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PYRAMID BASED DATA GATHERING SCHEME FOR WIRELESS SENSOR NETWORKS

ABDULLAH AL-DHELAAN
Computer Science Department
College of Computer and Information Sciences
King Saud University
Riyadh, Saudi Arabia

ABSTRACT

Wireless sensor networks are deployed to collect useful information from an area of interest. Consequently, the sensed data must be gathered by the nodes and transmitted to a base station for further processing. Due to the limited battery power and criticality of the applications in most cases, methods employed for data gathering and aggregation need to be power efficient and with minimum delay in order to achieve longer network lifetime and be effective. In this paper, we propose a novel scheme for data gathering based on the pyramid interconnection that uses the pyramid as a virtual backbone and collects data from all sensors to the base station upwards. Moreover, we provide an efficient construction mechanism for the virtual backbone. The proposed scheme achieves both objectives as it reduces the power consumption and provides minimum delay as well as providing better scalability, efficiency and fault tolerance. We analyze the performance of our scheme and conduct a comparative study to demonstrate its superiority compared to other schemes proposed recently in the literature.

Keywords: *Pyramid, Wireless Sensor Networks, Virtual Backbone, Data Gathering, Power Efficiency, Delay.*

1. INTRODUCTION

The introduction of low-cost processor, memory, and radio technologies, made it possible to build inexpensive wireless sensor nodes. These sensors have limited resources and processing capabilities. However, it is possible to build a high quality, fault-tolerant wireless sensor network (WSN) by using hundreds or thousands of them. Such networks are mainly used to monitor some events and collect useful information from an area of interest, especially where the physical environment is so harsh or dangerous. Recently, WSNs have emerged as a promising solution to a wide range of applications from data collection to distributed control in both military and civilian fields that may be realized by using different type of sensors with different capabilities for different kinds of environments [1-4]. The main weaknesses of the sensor nodes are their very low finite battery energy, which limits the lifetime and the quality of the network [1]. Moreover, in some WSN applications, especially during emergency conditions, gathering and delivering the data packets to the base station in time is much more important than saving power. Consequently, the protocols running on sensor networks must consume the power of the nodes efficiently in order to achieve a longer lifetime and with minimum delay to be effective.

The energy spent by a sensor node for communication is more than the energy required for processing [1]. Hence, there is a need for efficient data gathering algorithms with less communication activities to increase the lifetime of sensor network and the effectiveness. In each round of such data gathering protocols, data from the nodes need to be collected and transmitted to the base station (BS), Sensor nodes use different data aggregation techniques to achieve energy efficiency. The aim is efficient transmission of all the data to the BS so that the lifetime of the network is maximized in terms of *rounds*, where a round is defined as the process of gathering all the data from sensor nodes to the base station, regardless of how much time it takes. Data collected from the sensor network are often time critical so it is desirable for the data gathering scheme to reduce transmission latency. To achieve that, the scheme should adopt parallel data-gathering operations or divide the environment into certain sub-regions for concurrent functioning and balance node loads. Several data gathering approaches and protocols have been intensively

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studied in research literature [5-9]. One of the most interesting approaches is the use of virtual backbone for data gathering. A hypercube based data gathering scheme for WSN has recently been proposed in [9]. In fact, different interconnection network topologies have also been proposed as virtual backbone in MANETs. The hypercube and the graycube have been proposed to enhance the resource discovery process, in [10] and [11] respectively.

In this paper, we propose a new data gathering scheme based on the pyramid network. The scheme uses the pyramid as a virtual backbone for the wireless sensor networks utilizing its topological features to reduce the communication in each round of the data gathering process thus minimizing the power consumption. The proposed scheme outperforms other schemes proposed recently in the literature. Moreover, it is energy efficient with minimum communication delay and has the advantage of scalability, efficiency and fault tolerance through providing multiple data gathering parallel paths between every node and the BS. So, in case of node failure, other data gathering paths can be explored. This is an essential characteristic as the sensor nodes are prone to failure due to energy or other reasons.

The remainder of the paper is organized as follows: In Section 2, we provide some background and some related work. We introduce some recent well known data gathering schemes focusing on those that use the virtual backbone approach. In Section 3, we introduce the pyramid interconnection network and study its structure and topological properties that make it appealing to be used as virtual backbone for WSNs. Section 4, presents our new data gathering scheme with comparison of our approach to the hypercube based approach. We show that the proposed pyramid based data gathering is efficient in terms of energy and network throughput as well as scalable, avoiding congestion, and enhances tolerance against many node failures. In Section 5, the proposed scheme, is evaluated and analyzed and compared with some other well known schemes.

