Minimum Coverage Breach and Maximum Network Lifetime in Wireless Sensor Networks

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***Abstract*—Network lifetime is a critical issue in Wireless Sensor Networks. It is possible to extend network lifetime by organizing the sensors into a number of sensor covers. However, with the limited bandwidth, coverage breach (i.e, targets that are not covered) can occur if the number of available time-slots/channels is less than the number of sensors in a sensor cover. In this paper, we study a joint optimization problem in which the objective is to minimize the coverage breach as well as to maximize the network lifetime. We show a "trade-off" scheme by presenting two strongly related models, which aim to tradeoffs between the two conflicting objectives. The main approach of our models is organizing sensors into non-disjoint sets, which is different from the current most popular approach and can gain longer network lifetime as well as less coverage breach.**

We proposed two algorithms for the first model based on linear programming and greedy techniques, respectively. Then we transform these algorithms to solve the second model by revealing the strong connection between the models. Through numerical simulation, we showed the good performance of our algorithms and the pictures of the tradeoff scheme in variant scenarios, which coincide with theoretical analysis very well. It is also showed that our algorithms could obtain less breach rate than the one proposed in [2].

I. Introduction

Wireless sensor networks (WSNs) has attracted much attention of many researchers due to a wide-range of potential applications [5], [6], [7]. One of the most critical issues in WSNs is energy efficiency since sensors are battery powered. Therefore, conserving energy resource and prolonging network lifetime are very important in the design of large-scale WSNs.

An important problem addressed in WSNs is the coverage problem. The goal is to have each targets being monitored by at least one sensors. Due to the energy constraint, solving the coverage problem with the objective of maximizing network lifetime is very important. Many algorithms have been proposed, in which the major approach is to organize sensors into a number of subsets [1], [3], [4], [11] such that each set completely covers all the targets. These sensor sets are activated successively, such that at any time instant only one set of sensors is active. This approach efficiently extends network lifetime because of the following two reasons: 1) In [9], an analysis of the energy usage for WINS Rockwell seismic sensor indicates that the energy consumption in the sleep state is about 15 times less than that in the active state. 2) Battery lifetime is approximately twice as much if it is discharged in short bursts with significant off time as in a continuous mode of operation [10]. Having sensor nodes frequently oscillate between an active and an inactive state extends battery lifetime.

However, these approaches may have a major problem in networks with limited bandwidth. Bandwidth is defined as either the total number of time slots in a time division scheme for a single channel, or the number of channels if multiple channels are available [2]. The ultimate goal of sensor networks is to provide all the sensed data to an observer in a timely manner. To ensure data can be transmitted to base stations on time, one major requirement is that there must be sufficient bandwidth. However, in some applications, it is sufficient to cover most part of targets/area. In both a single-hop network or a multi-hop network with the real-time requirement, if there are W available channels and more than W sensors in a subset, then some sensors cannot access the channels for data transmission and consequently the observer cannot receive all data on time.

In this paper, we study the coverage problem under bandwidth constraints. One straightforward way to model the bandwidth constraints is to divide the sensors into a number of subsets where the size of each set doesn't exceed the number of available channels, W. However, this results in coverage breach (i.e., targets that are not covered). Hence, we can consider the joint optimization on energy and bandwidth utilization. That is to maximize network lifetime as well as to minimize the total coverage breach.

We present a tradeoff scheme including two new models, Minimum Coverage Breach under Bandwidth constraints (MCBB) and Maximum Network Lifetime under Bandwidth constraints (MNLB), to solve this joint optimization problem. The former is for applications that sufficient long network lifetime is desired while the latter is for those whose coverage breach is more critical.

In this paper, we use a discrete target model, in which the objective is to monitor a set of fixed targets. Indeed, we can transform the area coverage into a discrete target model by dividing the area into a number of fields where each field is monitored by the same set of sensors [4], [11]. Here, we can treat each field as a target.

