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An Enhanced Scheme in Controlling Both Coverage and Quality of Service in Wireless Sensor Networks

Hao-Li Wang[1], Rong-Guei Tsai[2], Long-Sheng Li[1]*
[1]Department of Computer Science and Information Engineering,
National Chiayi University, Chiayi, TAIWAN
[2]Department of Engineering Science, National Cheng Kung University, Tainan, TAIWAN
Email: sheng@mail.ncyu.edu.tw

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Abstract- With the increasing number of applications for Wireless Sensor Networks (WSNs), different Quality of Services (QoS) levels based on the type of applications are required. An increasing research interest has been noted in the provision of QoS support in WSNs. QoS support in WSNs is challenging because of very limited resources, such as battery power, processing power, memory, and bandwidth. An earlier study introduced a QoS control approach based on the Gur Game. The Gur Game-based scheme can maintain QoS without knowing the total number of sensors. However, the Gur Game-based scheme does not consider the active sensor coverage. The problems of collecting redundant data and wasting bandwidth and battery energy arise if active sensors are distributed too densely or too sparsely. Therefore, this study proposes a Coverage-Aware QoS Control (CAQC) to achieve both QoS and coverage control using an enhanced reward function. Simulations that compared our scheme with previous studies in various environments indicated that CAQC creates a robust sensor network capable of achieving both QoS and coverage targets.

Index terms: Wireless Sensor Network, Gur Game, QoS Control, Coverage

I. INTRODUCTION

The number of applications in wireless sensor networks (WSNs) has been increasing, where resources such as energy or bandwidth are very limited. The types of applications affect the resources allocation in WSNs. For a number of applications requiring stringent performance, such as military surveillance or fire monitoring, a large amount of resources is needed to satisfy hard, real-time constraints. A small amount of resource is required for a number of applications without hard, real-time constraints such as habitat or temperature monitoring. Communication procedure, hardware design, and energy consumption are important issues considered in various types of applications to simplify cost, which is also considered in this paper. This study focuses on controlling the Quality of Service (QoS) for applications in WSNs.

QoS is the measure of the service quality that a system offers to users. In the area of computer networks, QoS refers to several related aspects of networks that allow the transport of traffic with special requirements, such as bandwidth, delay, and jitter. Various QoS definitions have been proposed in WSNs. Examples of QoS measures in WSNs are coverage, event detection ratio, exposure, connectivity, requirements for continuous service, observation accuracy, and the optimum number of sensors that sends information toward information-collecting sinks [2]. This study follows the last definition of QoS: an optimum number of sensors that send information to the sink [1]. This definition is also used in numerous studies [3–5, 7–9]. In [7–9], authors called QoS as the spatial resolution in WSNs.

This definition is based on an over-deployed WSN. The number of deployed sensors is more than the minimum needed for the service. Over-deployment is widely applied in several WSN implements because the former can prolong network lifetime, improve robustness, and tolerate network dynamic. In an over-deployed WSN, controlling the QoS is challenging because of the network dynamic that sensor deaths (due to running out of battery) and sensor replenishments (due to redeployment of new sensors) caused.

Iyer and Kleinrock proposed this definition of QoS and presented a QoS-control scheme based on the Gur Game paradigm [1]. Given an optimal number of sensors that sends information to the sink, the QoS-control scheme can adjust the number of active sensors to the desired target, and then all active sensors send information to the sink. The Gur Game-based scheme creates a robust and long-lasting sensor network capable of dynamically adjusting active sensors in the WSN even with transmission delays and sensor births and deaths. However, the Gur Game-based scheme does not consider sensor coverage. If the selected active sensors are distributed too densely or too sparsely, this may cause the problem of collecting redundant data and wasting bandwidth and battery energy. Therefore, our study is motivated by the question: How good is the coverage of selected active sensors using the Gur Game-based scheme?

A Coverage-Aware QoS Control (CAQC) was proposed to achieve both QoS and coverage control using an enhanced reward function. Simulations that compared our scheme with previous studies in various environments indicated that CAQC creates a robust sensor network capable of achieving both QoS and coverage targets.

Our contributions are threefold. (1) This paper recognizes the coverage unawareness in the Gur Game-based scheme. (2) We enhance a prior work by modifying the reward function with the concerns of coverage, and keeping the potential distribution manner of the said prior work. (3) Simulations that evaluate our scheme in various environments indicate that sensor network exhibits great improvements in success rate with our method.

The remainder of this paper is organized as follows: Section II describes related studies on the current issue. Section III presents the proposed scheme. Section IV presents the simulation results. Section V concludes the paper.

II. RELATED WORKS

A. Previous Literature on QoS Control in WSNs

WSNs have been attracting the attention of researchers' for the past years. A huge amount of general literature on WSNs exists. However, few studies focused on controlling the number of power-on sensors to a desired target number. This subject is also called QoS control. Although QoS control is not a hot issue in WSNs, previous studies on this topic still exist. Iyer and Kleinrock [1] defined the QoS control problem and proposed the first QoS control approach based on the Gur Game algorithm. Their study motivated our work in this paper. A brief introduction of the gur game-based scheme is provided later in this section.

Many researchers extend the study of Iyer and Kleinrock in different ways [2–9]. Some studies are concerned with energy conservation in QoS control scheme [2–5], whereas others extend QoS scheme to cluster structures [6–9]. In addition, WSN lifetime is defined in [7-9] as the maintenance duration of the desired QoS.

