Efficient Field Coverage in Mobile Sensor Networks: A CPS Perspective

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***Abstract*— Mobile sensor networks (MSN) are an excellent example of Cyber-Physical Systems where motion capability of the network nodes offers an opportunity to co-design the physical and cyber components of the system. As sensor nodes have limited energy resources; the relocation strategy could have a significant impact on the operational lifetime of such networks. In this paper, a novel autonomous joint sensing range and relocation control algorithm is presented that achieves improved coverage and network life-span at the same time. In the proposed algorithm, the sensing range of each sensor is adjusted iteratively based on its residual energy. At the same time, the sensor is directed to move in a direction that will result in increasing the total sensing coverage in the field. Simulation results demonstrate the efficacy of the technique.**

I. Introduction

Rapid advances in mobile technology, transceiver miniaturization, and energy efficiency have resulted in tremendous growth of pervasive information technologies such as embedded systems. Increasingly, these technologies are combined with elements of the physical world (e.g., machines, devices, structures) to create smart and intelligent systems that offer increased effectiveness, productivity, safety, and speed. Integrated networking, information processing, sensing and actuation capabilities allow physical devices to interact with the environments surrounding them. Tightly coupled cyber and physical systems that exhibit this level of integrated intelligence are referred to as cyber-physical systems (CPS). Coordinated robots, intelligent buildings, network of implantable medical devices, driver-less cars or planes could all be instances of CPS. Everyday life is becoming increasingly dependent on these systems; therefore dramatic improvements in their performance are continually expected.

All CPS have computational processes that interact with physical components. These can be relatively simple (e.g., single component) or comprise multiple components in complex assemblies. The computational and physical processes of such systems are tightly interconnected and coordinated to work together effectively. However, to differentiate cyber-physical system against traditional embedded systems another level of integration (or optimization) at the system design phase might be required. In other word, a true CPS should involve the co-design of cyber and physical components. The methodology to accomplish this joint design is still subject of research for various applications; and, until such methodologies or appropriate design tools are developed, the differentiation between CPS and embedded systems might not be significant. In fact, a true cyber-physical system should exhibit performance gains that are beyond the simple integration of cyber and physical components (i.e. embedded systems). This is indeed the fundamental concept and motivation behind CPS.

Mobile sensor networks (MSN) are an excellent example of Cyber-Physical Systems where motion capability of the network nodes offers an opportunity to co-design the hardware (i.e. physical) system with various software (i.e. cyber) components. Wide range of monitoring applications of MSNs e.g. environmental, healthcare, defense, disaster response, surveillance (as well as cost effectiveness, reliability and safety advantages in hazardous environments) have prompted considerable attention to this technology in various research communities [1], [2], [3].

The locations of the sensors in a MSN affect both their ability to acquire information on the intended targets and events (i.e. field coverage) as well as their ability to communicate this information to the intended recipients. The capability of motion in MSNs allows for relocation of sensors to new locations that could result in enhancing the overall network performance. At the same time, constraint on energy expenditure of mobile sensors limits the amount of movement that is possible by each node. Longevity of the mobile nodes directly impact the network operational lifetime and therefore should be a design constraint in any cyber component of mobile sensor networks.

Our CPS vision for mobile sensor networks is that by exploiting joint physical and cyber component design, significant improvements in field coverage as well as network lifetime can be achieved. This paper outlines an effort in this direction where we propose joint control algorithms for relocation and sensing range. The control algorithm for relocation should be further integrated with the hardware (i.e. mechanical system) design to achieve a true cyber-physical system.

The relocation ability of the nodes in a MSN creates new possibilities for intelligent control of their individual motion in order to optimize the performance of the whole network. However, mobility adds additional burden to an already scarce energy resource in such networks. In the coverage problem, relocating each node to an appropriate position could lead to a much better global coverage throughout the field by the network. However, this comes at the cost of higher energy consumption, and since each node has limited amount of battery power, excessive movements for a node could deplete its remaining energy supply faster. This, in turn, results in an early termination of its sensing function, hence reducing the overall covered area. Therefore, relocation of nodes in a mobile sensor network has to be done very judiciously. Other than node's position in the field, the other parameter that directly affects the network coverage is the sensing range of each sensor. Similarly, larger sensing range requires higher energy consumption. Any practical relocation strategy for providing maximal field coverage by a mobile sensor network should take energy limitation of individual sensors into consideration. In fact, the solution should strive for maximal coverage while ensuring maximum network lifetime.