The rest of this paper is organized as follows. Section II presents the related works. In Section III, we precisely define the MCBB problem and MNLB problem respectively. In Section IV and Section V, a LP-based approximation algorithm and a greedy heuristic are proposed for the MCBB problem. We then design algorithms for the MNLB problem by using the two algorithms above in Section VI. Section VII provides the numerical performance, including the comparison between our algorithms and existing related algorithms through numerical simulation. In Section VIII, we concludes the paper.

II. RELATED WORK

Although prolonging network lifetime for the coverage problem in wireless sensor networks have been studied extensively, there is not much research on the consideration of transmission bandwidth constraints when organizing sensors into subset. To our knowledge, the first and also the only one addressed this problem is [2]. The authors in [2] modeled the Minimum Breach Problem as an Integer Programming in which sensors are organized into *disjoint* subsets where the size of each set is less than or equal to W and the overall breach is minimized. The number of these sets is set to $\frac{n}{W}$ where n is the number of sensors. In case n is not divisible by W, ceiling or floor is used. The authors then presented two heuristics called RELAXATION and MINBREACH. However, since the number of subsets is strictly fixed and disjoint subsets are utilized, the network lifetime is therefore fixed. On the other hand, the disjointness constraint is not necessary to obtain a maximum network lifetime nor to obtain a minimum coverage breach, which we will explore further in section III and VII. By relaxing the restriction on the total lifetime and the disjointness, we can not only achieve less coverage breach under the same network lifetime, but the way of tradeoffs between coverage breach and network lifetime as well, which may be more important in applications.

For the Maximum Network Lifetime problem, the most relevant works to our approach are [1], [3], [4], [11]. The objectives of these works are to prolong network lifetime without considering the bandwidth constraints. Both [4] and [3] proposed energy efficient centralized mechanisms by dividing the sensor nodes into disjoint sets and each set completely covers the monitored region. The goal is to determine a maximum number of disjoint sets, as this has a direct impact on conserving energy resources as well as on prolonging network lifetime. Specifically, the disjoint set cover problem in [3] was reduced to a maximum flow problem, which is then modeled as a Mixed Integer Programming. In [4], a polynomial time heuristic called Most Constrained-Least Constraining Covering Heuristic was proposed to compute the disjoint covers successively.

In [11], Berman *et al.* introduced another approach for the maximum network lifetime problem using a packing Linear Programming technique. In this approach, sensors are divided into *non-disjoint* sets. They proposed an approximation algorithm with the performance ratio of $(1+\varepsilon)(1+2\ln n)$ for any $\varepsilon > 0$. The running time of this polynomial-time approximation scheme is quite high. Authors in [1] proposed another model called Maximal Set Covers (MSC) in which they obtain a $(1+\varepsilon)$-approximation algorithm. They also showed that organizing sensors into non-disjoint sets instead of disjoint ones achieves a better result in terms of network lifetime.

Note that none of these solutions for the maximum network lifetime problem considers the bandwidth constraints. In this paper, we take the bandwidth constraints into account.

III. PROBLEM DESCRIPTION

In this section, we formally give the definitions of coverage breach and two optimization problems, Minimum Coverage Breach under Bandwidth constraints (MCBB) problem and Maximum Network Lifetime under Bandwidth Constraints (MNLB) problem.

Let us assume that n sensors s_i, $i = 1...n$, are deployed to cover m targets r_k, $k = 1...m$. We also assume that all of the sensors have the same initial energy. Without loss of generality, the initial lifetime for each sensor is set to 1, i.e., each sensor can be active continuously for 1 unit time. We define a *(Partial) Sensor Cover* of a network to be a non-empty subset of sensors.

Definition 1: A *Scheduling* is a set of ordered pairs (S_j, t_j), $j = 1...p$, where S_j is a sensor cover (not necessarily disjoint) and t_j is the active time duration for S_j. The *Total Lifetime (TL)* of a scheduling is the summation of t_j's, i.e., $TL = \sum_{j=1}^{p} t_j$.