Other related studies are briefly introduced as follows. A new WSN taxonomy with QoS is proposed in [10]; a reference model that enables the classification of WSNs is also established in this paper. A survey of QoS-aware routing techniques in WSNs is presented in [11]; middleware approaches and certain open issues for QoS support in WSNs are also explored. A traffic engineering model that relies on delay, reliability, and energy-constrained paths to achieve fast, reliable, and energy-efficient transmission of information routed by a WSN is proposed in [12]; this paper uses multipath routing to improve reliability and packet delivery in WSNs while maintaining low power-consumption levels. QoS requirement and the minimum number of active nodes are analyzed in [13] because the former is usually inversely proportional to energy consumption. A QoS protocol for WSNs that controls topology based on analytical results is proposed [13].

In reference [15], a dynamic clustering algorithm is presented to achieve the optimal assignment of active sensors while maximizing the number of regions covered by the sensors. Moreover, ant algorithm and genetic algorithm are also taken into consideration in QoS control. Although reference [15] also considers coverage in the QoS control scheme, the goal of the said paper is different from ours. The authors of the said paper aim to achieve the optimal assignment of active sensors while maximizing the number of regions that sensor nodes cover. By contrast, our goal is to achieve both the optimal assignment of active sensors and a given optimal coverage rate.

Although several aspects of QoS control in WSNs have been extensively investigated, the combination of QoS and coverage control is relatively unexplored. To the best of our knowledge, the current work is the first attempt to achieve both QoS and coverage targets in WSNs.

B. A Gur Game-Based QoS Control Scheme

We introduce the use of the Gur Game algorithm in controlling QoS in this section. The principle of the Gur Game algorithm is based on biased random walks of finite-state automata. The automata describe a set of states with assigned meanings and a set of rules to determine switches from one state to another. Figure 1 is a simple example of a finite-state automaton with four states for the Gur Game algorithm. Each state has its own meaning. States -1 and -2 represent sleep modes, whereas states 1 and 2 represent active modes.

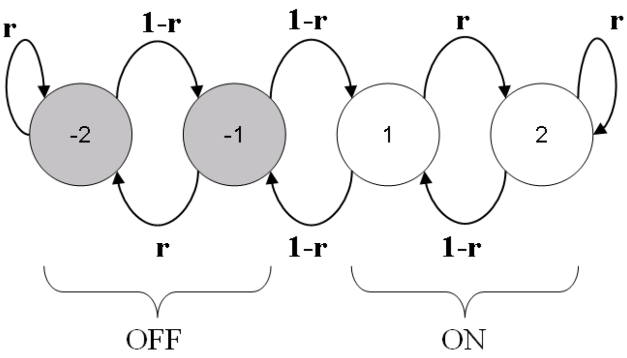


Figure 1. An example of an automaton with 4 states in the Gur Game-based scheme

The key in the Gur Game scheme is the reward function. The reward function is responsible for measuring performance of the system. An example of the reward function is given as follows:

$R^*(t) = 0.2 + 0.8exp\ (-0.002(K_t-n)^2)$

where K_t is the number of active nodes and n is the desired QoS value. When K_t is close to n, the R value approaches the top value (1). Figure 2 shows an example of the reward function with K_t =35.

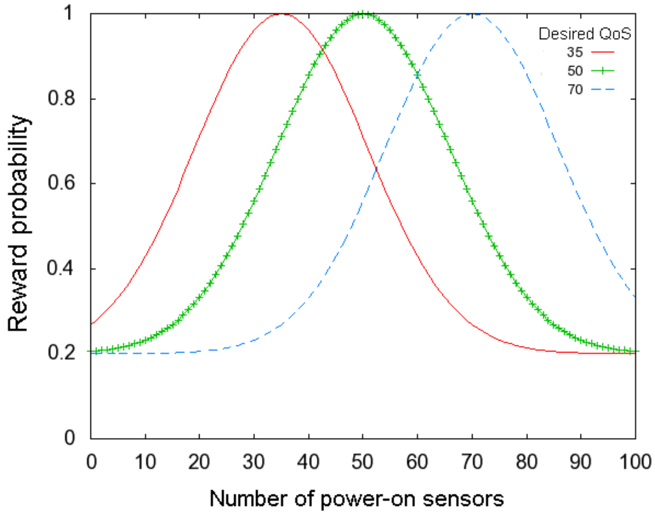


Figure 2. Reward function in the Gur Game-based scheme with K_t =35, 50, and 70

In a WSN, the number of active sensors contained in the sink (base) is determined by the number of received data from the active sensors. The sink broadcasts the reward value R to all sensors using the information and reward functions. The sensors can then determine whether to be active or idle in the next iteration based on the received R value from the sink. The decision is made by each sensor based on the finite-state automaton, the current state, and the received R value. The

Gur Game algorithm enables the number of active sensors to reach the target after a certain number of iterations.

III. COVERAGE AWARE QOS CONTROL

In the Gur Game-based scheme, active nodes are randomly chosen and may not be distributed evenly enough, leading to redundant information collection and unnecessary power consumption. Therefore, this paper proposes a CAQC scheme that considers both sensor number and sensor coverage. We first introduce how to measure the sensor coverage, and then present the proposed scheme.

Coverage Measurement

A simple way to measure sensor coverage was used because precisely identifying such coverage is challenging and is difficult to the sensors. The measure of sensor coverage in the paper is explained as follows. A sensing field is partitioned into n small square regions. If a sensor covers the center point of a region, then the sensor covers the region. A sensor can cover one or more regions, a region can be covered by one or more sensors. Based on the covered region number, the coverage rate for a sensing field can be derived as the ratio of covered region number to the total region number.

