# An Adaptive and Fault-Tolerant Gateway Assignment in Sensor Networks

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## Abstract

*Gateway nodes are important elements in a sensor network since they provide the ability to establish long-range reach-back communication in order to retrieve critical data to remote locations. The gateways are however, prone to failures just like any sensor nodes, and they consume significantly more energy since they transmit over longer distances compared with sensor-to-sensor links. We introduce an adaptive and fault-tolerant method for gateway assignment in sensor networks. Our approach is fully distributed and achieves the following objectives: (i) It allows surviving gateways to recover for other failed gateways. (ii) It distributes energy usage and traffic load between several gateway nodes within the sensor network. Each gateway adaptively controls its region of influence based on local conditions such as remaining energy level and traffic load. Our methodology was evaluated via simulation using a network model containing 400 sensor nodes with virtual targets. The simulation results indicate that our scheme is robust to gateway failures. Moreover, our scheme successfully balances the energy consumption and traffic load among the gateways.*

## 1 Introduction

A sensor network is very similar to a general purpose Mobile Ad Hoc Network (MANET) in that it is self-healing and self-forming. Sensor nodes have limited energy resource, and they are designed to work under hostile environments. Typical sensor-to-sensor links communicate over short distances of up to couple hundreds of meters and all sensor nodes participate in relaying critical data towards the sink. However, in a large sensor network with thousands of nodes (e.g., diameter of 10 hops), relaying large amount of sensor data all the way across the entire network might introduce heavy energy usage on intermediate sensor nodes, as well as increase the end-to-end delay. In addition, in a large-sensor network, the sink of information flow may not always be located within the network or at the edge of the network, since in many cases information may need to be retrieved by elements that are far away from the sensor network. Some of the desirable qualities of the gateway-based architecture include:

**Scalability**: A sensor network must scale up to hundreds or thousands of nodes. Deploying only one or few gateways can potentially result in excessive traffic concentration around the gateway nodes and significant amount of energy consumption in relaying sensor data across the entire network. However, using too many gateways is not necessary better either since gateway nodes are more costly to deploy than sensor nodes and this also defeats the purpose of using a low-powered sensor network.

**Random deployment & Failure resistant**: In many occasions the gateways and sensors will be deployed in hostile environments (e.g. enemy territory, high interference, harmful chemical, etc.). Hence, we can not assume that they can always be positioned with the most optimal topology since the sensors may be deployed in a random fashion using methods such as air-drops or artillery. Thus in this case we have no or very little control over the physical topology of the sensor network. Also, if the network is operating in a very unpredictable environment, a gateway can fail at any time due to factors such as hardware failure, enemy tampering, harmful interference, and others. Under these situations, the sensor network must be self configuring and self-healing without any assumption on the underlying physical topology. An energy efficient architecture of using gateways is described in [4]. This approach forms cluster of sensors by assigning a gateway to each cluster based on energy efficiency. However, the initial bootstrap and subsequent recovery process is based on the assumption that every sensor node's maximum transmission range can reach at least one gateway. In this paper we introduce an adaptive and fault-tolerant method to assign gateways to sensor nodes that meets all of the requirements mentioned above.

## 2 Adaptive Gateway Assignment Protocol

Assuming there exist gateways in the sensor network, our adaptive scheme uses a distributed algorithm to assign regions to gateways throughout the entire sensor network. The sensors within each region use their local regional gateway for all reach-back communications. The algorithm is adaptive and hence the region boundary does not remain fixed. During the network's lifetime, the region that each gateway serves will "grow" and "shrink"