Definition 2: Given a scheduling (S_j, t_j), the *total coverage breach* is defined as: $\sum_{j=1}^{p}\sum_{k=1}^{m}(t_j - t_j z_{jk})$, where $z_{jk} = 1$ if at least one sensor in S_j can covers target r_k; otherwise, $z_{jk} = 0$. The *Breach Rate (BR)* of a scheduling is defined as:

$$BR = \frac{\sum_{j=1}^{p}\sum_{k=1}^{m}(t_j - t_j z_{jk})}{m \cdot \sum_{j=1}^{p} t_j} .$$

In this definition, the TCB is the total time while coverage breach is happening for all targets. Since the value of TCB is strongly related to the total lifetime, we could use breach rate instead of TCB as the coverage performance criteria.

From the description in Section I, reducing the breach rate and extending the total lifetime of a sensor network scheduling are two critical but conflicting goals. In order to address the tradeoffs between them, we define the MCBB problem and the MNLB problem respectively.

Definition 3: **Problem MCBB** (W, T_0): Given a sensor network with n sensors and m targets, find a scheduling (S_j, t_j), to minimize the total coverage breach (TCB) while satisfying that the total lifetime (TL) is at least $T_0 (0 \leq T_0 \leq n)$. The total time for each sensor in $S_1, .., S_p$ is at most 1 and $|S_j| \leq W$ which indicate the bandwidth constraints.

Note that the *Minimum Breach* problem defined in [2], which restricts that all S_j are disjoint and T_0 is equal to n/W, is a special case of MCBB problem.

Definition 4: **Problem MNLB** (W, α): Given a sensor network with n sensors and m targets, find a scheduling (S_j, t_j), to maximize the total lifetime (TL) while satisfying that the breach rate (BR) is at most $\alpha (0 \leq \alpha \leq 1)$. The total time for each sensor in $S_1, .., S_p$ is at most 1 and $|S_j| \leq W$.

The MNLB problem can be regarded as a complementary problem of the MCBB problem. We can prove that both of them are NP-hard. Due to the page limitation, we conclude this in the following theorem without giving proof.

Theorem 1: Both MCBB and MNLB are NP-hard.

Specifically, MCBB and MNLP have different targets. In an application where the network lifetime is critical, a solution to the MCBB problem will give us a guarantee on sufficient lifetime. And in some other cases, if we have an threshold of breach rate but flexible network lifetime, it can be achieved by solving the corresponding MNLB problem. If both of the two parameters are flexible but a relative "balance" is desired, we can also get tradeoff pictures which could give helps.

A difference between the MCBB problem and the Minimum Breach problem proposed in [2] is that we use non-disjoint sensor covers instead of disjoint ones. Let us consider the following example which shows us the advantage of our one.

Assume that we have 3 sensors $\{s_1, s_2, s_3\}$ and 3 targets $\{t_1, t_2, t_3\}$, where s_1 covers $\{t_1, t_2\}$, s_2 covers $\{t_2, t_3\}$, and s_3 covers $\{t_3, t_1\}$. Suppose that the bandwidth constraint is $W = 2$ and we can define a MCBB instance with TL constraint $T_0 = 1.5$. One optimal disjoint solution is: $\{s_1, s_2\}$ with duration 1 and $\{s_3\}$ with duration 0.5. The breach rate is $\frac{3 \times 1 + 1/2}{3 \times 3/2} \approx 11.1\%$. However, by using the non-disjoint scheduling $\{\{s_1, s_2\}, \{s_2, s_3\}, \{s_3, s_1\}\}$ with the same duration $1/2$, the breach rate is reduced to 0. Similarly, if we construct a MNLB instance with the breach rate constraint $\alpha = 0$ and bandwidth $W = 2$, TL is improved from 1 to 1.5 by using a non-disjoint scheduling. The simulations in section VII will show some similar results.

IV. LP-BASED ALGORITHM FOR MCBB

In this section, we prensent an algorithm, called Maximum Sensor Cover-Minimum Breach (MSCMB), for the MCBB problem using LP-relaxation techniques. Before we introduce the algorithm, we first give the mixed integer programming formulation of MCBB problem.