An example was used to explain the coverage measurement. As illustrated in Figure 3, among the 9 regions in the square sensing field, sensor S covers the centers of regions 1, 2, 4, and 5. Therefore, sensor S covers regions 1, 2, 4, and 5 and the coverage rate in this case is 4/9.

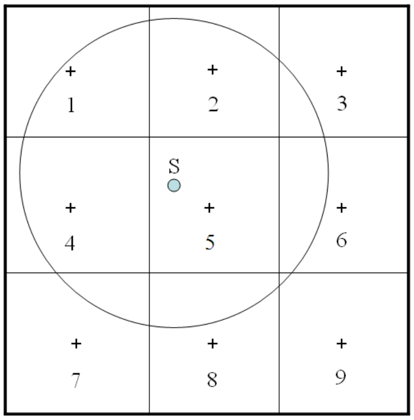


Figure 3. An example of coverage measurement

In our system model, the sink will broadcast to all sensors a reward value R with a partition information (i.e., the length of the square region). After receiving the broadcast packet, all sensors can determine their respective covered regions with the information of their positions. For a region R_i, with center C_i , S covers R_i if the distance between the sensor S and C_i is shorter than the sensing radius. The sensor is assumed to be aware of positional information and this can be done through personal setting or the use of positional systems such as GPS. This simple coverage measurement is feasible to sensors, but is not 100% accurate , as presented in Figure 3. Decreasing the size of a square region can increase the accuracy but can also cause more computing for sensors.

Proposed Scheme, Coverage-Aware QoS Control

Given the optimal number of active sensors (i.e., sensor target number) and the optimal coverage rate of active sensors (i.e., region target number), the goal of CAQC is to achieve both targets. CAQC will create an assignment of active sensors, which satisfies both the optimal number of active sensors and the optimal coverage rate of active sensors.

CAQC also retains the strengths of the Gur Game-based scheme such as distributed control and self-optimization. Although a centralized scheme can control sensors precisely, quickly, and effectively, such scheme may suffer from the scalability problem of a large number of sensors. We present CAQC in two parts as follows: the sensor node part and the sink part.

In the sensor node part, all sensors receive the broadcast packet from the sink and determine the covered regions. The sensors then decide to activate or sleep based on the automaton. All active sensors send sensing data to the sink with the ID of covered regions. This information help the sink derive the number of covered regions by all active sensors.

In the sink part, the sink gathers the sensing and coverage information from all active sensors. Removing a number of overlapped regions, the sink has the number of covered regions by all active sensors. The sink then utilizes both the number of active sensors and the number of covered regions to derive a reward value R using a modified reward function as follows:

$R^*(t)=(0.2+0.8exp(-0.002(K_t-P_n)^2)(0.2+0.8exp(-0.002(N_{CR} - C_n)^2)$,

where K_t is the number of active sensors, P_n is the optimal (desired) number of active sensors (i.e. sensor target number), N_{CR} is the number of regions covered by active sensors, and C_n is the target number of the regions covered by active sensors (i.e., region target number). The reward function considers both active sensor number (QoS) and their coverage. Controlling the coverage in CAQC is similar to that of the control QoS in the Gur Game-based scheme.

Figure 4 presents an example of the reward function in CAQC. In this example, the sensor target number is 35 and the region target number is 60. The reward function of the Gur Game-based scheme (Figure 2) is presented as a two-dimensional figure; however, CAQC requires three dimensions to present the reward function. Given the number of active sensors and the number of covered regions, the R value can be obtained by applying the reward function. The reward value goes high when the number of active sensors is close to the target. The reward value is highest as 1 (the peak point) when both the number of active sensors achieves the sensor target and the number of covered regions achieves the region target number.

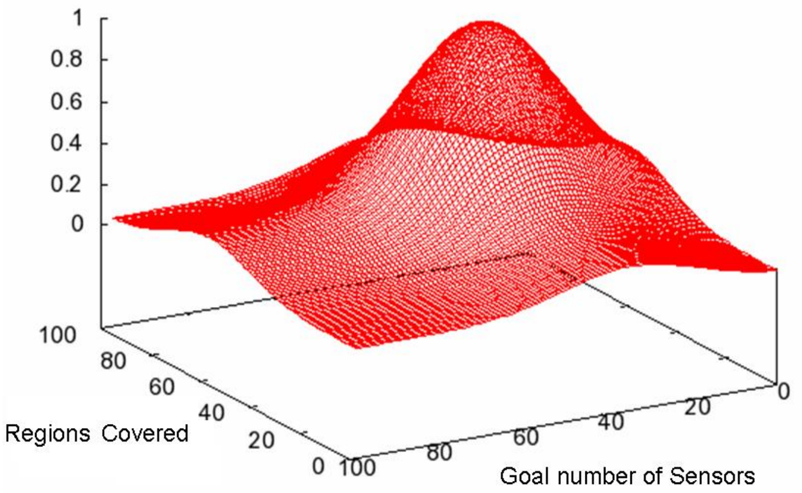


Figure 4. Reword function in CAQC with 35 as the sensor target number and 60 as the region target number.

IV. SIMULATION RESULTS

The performance of CAQC is compared with that of the Gur Game-based scheme because the latter is the most related to our proposed scheme.