2 BACKGROUND AND RELATED WORK

The data gathering in WSN is so critical to the performance and lifetime of the network. Consequently, it has been the focus of several studies with different approaches to provide better schemes. Comprehensive surveys of the literature can be found in [1-9]. In this section we introduce some of the prominent proposals reported in the literature and discuss their properties in relation to our scheme. Energy dissipation models are very important in WSNs, as they can be utilized to compare the performance of different communication protocols from the energy point of view. A very simple and commonly used energy dissipation model is the first order radio model introduced in [5]. The model gives:

$$E_{Tx}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^{\alpha}$$

$$E_{Rx}(k) = E_{elec} \times k$$

where $E_{Tx}(k,d)$ is the energy consumed by the transmitter to send a k-bit long packet over distance d, $E_{Rx}(k)$ is the energy consumed by the receiver in receiving a k-bit long packet, $E_{elec}(k)$ is the energy used by the electronics of the transmitter or the receiver, and $E_{amp}(k,d)$ is the energy expended by the transmitter amplifier. Typical theoretical values: $E_{elec} = 50\, nJ/bit$, $E_{amp} = 100\, \frac{pJ}{bit}/m^2$, and a path loss exponent α = 2 for a distance less than some crossover value ($d_{crossover}$). It is clear that receiving packets is not a low cost operation. Consequently, any proposed protocols should consider not only the number of transmitting messages but also number of receiving messages. Data gathering routes with many short links consume more energy than paths with fewer but longer links.

The Low-Energy Adaptive Clustering Hierarchy (LEACH) [5] is well known self-organizing, adaptive clustering protocol in which every node in the network will be selected as the cluster head with a probability p at each turn to distribute the energy load evenly among the sensors in the network. In LEACH, the nodes organize themselves into local clusters, with one node acting a *cluster-head*. After the heads are decided, each of the non-cluster-head nodes selects his own head according to the distance. The cluster head collects data from its cluster and transmits them to the BS. LEACH prohibits nodes from becoming a cluster head again within 1/p rounds to avoid the node power drainage. It utilizes a TDMA schedule-based for intra-cluster communications to avoid communication problems which is not a scalable feature. In LEACH, there is no inter-cluster communications (hierarchical clustering), instead cluster heads are meant to transmit directly using CDMA to the BS.

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PEGASIS (Power-Efficient GAthering in Sensor Information Systems) [6], an improvement to LEACH, is a near optimal chain-based protocol in which each node communicates only with a close neighbor and takes turns transmitting to the BS, thus reducing the amount of energy spent per round. i.e. it uses only one node in a chain to transmit data to the BS instead of using multiple nodes and avoids cluster formation. Starting from the two ends of the chain, transmission moves along the chain hop by hop and every node will fuse the received data with its own data and pass on where all nodes take turns in being chain leader. It uses collaborative techniques to increases the lifetime of each node leading to increasing the network lifetime. Moreover, to reduce the bandwidth consumed in communication, local coordination is only allowed between neighboring nodes. Several other data gathering techniques have been proposed in literature. LEACH and PEGASIS are the most studied and have been implemented for various platforms. The first is a clustering-based approach and the second is a chain-based approach. A survey of data gathering approaches is in [8]. Recently, a new emerging approach based on graphs and interconnection networks was introduced [9]. The hypercube, denoted as Q_n, is a network of $N = 2^n$ nodes where n is the dimension of the network and any two nodes are connected iff their addresses differ in exactly one bit as shown in Fig. 1.

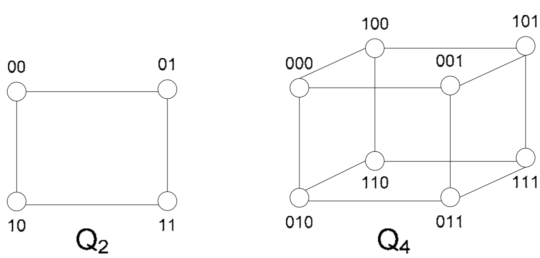

Fig. 1. Examples of the Hypercube Network

Formally, the Q_n is a connected graph $G = (V, E)$ where $|V| = 2^n$ nodes labeled with n-bit binary string $(b_{n-1} \dots b_0) \in \{0,1\}^*$ and $|E| = n2^{n-1}$. Two nodes $(b_{n-1} \dots b_k \dots b_0)$ and $(b_{n-1} \dots b'_k \dots b_0)$ where $b_k \neq b'_k, k \in \{0..n-1\}$ are connected iff they differ by exactly one bit position. If the position is the k^{th} then they are called k^{th} neighbors to each other.

It has several attractive properties such as regularity, symmetry, small diameter, strong connectivity and relatively small link complexity. Also, the hypercube, Q_n , has a diameter of n and average distance of $n \times (\frac{2^{n-1}}{2^n-1})$ and a communication tree of height $\log_2 N = n$ as shown in Fig. 2. The hypercube structure can be used to connect all nodes of a network and provides multi-hop fault-tolerant multi-path data collection policy.

One of the used schemes is the hypercube based approach [9]. The scheme uses the hypercube as virtual backbone for the WSN and utilizes it for data collection.