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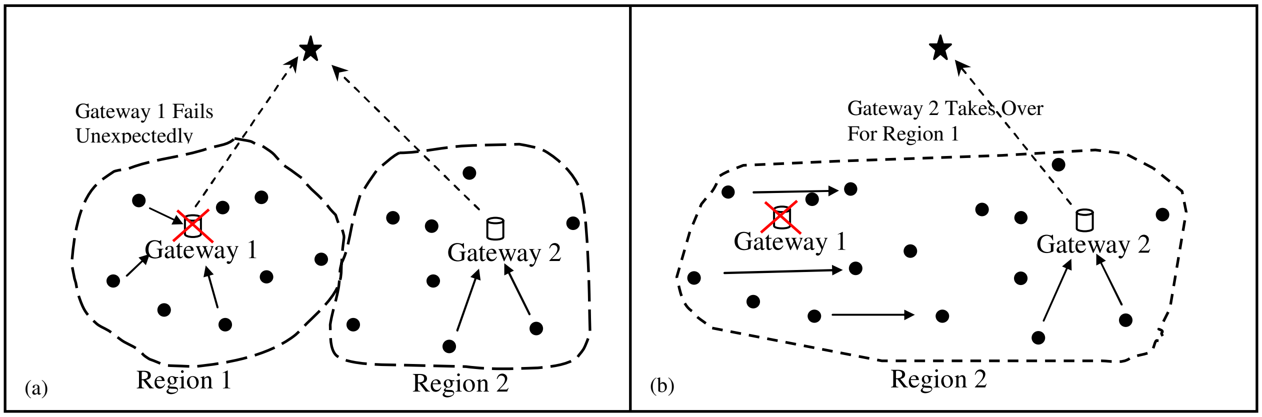

**Figure 1. An example showing the dynamic region assignment**

base on a combination of metrics such as gateway outages, gateway energy level, traffic load, and other factors. An example of our approach is illustrated in Figure 1. In Figure 1 (a), there are two gateways 1 and 2 in the network with their corresponding neighboring regions, and there are target activities in both regions. If gateway 1 fails unexpectedly, all the target events generated in region 1 will not be retrieved. In Figure 1(b), the algorithm expands the size of region 2 and thus allows gateway 2 to take over the task of reach-back communication for the sensors that were in region 1. Our algorithm dynamically assigns gateways and regions, based on gateway outages, remaining gateway energy resource, and distance to the gateway as the metrics. In real implementations, a combination of additional factors such as traffic, noise/interference/jamming level, reach-back link quality and numerous other metrics can be applied as well. Each gateway has a unique identifier in the network and it periodically broadcasts GW-ADV (Gateway Advertisement) messages. Each GW-ADV message, which reports various metrics of that particular gateway, is propagated within each region.

## 3 Simulation Model and Results

To evaluate our proposed scheme, we compare our dynamic gateway assignment protocol with a static scheme where the region and gateway assignment remain fixed. We have developed the simulation model using QualNet [3], a network simulation tool that is designed to simulation a large-scale ad hoc network. We have used the IEEE 802.11 model as the underlying MAC/PHY layer, with a modification implemented to account for energy consumption during transmitting, receiving, and idle states. Initially each sensor and gateway node is assigned a finite energy resource, with the energy value of gateway nodes significantly larger than regular sensor nodes. When a sensor or gateway node's energy resource is exhausted, all of its functions (TX, RX, Detection) will be shutdown and the node will cease to operate. The energy usage ratio we have followed is based on IEEE 802.11 DCF with energy consumption of transmission, reception, and idle that equals to 660mW, 395mW, and 35mW, respectively. The simulation area is a 2.5km by 2.5km square field, and all the sensors and gateways are placed randomly in the simulation area with no pre-planned assignment. We assign the CN (collection node), or the node at the other end of the reachback link, to be at the center of the simulation area with an altitude of 20,000 feet (6,096 meters). The reachback interfaces for the gateways require a very high transmission power to be able to close the long distance link to the CP (65 dBm compared with 15 dBm). The power consumption is adjusted according to the type of interface link being used; the reachback or regular low power. We have modeled the gateway node as a specialized node with two wireless interfaces, one using the high powered reachback link and the other using regular link for gateway to sensor communication. When a sensor node detects a target within its detection range it will trigger an event and send a data packet towards its regional gateway. In our model, each target will only be detected by one sensor node and one sensor data packet will be sent. This is a simplified model because in a real sensor network, each target will likely triggers multiple events at many sensors and the traffic flow will be more similar to data aggregation pattern such as the one described in [2]. However, we believe that this simplified traffic model is adequate to evaluate the effectiveness of our proposed scheme. We leave the investigation of a data diffusion method with our protocol as future work. When the simulation starts, there is a network initialization period when there are no target event generated and only control traffic (GW-ADV and GW-REQ) are generated to setup gateway assignments for both the dynamic and static models. After this initialization ends, the target event starts, but control traffic are no longer generated in the static gateway assignment model and the gateway assignment remains unchanged until the end of simulation.