Simulation model

One hundred sensors were randomly deployed in a 1000 m × 1000 m area with a sink at the center upon simulation. All sensors can receive the broadcast message from the sink and can transmit data to the sink in one hop. Sensors do not exchange messages among themselves, but only transmit to and receive data from the sinks. The sensing radius for a sensor is 100 m. The sensor target number is 35. The sensing field (1000 m×1000 m) is divided into 100 square regions (10×10), where each region is a small square (100 m×100 m). Each run lasts for 20000 epochs. The size of the automaton is 4 (state).

The performance of CAQC in terms of success rate was compared with the Gur Game-based scheme with different total sensor number, sensor target number, total region number, and region target number. The simulation model was implemented using Java, and the measured parameter, Success Rate, is defined as:

$$\frac{\text{The number of runs where both sensor target and region targets are achieved}}{\text{Total run number}}$$

The successful achievement of a sensor target number as the number of active sensor coverage close to a given sensor target number in 3000 runs is defined. ±1% of target number is tolerable.

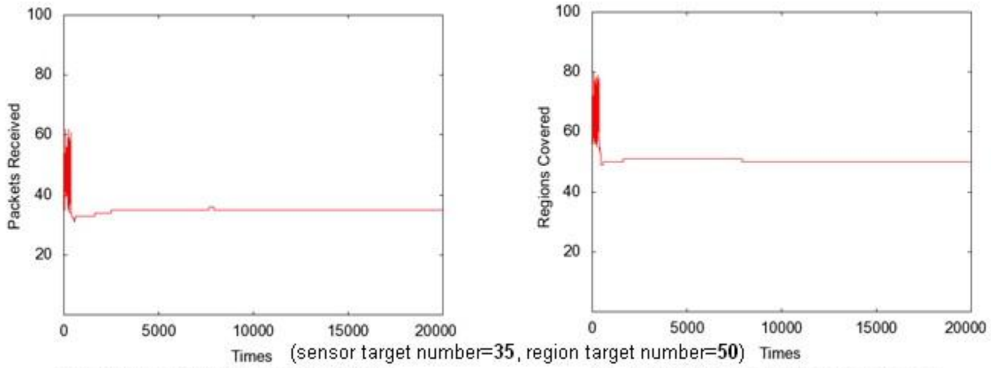
An example of a successful achievement is when the sensor target number is 35 and when the number of active sensor coverage is in the range of [34, 36]. All numbers in our simulation results are the average of 100 runs in the same parameters.

Simulation Results

Our simulation results are presented in six parts. First, given a sensor target number and a region target number, the process of convergence of the active sensor number and covered region number are presented. Second, a more realistic simulation is given. A special simulation case was designed to present how CAQC considers the coverage and the distribution of active sensors diffuses into a larger field. Third, two experiments were conducted to investigate the range of achievable covered region number and the average coverage rate of *n* sensors in a WSN. Fourth, the success rate of CAQC and the Gur Game-based scheme against the region target number are presented. Five, we present the success rate of CAQC against the total sensor number. A constant and a variable sensor target number are considered. Six, the success rate of CAQC against the total region number is presented. A constant and a variable region target number are considered.

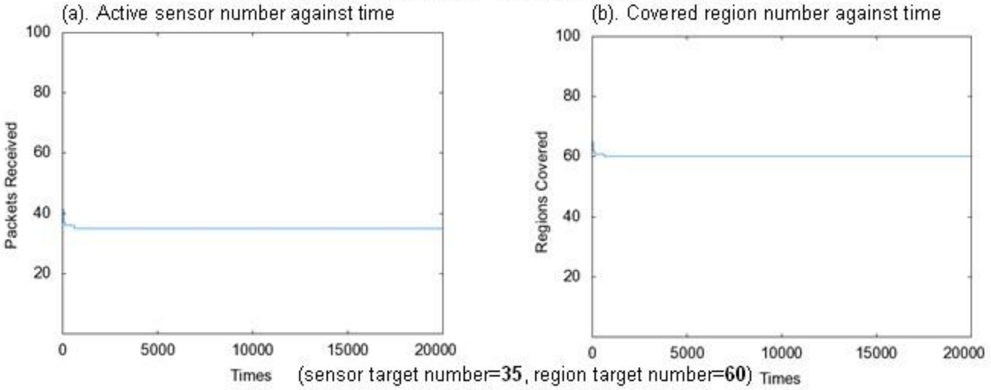
a. CAQC convergence process

In the first simulation, CAQC can effectively work as expected. Given a sensor target number and a region target number, the process of convergence of the active sensor number and covered region number in CAQC is presented. In this simulation, the sensor target number is 35, the total region number is 100, and the region target number is 50, 60, and 70. Given that the region target number is 50, Figs. 5 (a) and (b) present the active sensor number and the covered region number against the simulation time, respectively. In Figs. 5 (a) and (b), CAQC takes about 500 epochs to successfully achieve both targets. Given that the region target number is 60, Figs. 5 (c) and (d) present the active sensor number and the covered region number against the simulation time, respectively. In Figure 5 (c) and (d), CAQC successfully achieved both targets in a shorter period (about 90 epoch). Given that the region target number is 70, Figure 5 (e) and (f) present the active sensor number and the covered region number against the simulation time, respectively. In Figs. 5 (e) and (f), two targets were achieved after approximately 5000 epochs. Based on the results presented, CAQC works effectively in different settings.



