Grid-based Multi-path with Congestion Avoidance Routing (GMCAR) Protocol for Wireless Sensor Networks

Omar Banimelhem
Jordan University of Science and Technology
Department of Computer Engineering
Irbid 22110, P. O. Box 3030
omelhem@just.edu.jo

Samer Khasawneh
Jordan University of Science and Technology
Department of Computer Engineering
Irbid 22110, P. O. Box 3030
sakhasawneh06@cit.just.edu.jo

Abstract— A new routing protocol that handles real-time and non-real time applications in Wireless Sensor Networks (WSNs) is proposed. We employ the idea of dividing the sensor network field into grids. Inside each grid, one of the sensor nodes is selected as a master node which is responsible for delivering the data generated by any node in that grid and for routing the data received from other master nodes in the neighbor grids.

For each master node, multiple paths that connect the master node to the sink are stored as routing entries in the routing table of that node. These paths are the diagonal paths between the sink and the master node. In case of congestion occurrence, a novel congestion control mechanism is also proposed in order to relieve the congested areas.

Simulation results have shown that our proposed protocol has the capability to extend the lifetime of the sensor network and to utilize the available storage.

***Index Terms*— Real-time traffic, non-real time traffic, diagonal multi-path routing, grid network, congestion control.**

1. Introduction

Over the past few years, the number of applications that could be implemented using sensor networks is increasing rapidly. This necessitates developing new routing protocols that take into consideration the severe sensor resource constraints. These constraints represent major issues that make the implementation of traditional routing protocols infeasible.

Although an extensive and huge number of energy aware routing protocols have been proposed in the literature, the emergence of real-time applications in WSN's raises new design issues. To explain the requirements of these applications, consider an Air Defense Missile System (like patriot) that uses sensors to detect enemy rockets intrusion. Once a sensor detects an enemy rocket, it reports the event to the sink to launch an interception rocket. Needless to say that time here is very critical to trigger certain events.

The previous example shows how the routing delay for real-time systems greatly affects the network performance. This encourages the development of new delay aware routing protocols that are designed to deliver the delay sensitive data to the destination before missing the deadlines [1].

In sensor networks, there are two main reasons for the delay: packet queuing [2] and the congestion [3]. The packet queuing delay could be minimized by rescheduling the buffered packets in order to assign the data with the lowest deadline of the real-time applications a higher priority so that this data will be transmitted first [4]. On the other hand, congestion effects could be reduced by creating multiple paths to divert the traffic from the overloaded links to other idle ones [3,5] or by choosing the routes in a way that could deliver the delay sensitive packets with delays that meet their deadlines [1]. Congestion reduction mechanisms require the nodes to maintain and exchange neighboring information periodically. This adds extra overhead that may slow down the network, so that the protocols must also take care of minimizing the control messages as possible as it could be.

In this paper, we propose a new grid-based multi-path routing protocol intended to route packets fast, utilize and extend sensor nodes energy in addition to avoiding and handling network congestion when happens. We employ the idea proposed in [6] for dividing the sensor network field into squared-shaped grids. Then for each grid, a master node is selected to take the routing role for all data generated by the nodes in the same grid, or the role of routing the data received from neighbor grids. Our proposed protocol is suitable for real-time and non-real time traffic.

The reset of this paper is organized as follows. Section 2 surveys literature studies on multi-path routing and congestion control techniques. Section 3 presents our proposed protocol where we discuss the idea of diagonal multi-path routing and then we discuss the congestion control mechanism. In Section 4, we evaluate the proposed protocol in terms of energy consumption, number of alternative routes, and average buffer occupancy. Finally, the paper is concluded in Section 5.

2. Related work

Several protocols have been proposed in the literature to address the problem of routing delay sensitive data in wireless sensor networks. Their goal is to route the packets before missing their deadlines with minimum energy consumption. Congestion and topology changes are the main two reasons that hinder supporting soft or/and hard deadlines by forming hot spots in which any packet routed through these hot spots are if not dropped jeopardized to a large routing delay. In this section, part of the previous work and studies will be shown.

SPEED [3] is a stateless protocol for Real Time Communication in sensor networks. Nodes on SPEED maintain neighbor's information and periodically exchange beacon packets to update these information. Upon detecting a heavily loaded links, SPEED modules cooperate to distribute the traffic and this helps in reducing and even avoiding the congestion. Although SPEED is a robust QoS routing protocol it has a low reliability and does not take into consideration the dynamic packet deadline.

