Uniform_Link` for the uniform link reliability case is described as follows.

Algorithm 1 `Uniform_Link`

Input: $G(V \cup GW, E)$, monitoring period of τ, the data plan consisting Q, C_f and c_p, and link reliability p

Output: The network throughput $D^{(\tau)}$ and the cost C

1: $\mathcal{F} \leftarrow \emptyset$;
2: Partition the nodes in $V \cup GW$ into h disjoint subsets $V_1, V_2, \ldots, V_h$;
3: Construct $\mathcal{F}_h$ by calling **algorithm** `LBF`, the network throughput $D^{(\tau)}$ is then obtained;
4: Readjust the load among the gateways in $\mathcal{F}_h$ by calling **algorithm** `Refine_Cost`. Let C be the cost;
5: **return** $D^{(\tau)}$ and C.

Theorem 2. *Given an unreliable sensor network $G(V \cup GW, E)$ with uniform link reliability p with $0 < p < 1$, there is an approximation algorithm* `Uniform_Link` *which can achieve the maximum network throughput with at most $(1 + \frac{C_p}{C_f})$ times of the minimal service cost. The time complexity of the proposed algorithm is $O(|V||E|^2)$, assuming that $|GW| << |V|$.*

Proof. Omitted, due to space limitation. □

4. ALGORITHM FOR NON-UNIFORM LINK RELIABILITY

In this section we deal with the MTMC problem in wireless sensor networks with non-uniform link reliabilities.

4.1 Simple heuristic

Recall that $T_1, T_2, \ldots, T_K$ are the K routing trees rooted at the K gateway nodes. We now show that how to construct the K routing trees such that the network throughput is maximized. Initially, each tree T_i contains only gateway $g_i \in GW$ for each i with $1 \le i \le K$. Let $V' \subseteq V$ be the set of nodes that are not included in these trees but one hop neighbors of the nodes in $\cup_{i=1}^{K} V(T_i)$, i.e., $V' = \{v \mid (u, v) \in E, u \in \cup_{i=1}^{K} V(T_i), v \notin \cup_{i=1}^{K} V(T_i)\}$. The proposed algorithm proceeds iteratively. Within each iteration, only one node in V' is added to one of the K trees. A node $v' \in V'$ is added if the routing path between v' and the gateway of the tree that it joined is the most reliable. Node v' is then removed from V'. This procedure continues until $V' = \emptyset$. The service cost then can be calculated by Eq. (2). We refer to this iterative algorithm as `Simple_Alg`.

Theorem 3. *Given an unreliable sensor network $G(V \cup GW, E)$ with link reliability p_e for each link $e \in E$, algorithm* `Simple_Alg` *delivers a solution that has the maximum network throughput but the service cost is not optimized.*

Proof. Every node in V is added to forest $\mathcal{F}$ via the most reliable path, thus the accumulative volume of data collected by all gateways is the maximum one. Notice that the service cost is not taken into account in algorithm `Simple_Alg`, thus it is not optimized. □

4.2 Approximation algorithm

We now take into account the service cost in the design of an improved algorithm. For the sake of convenience, we assume that the reliability of each link in $G(V \cup GW, E)$ is within the range of $[p, (1+\delta)p]$, where $p > 0$ and $(1+\delta)p \le 1$. The improved algorithm proceeds as follows.