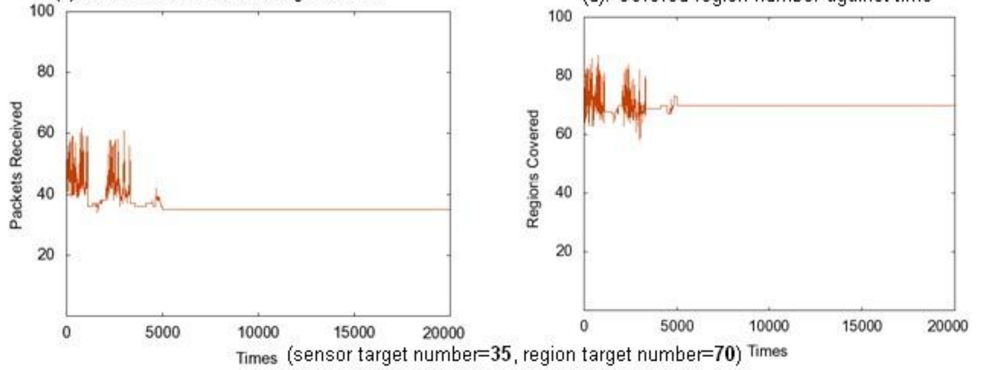
(a). Active sensor number against time

(b). Covered region number against time



(c). Active sensor number against time

(d). Covered region number against time



(e). Active sensor number against time

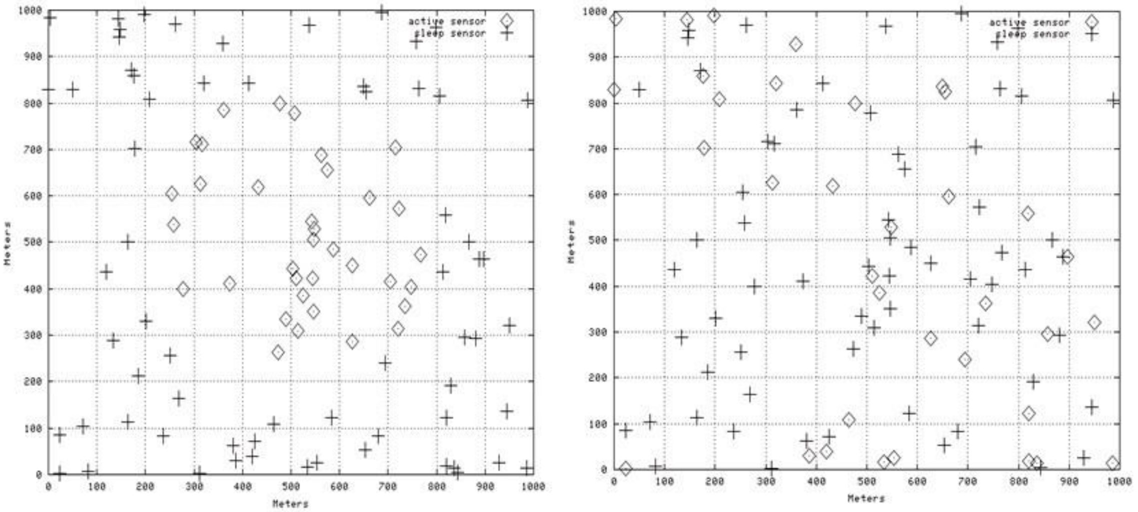
(f). Covered region number against time

Figure 5. Active sensor number and covered region against time in different target settings

b. A realistic example showing the effect of CAQC

In the second simulation, a more realistic example was given to observe how CAQC considers the coverage and the distribution of active sensor diffuses into a larger field. In this simulation, active sensors close to the center were initially selected on purpose, as presented in Figure 6(a).

The initial covered region number is 61. CAQC then runs with 70 as the target region number and 35 as the target sensor number. After a number of epochs (1201 epochs), CAQC helps the covered region number achieve the target (70) and makes active sensors diffuse into a larger field, as presented in Figure 6(b). In Figs. 6 (a) and (b), the CAQC can change a dense distribution of active sensors into a sparse one, according to the region target number.



(a) Initial node distribution
(Active nodes are close to the center)

(b) Node distribution at 1201 epochs
(Active nodes are distributed more evenly)

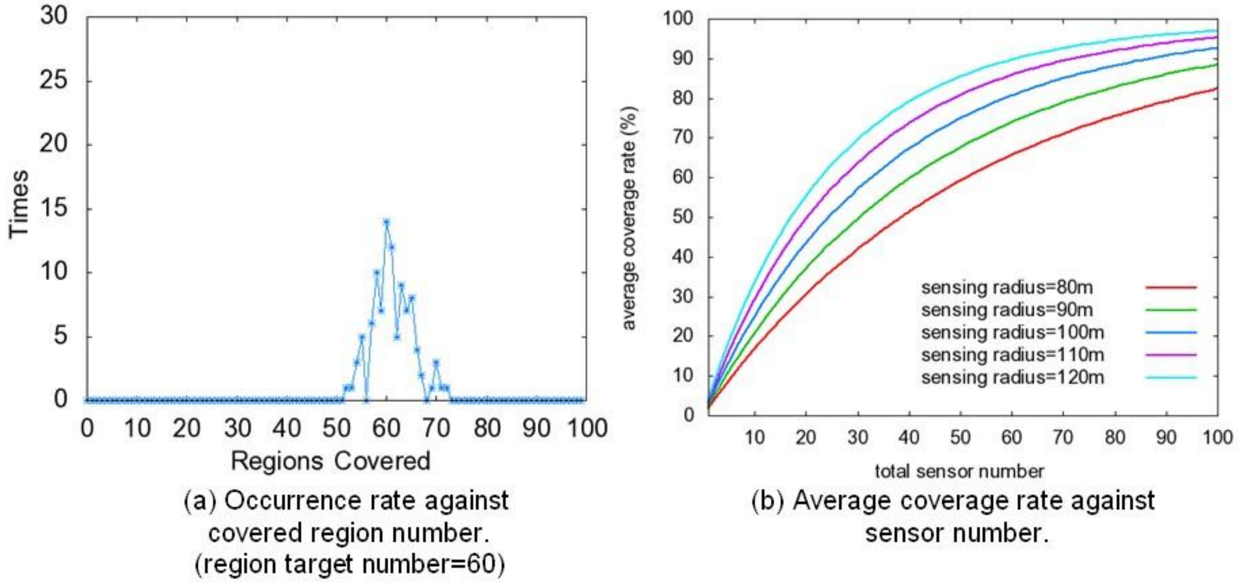
Figure 6. Two distributions of sensors to show the effects of CAQC