A. Mixed Integer Programming Formulation and its LP-relaxation

Let us first set a bound p for the number of sensor covers. In theory, p is 2^n. However, exponential size scheduling is unacceptable. Here we will preset it to be some fixed large enough number, e.g., n. Then we formulate the MCBB problem as follows:

Given: a set of n sensor nodes $C = \{s_1, ..., s_n\}$; a set of m targets $R = \{r_1, ..., r_m\}$; for each target r_k, define $C_k = \{i | \ s_i \text{ covers } r_k\}$.

Define variables:

- x_{ij}, boolean variables, for $i = 1...n$ and $j = 1...p$; $x_{ij} = 1$ iff sensor s_i is in the sensor cover S_j.
- z_{jk}, boolean variables, for $j = 1...p$ and $k = 1...m$; $z_{jk} = 1$ iff sensor cover S_j covers target r_k.
- $t_j \in (0, 1)$, represents the duration allocated for S_j.

The MCBB problem can be formulated as:

$$\begin{array}{ll} \text{minimize} & \sum_{j=1}^{p} \sum_{k=1}^{m} (t_j - t_j \cdot z_{jk}) \\ \text{subject to} & \sum_{j=1}^{p} x_{ij} t_j \leq 1, \text{ for all } s_i \in C \\ & \sum_{i \in C_k} x_{ij} \geq z_{jk}, \text{ for all } r_k \in R, j = 1...p \\ & \sum_{i=1}^{n} x_{ij} \leq W, \text{ for all } j = 1...p \\ & \sum_{j=1}^{p} t_j \geq T_0 \\ \text{where} & x_{ij} = 0, 1 \ (x_{ij} = 1 \text{ iff } s_i \in S_j) \\ & z_{jk} = 0, 1 \ (z_{jk} = 1 \text{ iff } S_j \text{ covers } r_k) \\ & 0 \leq t_j \leq 1 \end{array}$$

- the first constraints guarantee that the active time duration allocated to each sensor s_i, across the scheduling, is not larger than 1, which is the lifetime of each sensor.
- the second constraints imply that each target r_k is covered by at least one sensor s_i in each sensor cover S_j if $z_{jk} = 1$, and breach will occur otherwise.
- the third ones are the bandwidth (cardinality) constraints for each sensor cover.
- the fourth ones are the TL constraints, which guarantees the total lifetime of the network is at least T_0.

In order to obtain the LP-relaxation of the problem, we set $y_{ij} = x_{ij} t_j$ and $w_{jk} = t_j z_{jk}$ and then remove the integer constraints on y_{ij} and w_{jk} as follows.

$$\begin{array}{ll} \text{minimize} & \sum_{j=1}^{p} \sum_{k=1}^{m} (t_j - w_{jk}) \\ \text{subject to} & \sum_{j=1}^{p} y_{ij} \leq 1 \text{ for all } s_i \in C \\ & \sum_{i \in C_k} y_{ij} \geq w_{jk} \text{ for all } r_k \in R, j = 1...p \\ & \sum_{i=1}^{n} y_{ij} \leq t_j W \text{ for all } j = 1...p \\ & \sum_{j=1}^{p} t_j \geq T_0 \\ \text{where} & 0 \leq y_{ij} \leq t_j \leq 1 \\ & 0 \leq w_{jk} \leq t_j \leq 1 \end{array} \quad (1)$$

B. MSCMB algortihm

We are now ready to introduce our MSCMB algorithm. The MSCMB algorithm consists of three steps. At the first step, we solve the LP equation (1) to obtain an optimal solution $(w_{jk}^*, y_{ij}^*, t_j^*)$. Due to the relaxation technique, this solution might not be a solution of the Mixed Integer Programming. Thus at the second step, we need to find a feasible solution according to the optimal solution for the relaxed LP.