In this paper, a joint sensing range and relocation control strategy is introduced that leads to better overall coverage while maximizing the network life-span. The sensor movement is performed iteratively and in each iteration sensors adjust their sensing ranges based on their residual energies. Every sensor then moves in a direction that leads to a larger covered area. To accomplish this, a multiplicatively weighted Voronoi (MW-Voronoi) diagram is used to find the coverage holes. A weight proportional to the sensing radius is assigned to each sensing node [4]. A sensor relocates to a new location only if (i) it has sufficient energy to move to the new location, and (ii) the covered area in its new location is larger. If any one of these conditions is not met, then the senor remains in its current

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position. It is shown that the proposed algorithm increases the covered area while maximizing network life-span.

The organization of the remainder of the paper is as follows. The problem and all the assumptions made are formally introduced in Section II. The main contributions of the paper are presented in Section III, where a novel algorithm is developed for efficient sensor deployment. Simulation results are given in Section IV, and finally the conclusions of the work are summarized in Section V.

II. Problem Statement

Given a group of n nonidentical mobile sensors in a flat field, let each sensor be represented by a weighted node. The sensors are randomly distributed in a 2D field, and the position of sensor i is denoted by P_i, for any $i \in \mathbf{n}$.

One of the common design specifications in any sensor network is energy efficiency [5]. It is known that power consumption of a mobile sensor is mainly due to sensing, communication, and movement. Power consumption for communicating over a distance d is proportional to d^γ, where γ is a real value between 2 and 4 (it is closer to 4 for a near-ground channel, which is the case in typical mobile sensor network applications [6]). The power required for sensing from a distance d is also proportional to d^λ, where $\lambda \geq 2$. On the other hand, an energy consumption model for sensor relocation is given by

$$E_i^{reloc}(P_i, \acute{P_i}) = \eta \widetilde{\acute{P_i} P_i} \tag{1}$$

where η is a constant, $\acute{P_i}$ is the i-th sensor's position after relocation, and $\widetilde{\acute{P_i} P_i}$ is its traveling distance [7]. In this paper, it is assumed that the sensors can adjust their sensing ranges. Moreover, a sensor consume energy for stopping or starting to move (the latter is because of static friction). It is assumed in this work that the energy required for stopping a mobile sensor and then overcoming its static friction after a complete stop is equivalent to the energy required for continuously moving the sensor 1m [5].

While maximizing coverage area is an important objective in an MSN, in most applications it is also desirable to maximize the life-span of the sensors and consequently increase the durability of the entire network. Let the sensing range of sensor i at time instant t be a circle of radius $r_i(t)$, centered at the position of that sensor. It is desired to move the sensors and place them in proper locations in the field and adjust their sensing ranges using a distributed deployment strategy such that while the covered area increases, the life-span of the network is also increased as much as possible. Different definitions are provided for network lifetime in the literature [8], [9]. Here, network lifetime is defined as the time when 20% of the nodes in the network deplete their energy supply completely, and therefore stop functioning.

Consider a sensor S_i, $i \in \mathbf{n}$, and let its sensing radius and MW-Voronoi region be denoted by $r_i(t)$ and $\Pi_i(t)$, respectively. Let also Q be a point inside $\Pi_i(t)$. Throughout this paper, the intersection of $\Pi_i(t)$ and a circle of radius $r_i(t)$ centered at Q is called the *i-th coverage area w.r.t. Q at time t*, and is denoted by $\beta_{\Pi_i}^Q(t)$. In particular, the i-th coverage area w.r.t. the location of the sensor S_i at time t is called the *i-th local coverage area at time t*, and is denoted by $\beta_{\Pi_i}(t)$. Furthermore, the total covered area of the field by all sensors at time t is referred to as the *total coverage area at time t*, and is denoted by $\beta(t)$.