DEAP [Delay-Energy Aware Routing Protocol for sensor and actor networks] is a routing protocol that uses the packet delay in routing decision [2]. DEAP creates a Forwarding Candidate Set (FCS) which is a set composed of the nodes that are closer to the destination than the sender node by a certain threshold. Upon forwarding a packet, an active node is chosen from the FCS as the next hop thus more than one forwarding choice exists. To save nodes energy, DEAP suggested that each node can be waked up for a certain period in every time slot and sleep again. Thus nodes require to be synchronized with each other and inform each other when they become active.

A multi-path routing protocol that is resilient to node failure is proposed in [7]. This protocol aims to find multiple paths between the source and the sink, so that when the shortest path goes down an alternative path is selected quickly. The alternative paths could be disjoint or braided. This protocol does not focus on achieving high delivery ratio and balancing the load among the available alternative paths. Load balancing can extend network lifetime by utilizing nodes energy evenly whereas high delivery ratio is very desirable in real-time sensor applications.

Md. Obaidur et al. proposed a new QoS cross-layer congestion control scheme [8]. This protocol is able of supporting multiple applications by using three types of queues: real-time, non-real and an extra backup queue. A classifier is able to classify the traffic into these queues and the backup queue keeps track of the unacknowledged non-real-time data. Multiple routing paths are established towards the destination where a primary route is used only by the non-real-time data. For real-time data, the route is selected based on path delay since these data require certain delay. Implicit congestion notification is used to detect congestion. Upon detecting congestion, nodes can respond by distributing the traffic along different paths. We compare our proposed scheme to this one because we believe are common services and functionality both protocols offer.

O. Chipara et al. proposed Real time Power Aware Routing (RPAR) protocol, an approach to route real-time data based on their deadlines [9]. RPAR consists of four components: dynamic velocity assignment policy, delay estimator, forwarding policy and neighborhood manager. The dynamic velocity assignment policy assigns a velocity to each packet based on the packet deadline so that real-time packets are prioritized. Forwarding policy offers more than one forwarding option where the delay estimator estimates the delay for each one of these options. To determine the best forwarding option that meets the velocity requirements, RPAR checks the neighborhood table maintained by the neighbor manager. RPAR offers a dynamic adjustment to the transmission power based on the packets deadlines. Increasing the transmission power results in increases in the channel interference and thus reducing in the network throughput.

An implicit prioritized access protocol for wireless sensor network is a MAC protocol to support routing real-time traffic [4]. This protocol employs Earliest Deadline First (EDF) scheduling algorithm. EDF gives a priority to the packets with lower deadlines to forward them faster.

3. PROPOSED PROTOCOL

In our approach, we aim at building multiple paths that connect the master node in each grid with the Sink. Although, there are several approaches that have been proposed which also build multiple paths toward the sink, our proposed protocol is distinguished in the following points:

١- It is the first approach that employs the idea of dividing the sensor field into girds as presented in [6] in order to build diagonal paths from each grid toward the sink.
٢- To the best of our knowledge, our protocol is the first one that takes into consideration the density of nodes as a decision factor in data forwarding as will be presented later.

3.1. Grid-based Multi-path Routing Protocol

In order to simplify the discussion, we divide the function of the proposed protocol into three phases:

Phase 1: Grid formation. This is the protocol prerequisite phase. In the topology where the nodes are randomly deployed, squared-shaped grids of predefined size are formed. The maximum grid size must satisfy R = $2\sqrt{2}G$ (where R is the radio range and G is the grid size). This ensures that any node in one grid can reach any other node in the neighbor grids. For each grid, a master node is elected randomly and the remaining non-master nodes inform the master node that they belong to this grid before they enter the sleep state. The idea of phase 1 is proposed in [6].