CAQC works fine in a number of cases in the above simulations. However, we find that CAQC cannot achieve all kinds of target setting. The first reason is that not all target settings are achievable. For example, assigning 5 active sensors to cover 95 areas is impossible. Similarly, assigning 95 active sensors to cover only 5 areas is also impossible. A number of target settings are also easy to achieve and some are not. For example, if a given 35 sensors can cover 62 regions on average, the region target number 65 is easier than the region target number 75. Second, due to limitations of the Gur Game paradigm, CAQC can only work in a range of target number. CAQC cannot achieve the target when the target is not in the range. Thus, in the following simulations, we will investigate in the range of achievable region target number and the achievable rate at different settings.

c. Range of achievable covered region number and the average coverage rate

In the third part, two experiments were conducted to investigate the range of achievable covered region number and the average coverage rate of *n* sensors in a WSN. The two experiments are designed for a general case and not only for CAQC or the Gur Game-based scheme. The first experiment presents the range of covered region number for a specific sensor number. Thirty-five sensors in a sensing field were randomly deployed and summarize the covered region number by the 35 sensors. The process was repeated 100 times and presents the statistics of 100 runs in Figure 7(a). Figure 7(a) presents that 35 sensors cover 62 regions at a highest probability. The covered region numbers of the 100 runs are in the range of [50,70]. The second experiment presents the average coverage rate of n sensors in a WSN.

Given the sensor number n, we randomly deploy n sensors and summarize the covered region number by the n sensors. For each n, we repeat the process 100 times and get the average value of the 100 runs. Figure 7 (b) plots the average coverage rate against the sensor numbers. Concurring with our expectations, Figure 7(b) presents that the average coverage rate increases with an increasing sensor number, and that larger sensing radius can cover more regions. Figure 7(b) can help estimate the range of achievable region target number and measure the difficulty of the target settings. For example, Figure 7(b) presents that the average coverage rate of 35 sensors is approximately 62%, the range of achievable region target number is approximately 62, and achievement is easy when region target number is 62. Figure 7(b) also provides helpful information for later analysis of our simulation results.



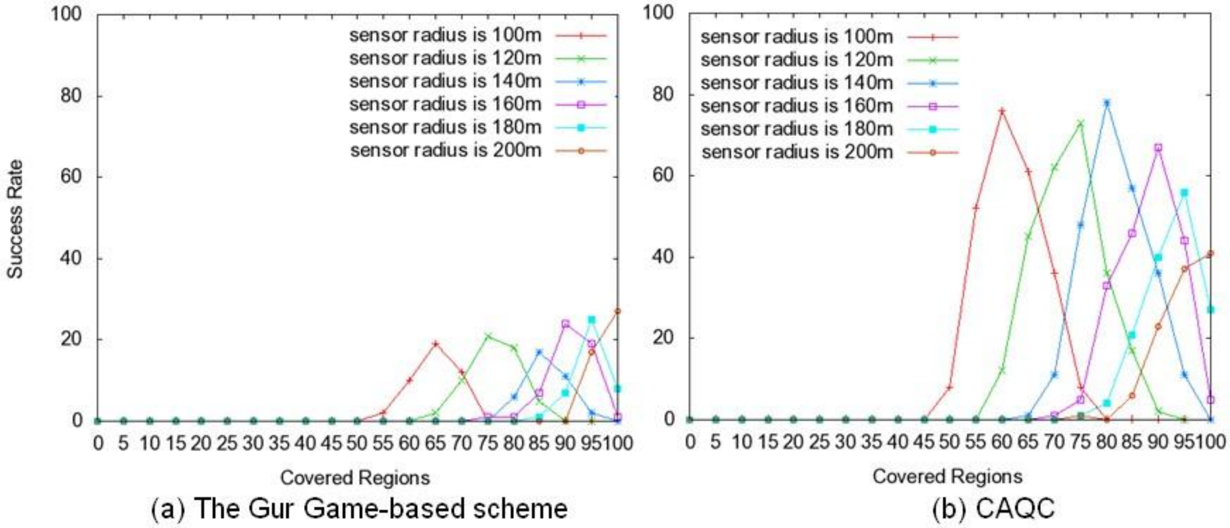
(a) Occurrence rate against covered region number. (region target number=60)

(b) Average coverage rate against sensor number.