In what follows, a performance criterion is defined, which accounts for both the MSN coverage area and life-span associated with non-renewable energy consumption of the sensor battery.

Throughout this paper, the expected value of the i-th local coverage area over the time interval $[t_a, t_b]$ is called the *i-th average coverage area over $[t_a, t_b]$*, and is denoted by $\beta_i[t_a, t_b]$. Also, the expected value of the total covered area over the time interval $[t_a, t_b]$ is called the *average total coverage area*, and is represented by $\beta[t_a, t_b]$.

Finally, consider an arbitrary point Q inside the MW-Voronoi region $\Pi_i(t)$, $i \in \mathbf{n}$. The area inside $\Pi_i(t)$ which lies outside the i-th coverage area w.r.t. Q at time t is referred to as the *i-th coverage hole w.r.t. Q at time t*, and is denoted by $\theta_{\Pi_i}^Q(t)$. The i-th coverage hole w.r.t. the location of the sensor S_i at time t is called the *i-th local coverage hole at time t*, and is denoted by $\theta_{\Pi_i}(t)$. Furthermore, the total uncovered area of the field at time t is called the *total coverage hole at time t*, and is denoted by $\theta(t)$.

III. Joint Relocation and Sensing Range Control Algorithm

A novel sensor relocation algorithm will be introduced in this section for efficient coverage and improved life-span of the network. The main characteristic of this algorithm is that the movement of sensors and adjustment of their sensing ranges are performed iteratively until the network dies. Each round in the proposed algorithm consists of five phases. The algorithm is run at the time instants t_0, $t_1 := t_0 + \Delta T$, $t_2 := t_0 + 2\Delta T$, ..., where ΔT is the time it takes to complete the computations and relocate the sensors accordingly. The details of the k-th iteration in the time interval $[t_k, t_{k+1}]$ are discussed below.

First phase: In this phase, every sensor S_i, $i \in \mathbf{n}$, at time t_k broadcasts its location $P_i(t_k)$ and residual energy $E_i(t_k)$ to other sensors and receives similar information from other sensor. Note that the sensors only need to communicate to each other in a short period of time at the beginning of the iteration and the communication links between sensors do not need to hold in the rest of the time interval. It is assumed that the consumed energy of the sensors E^{com} is fixed. For convenience of notation, the time argument will be omitted from the time dependent variables in the rest of the paper.

Second phase: In the second phase, each sensor adjusts its sensing range based on the remaining energy of all sensors in the network, and subsequently constructs its MW-Voronoi region. The sensing radius of every sensor is determined in this phase in such a way that a sensor which has less energy left consumes less power to increase the durability of the network. More precisely, the sensing radii are chosen in such a way that if the remaining energy of a sensor, say the i-th sensor, is m times larger than that of another sensor, say the j-th sensor, then the energy consumption rate of the i-th sensor due to sensing must be m times larger than that of the j-th sensor. Let the residual energy of the i-th sensor in the second phase be denoted by $\acute{E_i} = E_i - E^{com}$. As noted in the previous section, the power consumption of the i-th sensor due to sensing is proportional to R_i^λ, where R_i is its sensing radius. Choose the sensing radii of the sensors as follows:

$$R_i = \left[\frac{\frac{\nu}{\pi} (\acute{E_i})^{\frac{2}{\lambda}}}{\sum_{i=1}^{n} (\acute{E_i})^{\frac{2}{\lambda}}} \right]^{\frac{1}{2}} \tag{2}$$

where ν is a fixed parameter.