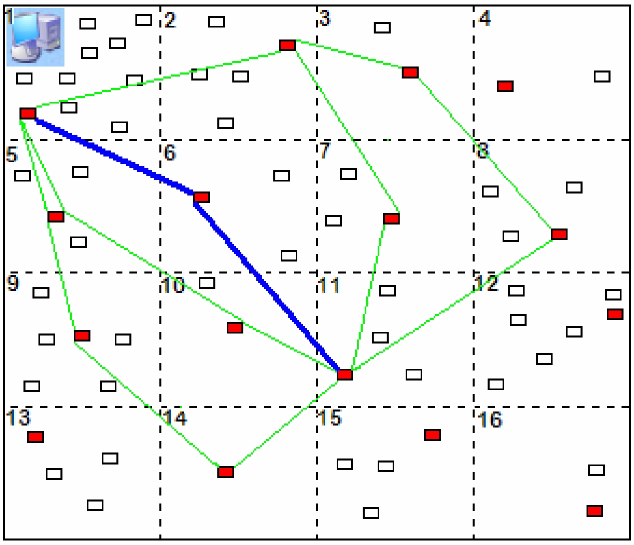

Figure 1: Multi-path routing in grid based network.

Phase 2: Establish Routing Information. After forming the grids, the sink initiates a flooding message in order to discover the available paths from each grid to the sink. Upon receiving the flooding message, each master node broadcasts routing information to its neighbors. The routing information being exchanged carries information regarding two metrics: *hop count* (H) and *grid density (Gd).* Hop count determines the number of hops the sink is far away from the grid and Grid density determines the total number of nodes in that grid. For example, Figure 1 shows a sensor field divided into 4X4 grids. The master node for each grid is shown as a filled square. In the figure, the master node of grid 11 receives a message with H = 1 and Gd =3 from the master node of grid 6.

Sensor networks have a variety of applications including real-time and none real-time applications. Real-time applications have hard deadlines and thus require fast forwarding and minimum network delay. To achieve this goal, the proposed protocol creates multiple paths towards the destination. We assume that at any time the sink is reachable and the network does not have a major cut that separate it into two isolated regions. This assumption is valid since sensor networks are densely deployed.

Assuming that the base station is located always in one of the topology corners, we can differentiae between two types of grids: boundary and non-boundary grids. Boundary grids are those grids that lie on the topology boundaries horizontally or vertically along the base station where the non-boundary grids are surrounded by boundary grids as shown in Figure 2(a). Master nodes for the non-boundary grids have one primary diagonal path (if the diagonal neighbor grid is not empty) and alternative diagonal paths through grid neighbors. Figure 1 shows the possible paths for the master node in grid 11 (primary path shown in bold blue line while the alternatives are shown in green).

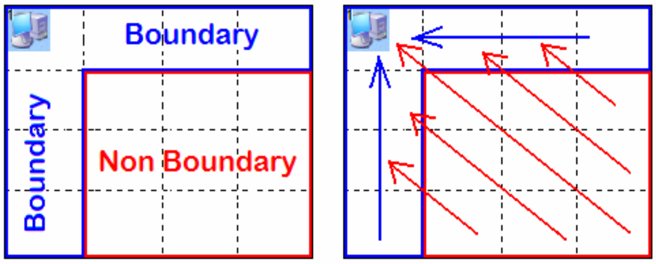

Figure 2: (a) Boundary and non-boundary grids in 4X4 grid network. (b) The traffic direction.

The maximum number of diagonal paths including the primary is five; this is because only 5 of the neighbors lead to a distinct diagonal path. On the other hand, boundary grids have one vertical or horizontal path. Figure 2(b) shows the traffic directions in 4X4 grid network. The traffic direction in GMCAR is not chosen spottily, the flow in boundary grids has a higher rate than the flow in non-boundary grids, and thus boundary grids must have multiple paths to the destination where single path can handle the traffic in non-boundary grids without additional overhead for maintaining alternative paths.

Since we aim to extend network lifetime while providing efficient forwarding paths, each one of the available paths is assigned a weight. Path weight depends on the weight of each link over that path. The weight of a link is a function of number of hops and the density of the first grid along this path. We choose this criteria because including path length will guarantee selecting the appropriate path based on the packet deadline while grid density factor help utilizing the network energy evenly by favoring the paths with higher density over other low density paths to let the low density paths last longer. In case that there are two links with the same weight, our protocol balances the load among these links. The weight of the link is calculated as:

$$W_l = \alpha.G_d - \beta.H \qquad (1)$$

Where W_l is the weight of link *l*, G_d is the grid density, *H* is the hop count, and α , $\beta \in [0,1]$ such that $\alpha+\beta=1$.

Grid density is given positive weight while hop count is given negative weight. This indicates that grids with higher densities and lower hop counts are preferred. Equation 1 shows that the weight of the link depends on two factors: Grid density and hop count. In one of the extreme cases, when α=1 and β=0 , the routing is done based on the grid density only. On the other hand, when α=0 and β=1, master nodes will select the shortest path to rout the data regardless of grid density. For the topology shown in Figure 1, master node of grid 11 has the routing table shown in Table 1 (α=0.6,β=0.4). Column two in the table shows the master node for each grid that is neighbor to grid 11. For instance, node30 is the master node for grid 6.