Figure 7. Range of achievable covered region number and the average coverage rate of *n* sensors

d. Effect of region target number for CAQC

In the fourth part, we investigate the relation between success rate and region target number for CAQC and the Gur Game-based scheme, where the total sensor number, sensor target number, and total region number are constant. In this simulation, the total sensor number is 100, sensor target number is 35, and total region number is 100. Figs. 8 (a) and (b) plot the success rate of the Gur Game-based scheme and CAQC, respectively, against the region target number of 1 to 100 for different sensing radius. As presented in Figure 8(a), when sensing radius is 100, the highest success rate of the Gur Game-based scheme is at the 65 region target number. Success rate decreases at other higher or lower region target number. The reason is that when sensor number is 35, the average coverage rate is 62%, as presented in Figure 7(b). Thus, achieving the target is easier when the region target number is 65 rather than any other target number. The covered region number increases in average with increasing sensing radius (as presented in Figure 7(b)) thus, the curve of the larger sensing radius shifts to the right more. All these results concur with our expectations. Figure 8(b) has a similar pattern to Figure 8(a). Comparing Figure 8(b) with Figure 8(a), we can observe that CAQC has a two times higher success rate than the Gur Game-based scheme in all region target numbers. This is attributed to the concern of CAQC coverage.



(a) The Gur Game-based scheme

(b) CAQC

Figure 8. Success rate of the Gur Game-based scheme and CAQC against region target number.

e. Effect of total sensor number for CAQC.

In the fifth part, we investigate the relation between success rate and total sensor number for CAQC in the case of a variable sensor target number and in the case of a constant one. In the case of a variable sensor target number, the ratio of sensor target number to total sensor number, region target number, and total region number are constant. More sensors deployed in a sensing field increase the density of the sensing field. In this simulation, the ratio of sensor target number to total sensor number is 35%, region target number is 60, and total region number is 100. Figure 9 plots the success rate of CAQC against total sensor number from 100 to 200 for different sensing radius. As shown in Figure9, the curve of success rate shifts to the right at a shorter sensing range. The reason is that a shorter sensing radius favors a dense deployment. Figure 9 presents that, when sensing radius is 90, CAQC has the highest success rate at 120 total sensor number. The success rate decreases at other higher or lower total sensor number. The reason is that when sensor number is 42, the average coverage rate is 70%, as presented in Figure 7(b). Thus, when the region target number is 70, 42 sensors can achieve the target easier than any other sensor number. This means that when the sensor target number is larger than 42, the success rate decreases due to too many regions covered by too many active sensors. By contrast, when the sensor target number is fewer than 42, the success rate decreases due the small number of regions covered by too few active sensors. All these results concur with our expectations.

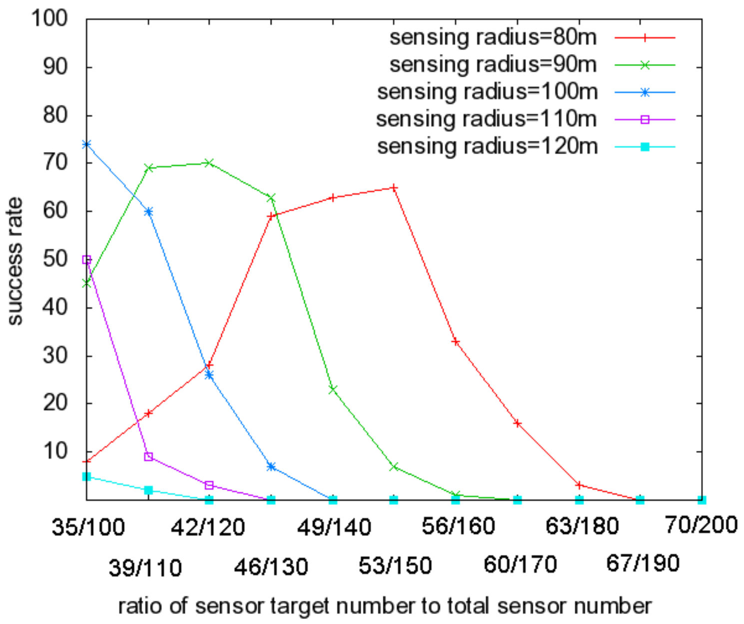


Figure 9. Success rate of CAQC against total sensor number with a variable sensor target number.

In the case of a constant sensor target number, the sensor target number, region target number, and total region number are constant. In this simulation, the sensor target number is 35, region target number is 60, and total region number is 100. Figure 10 plots the success rate of CAQC against the total sensor number from 50 to 150 for different sensing radius. Figure 10 has a similar pattern to Figure 9. Figure 10 presents that when sensing radius is 100, CAQC has the highest success rate at 70 total sensor number. The success rate decreases at other higher or lower total sensor number. The reason is that the Gur Game paradigm works fine only when the total sensor number is in the range of [50,110] at 35 sensor target number. The limited availability of the Gur Game paradigm causes the results presented in Figure 10.

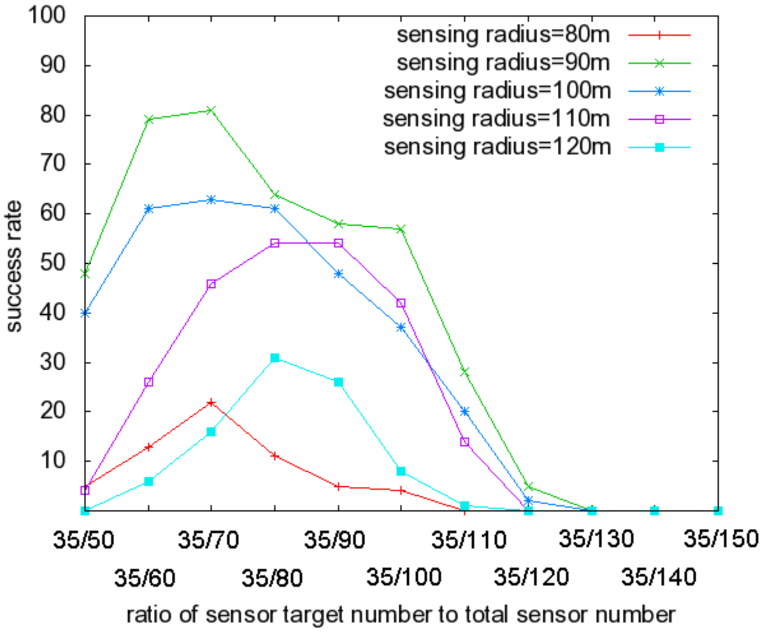


Figure 10. Success rate of CAQC against total sensor number with a constant sensor target number.