We initialize variables y_{ij}^h to 0 for saving the feasible solution. For each j, we sort $\{w_{jk}^*\}$, for $k = 1 \ldots m$, into a non-increasing sequence. Then we pop up the first element $w_{j_1 k_1}^*$(recall that w_{jk} indicates if the target k is covered by the j-th sensor cover) from the sequence. If the target k has already been covered by the sensors which has been selected into j-th sensor cover, the target k will be omitted in this iteration. Otherwise, we sort $\{y_{ij_1}^*\}$, for $i \in C_{k_1}$ (y_{ij} indicates if the sensor i is selected in the j-th sensor cover), in non-increasing order separately. Next we select the largest y_{ij}^* in the sequence and let $y_{ij}^h = t_j^*$ if the sensor i still have remaining lifetime more than or equal to t_j^*. We continue selecting sensors until the size of the j-th sensor cover exceeds W or all the targets are already covered by current sensor cover. We repeat this process for $j = 1 \ldots p$ to obtain a feasible solution and output it. The algorithm is shown in Algorithm 1.

Note that in the model of [2], the number of sensor covers is set to $\frac{n}{W}$ and the time duration of each sensor cover is fixed to 1, resulting in the maximum network lifetime bounded by $\frac{n}{W}$. In our algorithm, we can set p to a large number and also obtain fractional number time duration for each sensor cover, which can obtain better breach rate as well as handle the case with network lifetime longer than $\frac{n}{W}$.

Algorithm 1 MSCMB

```
Initialize the coverage breach B = 0
Initialize network lifetime for each sensor s_i: T_i = 1
Solve the LP equation (1) to obtain (w*_jk, y*_ij, t*_j)
B = 0 /* Total Coverage Breach */
for j = 1 to p do
    Set S^h_j = ∅; w^h_jk = 0; y^h_ij = 0 for all i = 1,...,n, k = 1,...,m
    Sort w*_jk's, for all k = 1,...,m, into a non-increasing sequence W
    while W is non-empty do
        Pop up the first element w*_jk' from the sequence W
        if w^h_jk' == 0 then
            Choose a sensor s_i' ∈ C_k' such that y*_i'j is the largest among all y*_ij's
            if |S_j ∪ {s_i'}| ≤ W and T_i' ≥ t*_j then
                /* Check the remaining lifetime of s_i' and the size of S_j */
                set y^h_i'j = t*_j
                S^h_j = S^h_j ∪ {s_i'}; T_i' = T_i' − t*_j
                Set w^h_jk = 0 if s_i' ∈ C'_k, for all k = 1,...,m
            else
                w^h_jk = 0 /* sensor cover S_j does not cover target r_k */
            end if
        end if
    end while
    B = B + Σ_{k=1}^{m} (t*_j − w^h_jk)
end for
Return B, (S^h_j, t^h_j)
```

V. GREEDY HEURISTIC FOR MCBB

The MSCMB algorithm has a scalability problem since to obtain the optimal solution of a linear programming instance requires at least $O(n^3)$ running time. It significantly slows down the algorithm. Even for centralized controlling, the time cost of MSCMB for a large-scale network may not be affordable. To solving this difficulty, we develop a fast greedy heuristic GREEDY-MSC.

Different from the MSCMB algorithm, we need to preset a time granularity l_0, which is the specified time length of each sensor covers (clearly, if $l_0 = 1$, the algorithm actually computes a disjoint scheduling). Accordingly, we set $p = T_0/l_0$.

The basic idea of GREEDY-MSC is to find a max-coverage sensor cover using a greedy strategy. Assuming that T_i is denoted the remaining lifetime for the sensor s_i, in iterations, we select the sensor with the maximum "weight" u_i, where $u_i = T_i \times |\{k|s_i \text{ covers target k}\}|$. For each sensor cover, we keep selecting until the size of the sensor cover exceeds W or all targets are covered.