Table 1. Grid 11 master node routing table.

Destination Grid	Master Node	Hop count	Density	Link weight	Valid
"6"	Node30	2	3	1	V
"7"	Node14	3	3	0.6	V
"8"	Node82	4	4	0.8	V
"10"	Node5	3	2	0	V
"14"	Node37	4	1	-1	V

The valid field indicates the route validity. Congestion can cause paths to be invalidated as we will describe later.

Phase 3: Data transmission. After establishing the routing tables, nodes can start transmitting their data. Each non-master node transmits any information to the grid master node, and the grid master node in turn is responsible for selecting the suitable path to forward the data to. Non-master nodes can go back to sleep state if it has no more data to send while master nodes cant go to sleep state in order to receive any routing updates. This situation is continued until the master node energy is about to drain out where the master node starts an election process to select the master node that will be in charge. The node with the highest residual energy will be chosen. If the master node is the only remaining node in the grid, the master node broadcasts a routing update message to the neighbor grids to invalidate any path going through this grid.

3.2 Congestion Avoidance and Control

Real-time applications have high transmission rates which may cause network congestion. In WSNs that deliver real-time information, a robust routing protocol should employ a control mechanism that has the capability to handle network congestion. Usually, a congested path is formed when the nodes keep forwarding their packets throughout the same path almost all the time. Network congestion is usually relieved using traffic load balancing between two or more paths. In this research we will focus on avoiding congestion occurrence but in case congestion happens, actions are taken to recover congested areas. We propose an efficient congestion detection scheme by monitoring sensor nodes buffers.

3.2.1 Congestion Avoidance

We avoid congestion occurrence by creating multiple diagonal paths to the sink where the master nodes can distribute the traffic along these paths. Load balancing is used when two of the alternative paths have the same weight keeping the load evenly distributed.

In addition to that, we observe sensor buffers and before buffers getting full the node can select one of congestion control scheme discussed bellow.

3.2.2 Congestion Control

We proposed two congestion control schemes one for short term congestion and another for long term congestion.

- **Short Term Congestion Control**

Short term congestion happens in intermediate nodes due to a sudden increase in the traffic going to these nodes. Due to the fact that sensor networks are densely deployed, this kind of congestion could be eliminated by diverting the traffic to other nodes. Fortunately, we built multi-path protocol that is capable of doing this. In the proposed protocol, each routing entry has a valid flag indicates the validity of this routing path as shown in Table1. Upon detecting congestion (when buffer occupancy reaches a threshold), the node sets up a timer with random timeout and broadcasts a route invalidate message to the neighbors. Any master node in neighbor grids receives this message invalidates the paths to the node who initiated the invalidate message and start using only the alternative paths. When the timer timeout elapses, the node initiates route valid message to enable the route previously invalidated. If the node finds it's buffer overloaded again the node decides to start long term congestion control mechanism that is described in the next paragraph.

- **Long Term Congestion Control**

Sometimes when a path has small hop count and high density compared with the other paths, that path will be preferred for pack forwarding. This situation will lead to what we call long term congestion. To handle long term congestion we suggest that the master node on the congested path wakes up another node (if it is in sleep state) to work as a secondary master node. The secondary master node is selected based on it's residual energy. The routing table in the master nodes is then passed to the secondary master node. The master node can choose between handling the traffic or dispatching the traffic to the secondary master node in a way that guarantee fairness. The proposed congestion control scheme is shown in Figure 3.

4. Experimental Results

Several simulations have been performed to evaluate the performance of our routing protocol. We assume that there is only one stationary sink in the sensor field. A one hundred sensor nodes are deployed over a 700X700 m^2 area, with initial energy equal to 10 joules. The area is divided into 49 grids each of 100 m width; thus the minimum acceptable radio range equal to 282 m but we use radio range of 300 m. The MAC layer protocol used in our experiments is distributed coordination function. Since our protocol supports different types of traffic, we suggest generating the data in a variable bit rate. The complete set of parameters used in our simulation is given in Table 2.