Third phase: In this phase, each sensor checks its MW-Voronoi region to find the possible coverage hole. If a coverage hole exists, the sensor finds a target location for itself (but does not move there) using a proper scheme, such that by moving there the coverage hole would be eliminated, or at least its size would be reduced by a certain threshold. Various strategies are reported in the literature for finding the target location and any of them can be used in this phase (e.g. see [10], [11]). In this paper, the farthest point boundary (FPB) strategy proposed in [10] is adopted in this phase. In this strategy, each sensor first finds the farthest point in its MW-Voronoi region, which is denoted by $X_{i,far}$ for the i-th region. Then, a point on the segment connecting $X_{i,far}$ to the i-th sensor whose distance from $X_{i,far}$ is equal to R_i is chosen as the target location $\acute{P}_i$ for the i-th sensor. The proposed algorithm is called the *life-span maximization farthest point boundary (LMFPB)* algorithm. It is important to note that the sensors do not move in this phase.

Fourth phase: Once the new candidate location $\acute{P}_i$ is calculated, the coverage area w.r.t. this location, i.e. $\beta_{\Pi_i}^{\acute{P}_i}$, is obtained in this phase.

Fifth phase: If the coverage area w.r.t. the new candidate location is less than or equal to the current local coverage area, i.e. $\beta_{\Pi_i}^{\acute{P}_i} \leq \beta_{\Pi_i}^{P_i}$, the sensor does not move to the new destination and remains at its current location. If on the other hand $\beta_{\Pi_i}^{\acute{P}_i} > \beta_{\Pi_i}^{P_i}$, one of the following three cases can happen:
i) $E_i \leq E^{com} + (\Delta T)E_i^s + E_i^f$
where E_i^f is the energy required to stop the i-th sensor and then start to move it as noted earlier. In this case, the i-th sensor does not move and remains in its current location.
ii) $E_i \geq E^{com} + (\Delta T)E_i^s + E_i^f + E_i^{reloc}(P_i, \acute{P}_i)$.
In this case, the i-th sensor moves to $\acute{P}_i$ (because it has enough energy to move, sense, and communicate).
iii) $E^{com} + (\Delta T)E_i^s + E_i^f < E_i < E^{com} + (\Delta T)E_i^s + E_i^f + E_i^{reloc}(P_i, \acute{P}_i)$.
In this case, the energy of the i-th sensor is not enough for moving to $\acute{P}_i$ (although it is enough for overcoming static friction). Hence, it obtains the point $\tilde{P}_i$ from the following equality:

$$\tilde{P}_i = P_i + \left(\frac{E_i - E^{com} + (\Delta T)E_i^s + E_i^f}{E_i^{reloc}(P_i, \acute{P}_i)} \right) \overrightarrow{P_i \acute{P}_i}$$

and moves to $\tilde{P}_i$ if and only if $\beta_{\Pi_i}^{\tilde{P}_i} > \beta_{\Pi_i}^{P_i}$.

Different definitions are provided in the literature for network lifetime [8], [9]. In this paper, the network is said to be dead once 20% of the sensors completely deplete their energy, at which point the above algorithm is terminated.

Similar to Theorem 1 of [12], one can show that by moving the sensors to their new destinations the total coverage increases.

One of the important features of the proposed sensor deployment strategy described in this paper is that every sensor moves to its new candidate location only if its coverage area w.r.t. the new location in the current MW-Voronoi region (corresponding to the positions of the sensors before moving) increases. Consequently, according to Theorem 1 of [12] by moving the sensors to their new destinations the total coverage increases. Note that once the sensors adjust their sensing ranges, the total coverage may change.

IV. Simulation Results

Consider 20 mobile sensors with the initial sensing range of 6m randomly distributed in a 50m by 50m 2D plane. The initial residual energy of every sensor is assumed to be a random number between 2500J and 5500J with uniform distribution. Let also $\Delta T = 25$sec, $\lambda = 2$, $m = 40$J/m, $\alpha = 0.032$J/m^2, and E^{com} = 10J. Furthermore, it is assumed that $E_i^f = 40$J, which is equal to the energy required to continuously move the sensor 1m [5]. Fig. 1 demonstrates the residual energy of every sensor versus time, under the FPB deployment technique [10] without adjusting the sensing radii of the sensors. As it can be seen from this figure, after 1500sec the first sensor runs out of energy and after 2025sec 4 sensors (20 percent of sensors) deplete their energies completely, and hence network dies. In Fig. 2, the remaining energy of every sensor is given versus time, under the proposed strategy. It is observed from the figure that all sensors run out of energy almost at $t = 2450$sec. From Figs. 1 and 2, one can deduce that the sensors operate 21% longer under the LMFPB algorithm proposed in this paper compared to the FPB algorithm in [10].