However, in the case that $W > n/T_0$, since the total battery supply of all the sensors is n, if we choose more than n/T_0 sensors in each sensor cover, the TL constraint may be violate. Thus, we use a dynamic sensor selection process: Suppose that j' sensor covers are already selected, and the size of each sensor cover is $W_j (j = 1, \ldots, j')$. Then we put at most $\min\{W, \lfloor \frac{(n - \sum_{i=1}^{n} T_i)}{\sum_{j=1}^{j'} W_j \times l_0} \rfloor\}$ sensors in the next set. The algorithm is shown in Algorithm 2.

Algorithm 2 GREEDY-MSC

```
Preset: time granularity l_0
T_i = 1 for each i = 1,...,n /* Lifetime of each sensor s_i */
t = 0 /* Total lifetime for already selected sensor covers */
j = 1 /* Index of sensor covers, which doesn't exceed ⌈T_0/l_0⌉ */
while t < T_0 do
    SC_j = ∅ /* Sensor cover j */
    W_j = 0 /* Cardinality of sensor cover j */
    while |SC_j| + 1 ≤ min{W, ⌊(n − Σ_{i=1}^{n} T_i) / (Σ_{j=1}^{j'} W_j × l_0)⌋} do
        For each sensor s_i ∉ SC_j, compute its weight u_i = T_i ×
        |{k| target k is covered by s_i and not covered by SC_j}|
        Assuming u_i' is the largest, SC_j = SC_j ∪ {s_i}
        T_i' = T_i' − l
        W_j = W_j + 1
    end while
    t = t + l
    j = j + 1
end while
Return {SC_j}
```

VI. MNLB PROBLEM VS. MCBB PROBLEM

Although the MNLB problem has a similar formulation of MCBB, this problem may be harder. Since the breach rate (BR) constraint is an average property over all sensor covers, it is more difficult to handle. Specifically, for instance, when we try to use a similar GREEDY heuristic to solve MNLB, on one hand we can only guarantee BR constraint by only select sensor covers with smaller breach rate. But on the other hand, we might lose too much lifetime due to omit all the sensor covers with higher breach rate, adding which doesn't affect the "average" BR constraint over the total lifetime.

Fortunately, instead of designing complicated algorithms, we can use above two algorithms as a subroutine, to solve the MNLB problem, which is regarded as a complementary problem of the MCBB problem.

Assume that we have already had an algorithm, say, MCBB-ALG, to solve the MCBB problem. Obviously, the possible optimal TL can only fall between 0 and n (the total battery supply). Hence, we can use an binary search technique.

Specifically, we keep guessing the optimal TL for the given MNLB problem to be the middle point between the lower and upper bound. Then we solve an MCBB instance with this guessed TL constraint and check if the output solution from the MCBB-ALG is better than the original BR constraint. And accordingly, we modify the upper bound and the lower bound, and repeat, until the difference between the bounds are small enough. The algorithm is described in Algorithm 3.

Algorithm 3 Binary Search Algorithm for MNLB

Given: an algorithm MCBB-ALG which can solve the MCBB problem
Preset the accuracy parameter ϵ
$LB = 0$ /* initialize the lower bound of TL */
$UB = n$ /* initialize the upper bound of TL */
$SC = \emptyset$ /* initialize the scheduling */
while $UB - LB \leq \epsilon$ **do**
  $T_0 = \frac{UB+LB}{2}$
  Solve the MCBB problem with TL constraint T_0 through MCBB-ALG. Assume that the BR and TL of the MCBB-ALG's output is β and T, respectively
  if $\beta \leq \alpha$ **then**
    $LB = T$
    Update SC to be the output scheduling from the MCBB-ALG
  else
    $UB = T$
  end if
end while
Return LB and SC

We denote the algorithms for MNLB using MSCMB and GREEDY-MSC as MNLB-LP and MNLB-GREEDY, resp..

VII. Numerical Results

In this section, we evaluate the performance of the MSCMB and the GREEDY-MSC algorithms using BR as a performance metric. We also evaluate the network lifetime obtained from the MNLB-LP and the MNLB-GREEDY algorithms. As comparison, the RELAXATION [2] and the LP-MSC algorithms [1] are also simulated.