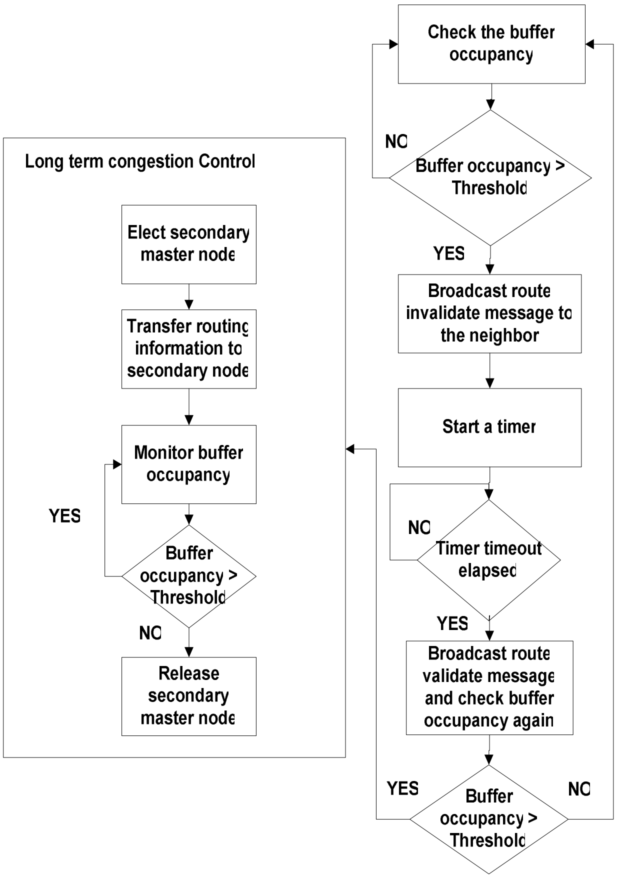

Figure 3: Flowchart of congestion control.

Table 2. Parameters used in the simulation.

Simulation parameter	Value
Topology size	700X700 m^2
Number of sensors	100
Deployment type	Random
Number of grids	49
Grid size	100X100 m^2
Radio range	300 m
Traffic type	Variable bit rate
Data packet size	128 bytes
Initial sensors energy	10 Joules
Energy to run transceiver circuitry	50 nJ/bit
Transmit amplifier	100 pJ/bit/ m^2

Real-time sensors generate packets with high rates and priorities. GPRS system could be used initially so that each node knows to which grid it belongs. The grid master node is selected randomly initially (random selection of master nodes is done only at network startup because all nodes have the same residual energy).
We compared our proposed protocol to the protocol proposed in [8]. Both the protocol proposed in [8] and our protocol establishes multiple routing paths (although the paths in our proposed protocol selected in a completely different manner), differentiate between and support two types of traffic: real and non-real and address congestion problem. Besides the similarities mentioned above between the two protocols, still there are major differences between them. We use grid based information to establish diagonal routing paths. We use grids densities in giving each link a weight, where the forwarding decision is taken based on paths weights. Also we suggest a novel technique to handle congestion by invalidating paths along the hot spots to recover congested areas. Finally, in our protocol the master node can employ fusion to minimize outgoing traffic.

4.1 Energy Analysis

Simulation results show that our protocol is superior in saving nodes energy and extending network lifetime. Figure 4 shows average residual energy during different points of simulation time. The energy saving in proposed protocol comes from the multiple energy aware schemes that are used.
First, not all nodes participate in paths establishment phase; just one node per grid broadcasts/receives grid based routing information. Second, non-master node sends any available data to the grid master node, which take routing decisions. Although this drains master nodes energy it saves grid nodes energy. Third, upon detecting topology changes (such as when a grid becomes empty or when an area became congested) few control messages are exchanged between involved master nodes whereas other protocols flood the network with updating messages. It’s worth to mention that these topology update messages are exchanged on demand not periodically. Forth, the way in which the paths are established (diagonal for non-boundary and vertical/horizontal for boundary) aim to utilizing network grids evenly.
Finally, grid density participates in deciding which route will be selected to forward the data to. Paths going through high density areas are favored among others, this help maintaining network connectivity and extending network lifetime.

4.2 Multiple Routing Paths

We proposed a novel way for establishing routing tables. Regardless the number of node in the network, each master node (for non-boundary grid) has multiple diagonal paths towards the sink through the neighbors (depending on the neighbor grid availability). The figure bellow shows the number of nodes that have 1, 3, 4 or 5 alternative paths for a network of “49” grid and a network of “64” grid.