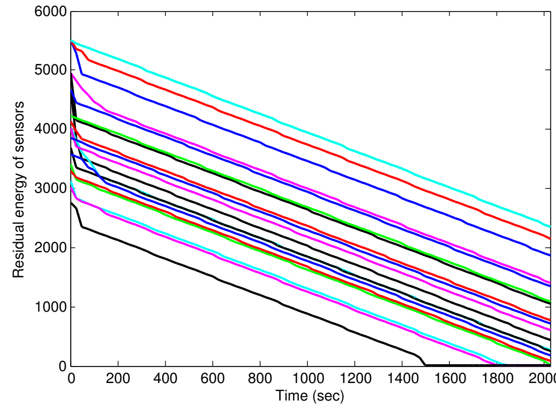


Fig. 1. Residual energy of sensors under the FPB algorithm in [10].

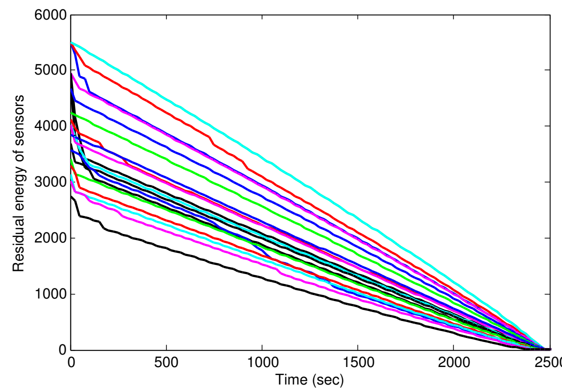
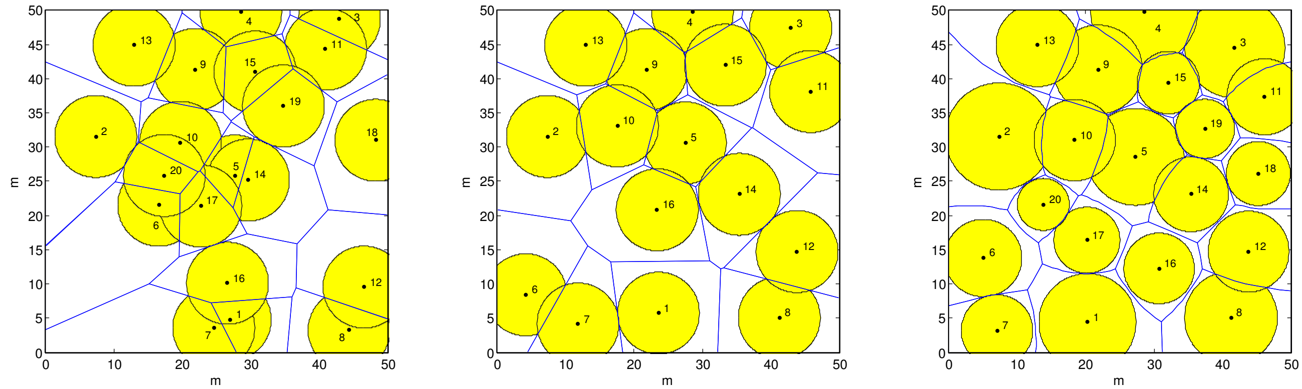


Fig. 2. Residual energy of sensors under the LMFPB algorithm.