f. Effect of total region number for CAQC

In the sixth part, the relation between success rate and total region number for CAQC at a case of a variable region target number and a case of a constant one was investigated. For a variable region target number, the ratio of the region target number to the total region number, sensor target number, and total sensor number are constant. Note that more regions in a sensing field lead to a smaller area for each region. In this simulation, the ratio of sensor region number to total region number is 60%, sensor target number is 35, and total sensor number is 100. Figure 11 plots the success rate of CAQC against total region number from 64 (8 x 8) to 225 (15 x 15) when sensing radius is 90. Figure 11 presents that the success rate of CAQC in all total region numbers are very close, and that the total region number does not affect the rate. The reason is that the probability of successful achievement is the same when the ratio of region target number to total region number is constant.

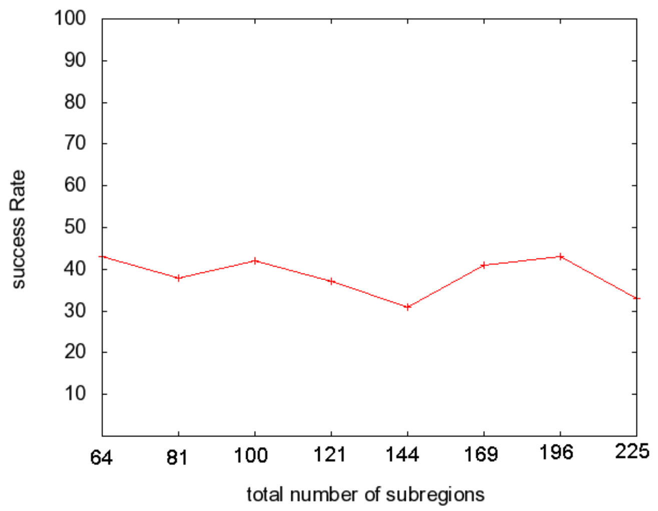


Figure 11. Success rate of CAQC against total region number with a variable region target number.

In the case of a constant region target number, the region target number, sensor target number, and total sensor number are constant. In this simulation, the sensor target number is 35, region target number is 60, and total region number is 100. Figure 12 plots the success rate of CAQC against the total region number from 64 (8 x 8) to 225 (15 x 15) when sensing radius is 100. Figure 12 presents that CAQC has the highest success rate at 100 total region number. The success rate decreases at other higher (121 or 144) or lower (81 or 64) total region number. The reason is that when sensor number is 35, the average coverage rate is 62%, as presented in Figure 7(b). Thus, 35 sensors can achieve the target easier than any other sensor number when the region target number is 62. Given that the region target number is 60, the coverage rate is closest to 62% when the total region number is 100. Thus, CAQC has the highest success rate..

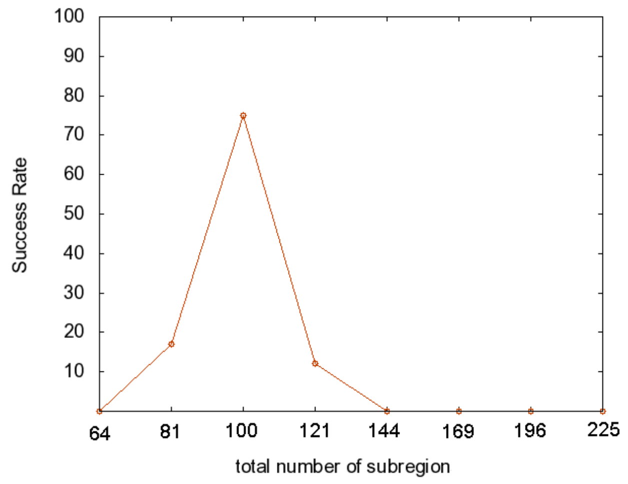


Figure 12. Success rate of CAQC against total region number with a constant region target number.

V. CONCLUSION

Providing QoS support and controlling QoS in WSNs are emerging areas of research. Legacy Gur Game-based QoS control can make the number of active sensor to the target, but cannot control the coverage of active sensors. Without the concern of coverage, selected active sensors may be too close to or too far away from one another, which can cause the coverage of active sensors to have overlapped regions, which leads to redundant data collection. This paper proposes a Coverage-Aware QoS Control (CAQC), which considers both the target number of active sensors and the distribution of their coverage areas. CAQC retains the strengths of the Gur Game-based scheme such as distributed control and self-optimization, and adds the new feature of coverage control. Simulation results indicate that CAQC can help active sensors be distributed more evenly. CAQC success rate is much higher than that of the Gur Game-based scheme. The success rate is related to the total sensor number, target sensor number, total region number, and target region number. These relations are presented and analyzed in our simulation results.

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