In this simulation, sensors and targets are uniformly deployed in a $500m$ by $500m$ area in random. To thoroughly evaluate the performance of these algorithms, we considered the following tunable parameters:

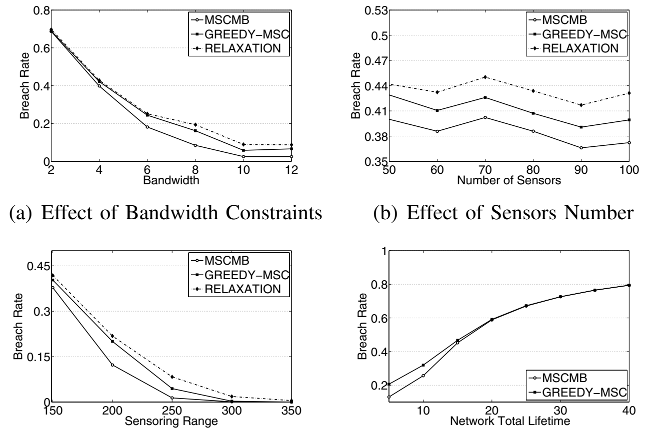
- **W**, the bandwidth.
- **n**, the number of sensor nodes.
- **range**, the sensing range.
- $\mathbf{T_0}$, the network lifetime constraint for MCBB. [1]
- α, the breach rate constraint for MNLB.

A. Results of Algorithms for MCBB

For the algorithms for MCBB, four different scenarios are considered. Figure 1 shows comparisons between our algorithms and RELAXATION. For all the scenarios, the default parameter is $n = 50$, $m = 30$, $W = 4$, $range = 150$ and $T_0 = \lceil \frac{n}{W} \rceil$.

Figure 1(a) presents the performance of the three algorithms with respect to the bandwidth. In this experiment, the bandwidth W increased from 2 to 12 with an increment of 2. As predicted by the models, the breach rate obtained from our algorithm is smaller than the RELAXATION's. In addition, we

[1]Since in the case of the algorithm RELAXATION, the total lifetime is fixed to $\lceil \frac{n}{W} \rceil$, we will also fix $T_0 = \lceil \frac{n}{W} \rceil$ in the case when T_0 is not considered as the variable parameter.



(a) Effect of Bandwidth Constraints (b) Effect of Sensors Number (c) Effect of Sensing Range (d) Effect of Network Total Lifetime

Fig. 1. Performance of MSCMB and GREEDY-MSC Compared with RELAXATION

notice that the BR decreases when the bandwidth increases. It indicates that the bandwidth constraints have a major impact on improving the network coverage.

To study the effect of the number of sensors under bandwidth constraints, we set up the networks with the number of sensors increasing from 50 to 100 with an increment of 10. As can be seen in Figure 1(b), for the MSCMB algorithm and the GREEDY-MSC algorithm, as well as for the RELAXATION algorithm, increasing the number of sensors does not result in the decreasing of BR. The main reason for this phenomenon is the size constraint of each sensor cover. Note that our algorithms can also obtain smaller breach rate. The BR from both the MSCMB algorithm and GREEDY-MSC algorithm are less than the one from the RELAXATION due to the utilization of non-disjoint sensor covers.

Figure 1(c) reveals the effect of sensing range on improving the network coverage as well as the performance comparison of the algorithms. The sensing range increased from 150m to 350m with an increment of 50. As shown in Figure 1(c), the performance of both MSCMB and GREEDY-MSC are still better than RELAXATION. As expected, the BR decreases when the sensing range increases since each sensor can cover more targets.

At last, to study the effect of total lifetime constraint, we deploy the networks and vary the TL from 5 to 40. Figure 1(d) supplies a desired tradeoffs curve. As expected, the BR increases when the TL increases since the average energy resource for each sensor cover decreases, and the curve gives all possible choices for our decision. Note that in a large range, the performance of our greedy algorithm is quite close to the one of the MSCMB algorithm. In addition, since the RELAXATION algorithm only works in the case that $T_0 = \lceil n/w \rceil$, we cannot compare with it for this scenario.