Fig. 3 shows three snapshots of the network configuration under the FPB and LMFPB algorithms for the above-mentioned set-up. In each snapshot, the coverage area of every sensor is depicted by a filled circle around it. Since all sensors have the same sensing radius initially (as can be observed in the first snapshot) and also in the final deployment at time $t = 2025$sec (second snapshot) under the FPB algorithm, the corresponding regions are polygons, as in conventional Voronoi diagram. On the other hand, since the sensors do not have the same sensing radius under the LMFPB algorithm, the regions are not polygons in the third snapshot and are, in fact, MW-Voronoi regions. The initial coverage in this set-up is 56.8%. As it can be seen from the second snapshot, under the FPB algorithm four sensors die at $t = 2025$sec, at which point the network coverage is 62.9%. Finally, Fig. 3(c) shows that at time $t = 2025$sec all sensors are still operating under the LMFPB algorithm, and the network coverage is 77.5%.

The coverage factor (defined as the ratio of the covered area to the overall area) of the sensors versus time is depicted in Fig. 4 for both FPB and LMFPB algorithms. As it can be observed from this figure, under the FPB algorithm the first sensor runs out of energy at time $t = 1500$sec and the coverage factor decreases accordingly. Also second and third sensors die at $t = 1825$sec and $t = 1850$sec, respectively, and again the coverage factor drops significantly. Finally, the fourth sensor runs out of energy at $t = 2025$sec and consequently the network dies. However, under the LMFPB algorithm all sensors are still operating at $t =$



(a) (b) (c)

Fig. 3. Snapshots of the execution of the movement of the sensors under the FPB and LMFPB algorithms. (a) Initial coverage; (b) network coverage at time $t = 2025$sec under the FPB algorithm, and (c) network coverage at time $t = 2025$sec under the LMFPB algorithm.

2025sec, and the coverage factor of the network is satisfactory. The average total coverage area of the network $\beta[0, t]$ is plotted in Fig. 5 for both algorithms. It can be observed from this figure that the LMFPB algorithm outperforms the FPB algorithm in terms of average coverage.

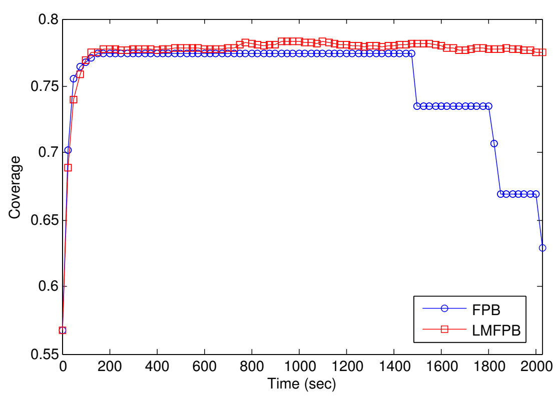


Fig. 4. Network coverage under the FPB and LMFPB algorithms.

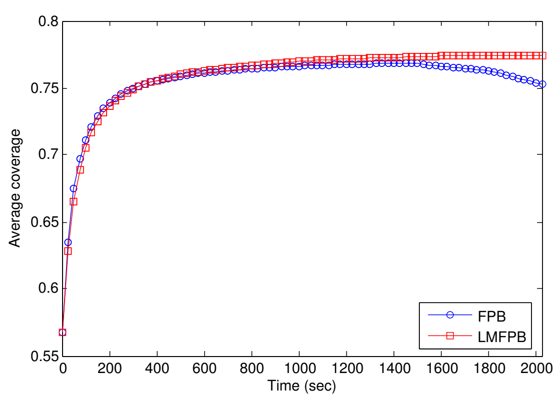


Fig. 5. Average coverage under the FPB and LMFPB algorithms.

V. Conclusions

This paper outlined a CPS perspective in the coverage design of a mobile sensor network. An initial effort in the joint design of control algorithms for relocation and sensing range was presented. The proposed strategy monitors the residual energy of every sensor, and adjusts the sensing radii of all sensors accordingly, while relocating them. The multiplicatively weighted Voronoi (MW-Voronoi) diagram was used to plan for relocation of the sensors. Every sensor moves iteratively to improve coverage within its MW-Voronoi regions, which is guaranteed to increase the coverage of the entire network. Simulations and comparison with other strategies demonstrate the advantages of the joint design approach. The control algorithm for relocation should be further integrated with the corresponding hardware design to further materialize the gain associated with the cyber-physical system concept.

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