We simulated many scenarios to study the effectiveness of our dynamic gateway selection protocol against a static gateway assignment scheme. In our first experiment, 10 stationary targets are placed randomly within the simulation area at the beginning of the simulation. Each target triggers events at any active sensor nodes within its detection area by a Poisson processes with exponentially distributed inter-arrival time of 1 second throughout the simulation time (10 packets/second total). In our second experiment, the 10 targets are mobile and follow a waypoint mobility pattern [1] with uniform random speeds between 18 km/hr to 72 km/hr and a pause time uniform distributed from 5 to 60 seconds.

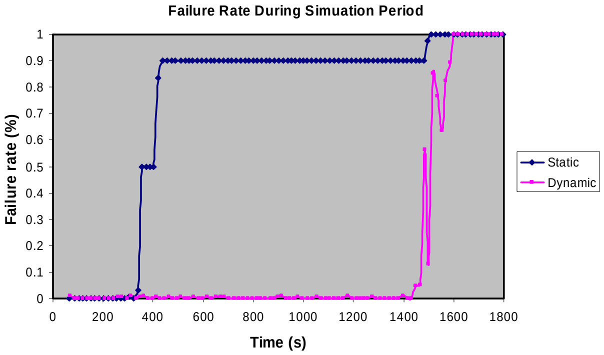

**Figure 2. Data delivery failure rate during simulation**

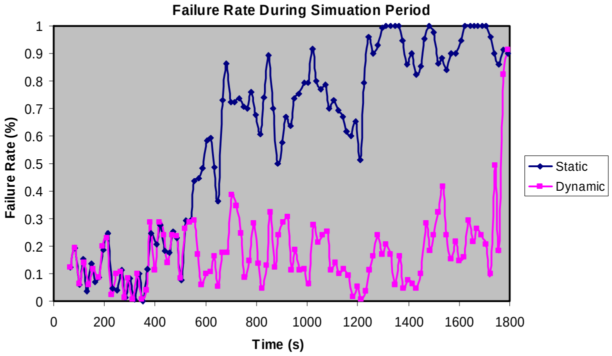

**Figure 3. Data delivery failure rate during simulation**

Figure 2 shows the failure rate during the stationary target scenario. We can see that after t = 350 seconds, the failure rate for the static method increased to about 50% and after 420 seconds it is no longer effective since 70% of the sensor data are not delivered. However, the dynamic scheme maintains a very high delivery ratio until about 1430 second when some of the gateways begin to fail. The remaining surviving gateways are used until all the gateways are exhausted at time of 1600 seconds. Therefore the lifetime for the dynamic approach is about 3.6 times of that of the static scheme. Since the static algorithm does not offload traffic from one region to another, once the energy in one region's gateway is exhausted, the target activities in that particular region is no longer traceable. However, with the dynamic approach a region shares its gateway's energy and traffic load with surrounding regions and thus when there is heavy energy usage in one region, gateways in other regions can assist in handling the traffic load. The "dips" behavior of the dynamic curve between 1400 and 1600 is due to the soft-state timeout process to detect the gateway outage.

Figure 3 shows the failure rates for both schemes when the targets are mobile using a waypoint mobility model. Here the numerous "dips" in both curves are caused by targets going in and out of the detection range of the sensor. Since we are dropping all sensor nodes in a random manner within the simulation area there are going to be some "blind" spots. We observe that the dynamic approach effectively maintains a fairly low failure rate (<30%) even with despite the mobile targets, while the values for static scheme experienced a significant jump after t=600. This jump is due to the failures of some gateways that were heavy used before t=600. Therefore some regions in the network became "blind" since their regional gateways are no longer operational. Other regional gateways continue to deliver target events as targets pass through their region therefore its failure rate is not at 100%.

## 4. CONCLUSIONS

We have proposed an adaptive and self-healing gateway discovering protocol to facilitate reachback communications in sensor networks. Our scheme is able to function in any random network topology and it is highly scalable as it divides the sensor network into separate regions to spread energy consumption and traffic loads and prolong the effective lifetime of the sensor network. Simulation results indicate that our proposed approach performs significantly better and increases the effective lifetime of the sensors when compared with the static allocation method. Results also confirmed that when a gateway unexpectedly dies or if its energy is exhausted, other gateways in surrounding regions act as backup gateways that can pick up its workload.

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