We first call algorithm `LBF` with uniform link reliability of p to construct a forest consisting of load-balanced routing trees $\mathcal{F} = \{T_1, T_2, \ldots, T_K\}$, clearly $\mathcal{F}$ is a feasible solution to the problem. We then perform dynamic load readjustment on the trees in $\mathcal{F}$ to further improve the network throughput while optimizing the service cost too. Similar to the discussions in the previous section, we only consider the edge swapping in the same neighboring layers. Consider swapping a pair of edges: a tree edge $e_1 = (u, v)$ and a non-tree edge $e_2 = (u, v')$, where node u is in layer $l+1$ and nodes v and v' are in layer l of trees T_i and T_j rooted at gateways g_i and g_j respectively. We distinguish into five cases. Case one: when $T_i = T_j$ and $L(g_i) > Q$, perform swapping only if $\Delta d = (p_{u,v'} \cdot p_{v',g_i} - p_{u,v} \cdot p_{v,g_i}) \cdot L(u) > 0$. Case two: when $T_i = T_j$ and $L(g_i) < Q$, perform swapping only if $\Delta d = (p_{u,v'} \cdot p_{v',g_i} - p_{u,v} \cdot p_{v,g_i}) \cdot L(u) > 0$. Case three: when $T_i \neq T_j$, $L(g_i) > Q$ and $L(g_j) < Q$, perform swapping only if (i) $\Delta d = (p_{u,v'} \cdot p_{v',g_j} - p_{u,v} \cdot p_{v,g_i}) \cdot L(u) > 0$, and (ii) either $L'(g_i) = L(g_i) - p_{u,v} \cdot p_{v,g_i} \cdot L(u) \ge Q$ or $Q - L(g_j) > Q - L'(g_i)$. Case four: when $T_i \neq T_j$, $L(g_i) < Q$ and $L(g_j) < Q$, perform swapping only if (i) $\Delta d = (p_{u,v'} \cdot p_{v',g_j} - p_{u,v} \cdot p_{v,g_i}) \cdot L(u) > 0$, and (ii) either $L'(g_j) \le Q$ or $Q - L(g_j) \ge p_{u,v} \cdot p_{v,g_i} \cdot L(u)$. Case five: when $T_i \neq T_j$, $L(g_i) > Q$ and $L(g_j) > Q$, perform swapping only if (i) $\Delta d = (p_{u,v'} \cdot p_{v',g_j} - p_{u,v} \cdot p_{v,g_i}) \cdot L(u) > 0$, and (ii) $L'(g_i) = L(g_i) - p_{u,v} \cdot p_{v,g_i} \cdot L(u) \ge Q$.

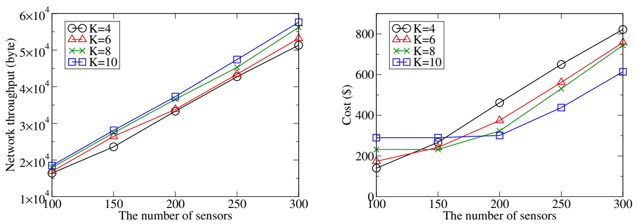
Having performed a series of edge swapping, the network throughput is increased while the service cost is further optimized. We refer to this improved algorithm as `Impro_Alg`.

Theorem 4. *Given an unreliable wireless sensor network $G(V \cup GW, E)$ with link reliability in $[p, (1+\delta)p]$ and $0 \le \delta \le \frac{1}{p} - 1$, there is an approximation algorithm* `Impro_Alg` *for the MTMC problem, with delivered a throughput no less than $\frac{1}{(1+\delta)^h}$ times of the maximum one and the service cost is no more than $(1 + \frac{C_p}{C_f})$ times of the minimum one, where h is the maximum number of hops from any sensor to its nearest gateway. The algorithm takes $O(|V| \cdot |E|^2)$ time.*

Proof. Omitted, due to limited space. □

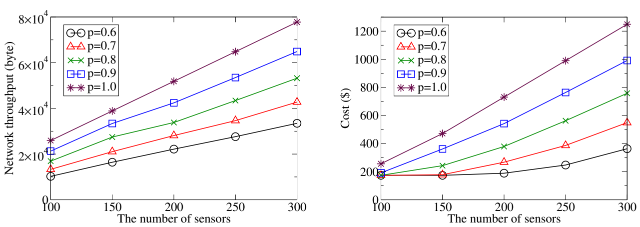
5. PERFORMANCE EVALUATION

In this section we evaluate the performance of the proposed algorithms in terms of network throughput and the service cost. We consider a sensor network consisting of 100 to 300 sensors randomly deployed in a $1000m \times 1000m$ square region. The transmission range of sensors is 120 meters, and the data generation rate is $r = 100 bytes/s$. The number of gateways K varies from 4 to 10, and they are deployed as follows. The monitoring region is divided into roughly equal-size K sub-regions with each containing one gateway randomly deployed. In our experiments, the following three different data plans provided by Vodafone [5] for one month monitoring period (i.e. $\tau = 30days \times 24hours \times 3,600seconds$) will be examined: (I) $Q = 2GB$ and $C_f = \$19$; (II) $Q = 4GB$ and $C_f = \$29$; and (III) $Q = 10GB$ and $C_f = \$39$. Each of these three data plans has the same penalty rate $c_p = \$0.02/MB$. Each value in the figures is the mean of the results by applying the mentioned algorithm to 20 different network topologies of the same size.