B. Results of Algorithms for MNLB

For the algorithms for MNLB, effect of constraints on W and α are studied, respectively. We use the following value

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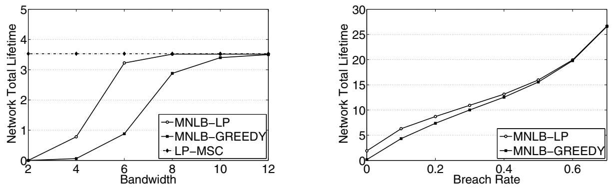

(a) Effect of Bandwidth Constraints (b) Effect of Breach Rate

Fig. 2. Performance of MNLB-LP and MNLB-GREEDY Compared with LP-MSC

for the parameters as default: $m = 20$, $n = 50$, $range = 150$, $\alpha = 0$, $W = 5$. The results is shown in Figure 2. Because that the MNLB problem is first studied and there are few similar works, we cannot find a proper algorithm to compare, except some algorithms regardless of bandwidth constraints.

In Figure 2(a), the effect of bandwidth constraints are illustrated. We vary W from 2 to 12 and present the TL obtained by the MNLB-LP and MNLB-GREEDY, respectively. We compare our algorithm with the LP-MSC algorithm which is proposed in [1] for the MSC problem without bandwidth constraint. As can be seen in Figure 2(a), network lifetimes of both MNLB-LP and MNLB-GREEDY are approaching to the LP-MSC's when W is increasing. This is because when W is large enough, the bandwidth constraint can be removed and the MNLB problem will actually become the MSC problem. Interestingly, if $W \geq 8$ (12, resp.), the MNLB-LP (MNLB-GREEDY, resp.) algorithm can actually offer an result with guaranteed small size of each sensor set, which has as long lifetime as that from the LP-MSC algorithm. This implies that our algorithm is also competitive even for the model without bandwidth constraints.

Figure 2(a) reveals the effect of the breach rate constraint. The BR increased from 0 to 0.8 with an increment 0.2. As we can expect, the output TL from either MNLB-LP and MNLB-GREEDY increases when BR increases since we need even less than W sensors in each sensor cover when BR constraint is not tight. Also, the results coincide with the conclusion in Figure 1(b) very well.

C. Summary of Experimental Results

In conclusion, the simulation results reveal that the limited bandwidth effects dramatically on the network coverage as well as network lifetime. Tradeoffs between the two main objectives, are shown through the simulation, which can give useful suggestions on an optimal configuration in various applications. In addition, non-disjoint sensor cover can give better results than disjoint ones. For all aspects that we have studied, the MCBB model can improves the network coverage rate than the model in [2]. Specially, the average improvement for breach rate is 10% according to comparisons between MSCMB and RELAXATION.

VIII. Conclusions

Wireless sensor networks are limited in power and radio spectrum. Therefore, maximizing network lifetime and minimizing coverage breach through a power aware node organization are highly critical. In this paper, we studied this joint optimization problem. Our solution is to organize the sensors into non-disjoint sensor covers such as to minimize the overall coverage breach and the size of each sensor cover is less than or equal to the number of available slots/channels. Sensor covers are activated successively, such that at any time instant, only one is responsible for sensing the targets while all the others are in the sleep state. We addressed a tradeoff scheme including two complementary problems, MCBB and MNLB. We studied and proposed an LP-based algorithm and a greedy heuristic for the MCBB problem. Due to the relation between the MCBB problem and the MNLB problem, we can apply the two algorithms to solving the MNLB problem effectively. Through the numerical simulation, we show the performance of our algorithms and tradeoff pictures between breach rate and network lifetime, which both coincide the theoretical analysis very well in different scenarios. Furthermore, we also showed the breach rate obtained from our solution is less than the RELAXATION's due to the use of non-disjoint sensor covers.

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