4.3 Average Queue Occupancy

Several experiments are performed to compare proposed protocol average queue occupancy with the one in [8]. Each sensor has a buffer size of 15 packets. It is evident from Figure 6 that GMCAR makes grater use of the available queues. High queue occupancy is really desirable for sensor networks because it indicates higher resource utilization and fairness. Fairness is a major issue due to the existence of several alternative paths. Guaranteeing fairness by assigning

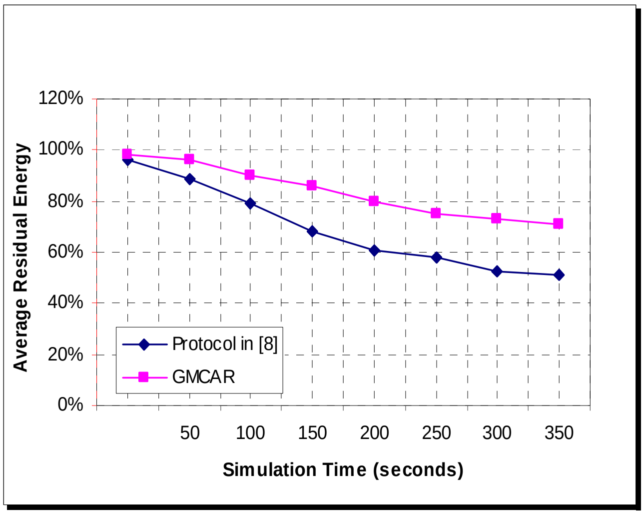

Figure 4: Average residual energy

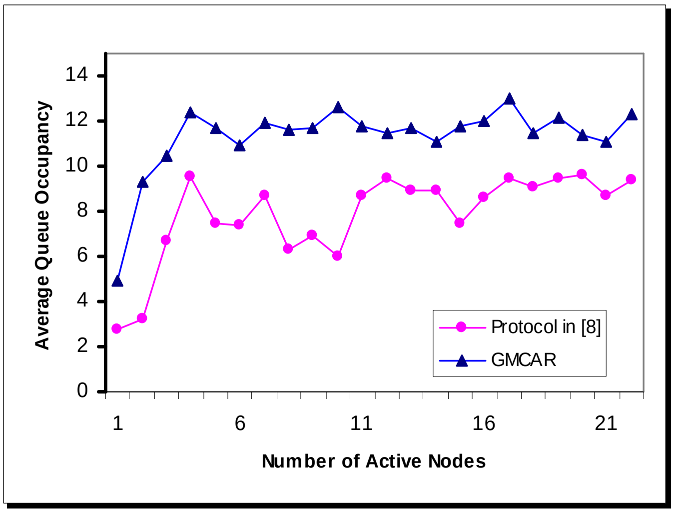

Figure 6: Average queue occupancy

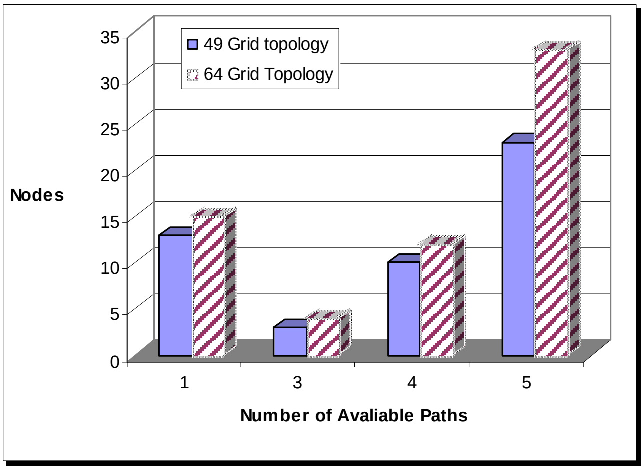

Figure 5: Number of alternative paths for “49” and “64” grid topology

higher weights for paths going through densely deployed areas extend low density paths lifetime.

5. Conclusion

In this paper, GMCAR protocol is designed to address two main important issues in sensor networks: extending network lifetime and routing real-time traffic. Moreover, a novel congestion control mechanisms are proposed to overcome the delay problem when congestion occurs. The simulation results have shown that our proposed protocol extends the life time of the sensor network and utilizes the available storage. As a future work, we are planning to study the protocol performance for networks with mobile base station or multiple base stations.

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