(a) Network throughput (b) Cost with Plan (II)

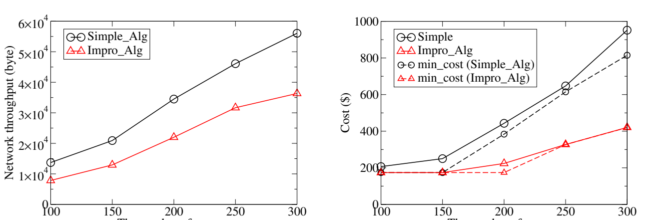
Figure 1: Impact of K on the network performance when $p = 0.8$ and Plan (II) is adopted.



(a) Network throughput (b) Cost with Plan (II)

Figure 2: Impact of link reliability p on the network performance when $K = 6$ and Plan (II) is adopted.

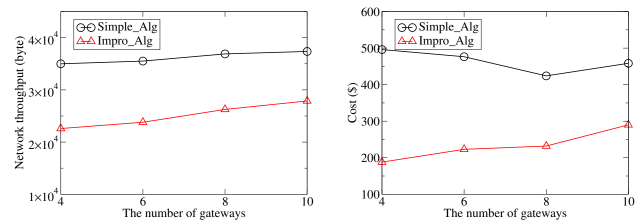
We first study the performance of algorithm `Uniform_Link`. Fig. 1 shows the larger number of gateways K, the higher network throughput the algorithm delivers and so is the service cost. Fig. 2 indicates that the higher the link reliability, the larger the network throughput, and the higher the service cost.



(a) Network throughput (b) Cost with Plan (II)

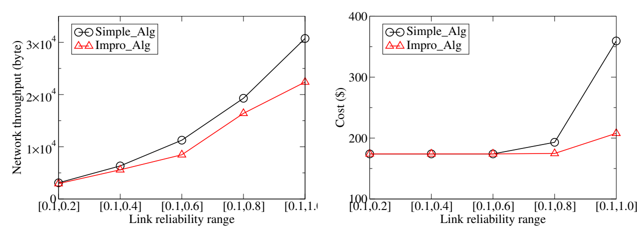
Figure 3: Performance of different algorithms when $K = 6$, $p_e \in [0.1, 1]$ for each link $e \in E$, and Plan (II) is adopted.

We next evaluate the performance of algorithms `Simple_Alg` and `Impro_Alg`. Fig. 3 plots that the network throughput delivered by algorithm `Impro_Alg` is no less than 78% of the maximum throughput, while its service cost is no more than 103% of the minimal cost. The dashed curve in Fig. 3(b) is a lower bound on the minimum service cost, which is calculated by assigning data relay workload equally to gateways. The costs delivered by algorithms `Simple_Alg` and `Impro_Alg` are respectively 116% and 103% of their minimum costs. Fig. 4 illustrates that a larger K will result in a higher network throughput but does not necessarily incur a higher service cost. Fig. 5 shows that with the growth in the range of link reliability, the network throughput increases, so does the service cost.



(a) Network throughput (b) Cost with Plan (II)

Figure 4: Impact of K on the network performance when $n = 200$, $p_e \in [0.1, 1]$ for each link $e \in E$, and Plan (II) is adopted.



(a) Network throughput (b) Cost with Plan (II)

Figure 5: Impact of the range of link reliability on the network performance when $K = 6$, $n = 200$, and Plan (II) is adopted.

6. CONCLUSION

In this paper we first formulated the MTMC problem and showed its NP-completeness. We then proposed an approximation algorithm with guaranteed approximation ratio. We finally conducted experiments by simulations to evaluate the performance of the proposed algorithms. Experimental results demonstrated that the proposed improved algorithm is very promising, and the solution is fractional of the optimum.

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