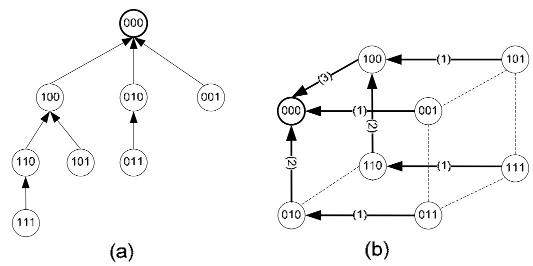

Fig. 2. Communication Tree for the Hypercube based Scheme with Q_3 . (a) The tree (b) Transmission phases

Moreover, the hypercube is used to concurrently collect data from all sensor nodes to the base station BS through the communication tree of the hypercube. The hypercube based scheme works by making each node $(b_{n-1} \dots b_i \dots b_0)$ transmits to its i^{th} neighbor if ($b_i = 1$ and b_j=0 for all j<i) for all i= 0 to n-1 as shown on the communication tree in Fig. 2. It has been shown that hypercube can shorten communication delay by parallel transmission and can reconfigure itself to replace a dead node.

3 THE PYRAMID NETWORK

The pyramid network is a hierarchical structure composed of 4-ary tree and meshes distributed over the layers with one node at the root and each layer having four times the nodes in the previous layer [12-13]. A pyramid $PM[n]$ has $n + 1$ layers, the root being number 0 and moving downwards, with 4^l nodes in the l^{th} layer as shown in Fig. 3.

Formally, the pyramid of dimension n, $PM[n]$, is a set of nodes $V(PM[n]) = \{(l, x, y) | \, 0 \leq l \leq n, 0 \leq x, y \leq 2^l\}$, where $n \geq 1$ and l is the layer number. Moreover, for a node $v = (l, x, y)$ the parent is $P(v) = (l - 1, \lfloor \frac{x}{2} \rfloor, \lfloor \frac{y}{2} \rfloor)$ and the four children are $(l +$

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$1, 2x, 2y)$, $(l+1, 2x, 2y+1)$, $(l+1, 2x+1, 2y)$, $(l+1, 2x+1, 2y+1)$. The mesh of dimensions $m \times n$, $M(m,n)$, is a set of nodes $V(M(m,n)) = \{(x,y) | 0 \le x \le m, 0 \le y \le n\}$ where two nodes (x_1, y_1) and (x_2, y_2) are connected iff $|x_1 - x_2| + |y_1 - y_2| = 1$.

The $PM[n]$ is composed of meshes in such a way that each layer l is composed of the mesh $M[l,l]$. Consequently, it has 2^l nodes in every layer l. Each node in layer l of the pyramid is connected horizontally with the other nodes in the same mesh $M[l,l]$ via edges call *mesh-edges* and vertically with its parent and children via *layer-edges*.

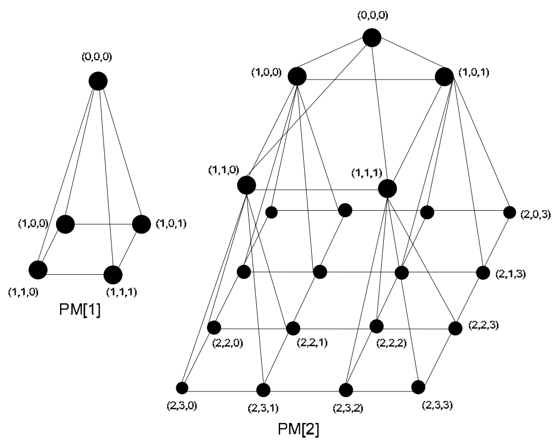

Fig. 3. Examples of Pyramid Networks

The pyramid has some very interesting features as it is hierarchical, recursive, and dense. The node degree, the number of adjacent nodes, for the pyramid varies and ranges from 3 to 9. One of the most appealing features of the pyramid is that the node degree will never exceed 9 regardless of the size of the network. For the pyramid $PM[n]$, the diameter which is the longest path between any two nodes is $2n$.

Lemma 1:

The total number of nodes, N, in the pyramid PM[n] is

$$N = \frac{4^{n+1} - 1}{3}$$

Proof:

The pyramid PM[n] has n+1 layers and each layer l has 4^l nodes. Thus, the total number of nodes is:

$$N = 1 + 4 + 16 + \cdots . + 4^n = \sum_{l=0}^{l=n} 4^l = \frac{1 - 4^{n+1}}{1 - 4}$$

$$= \frac{4^{n+1} - 1}{3}$$

Lemma 2:

The number of layers, L, in the pyramid $PM[n]$ is $L = \frac{\log_2(3N+1)}{2}$

Proof:

Using the equation $N = \frac{4^{n+1}-1}{3}$ in lemma (1), we can show that:

The number of layers in $PM[n]$ is:

$$L = n + 1 = \log_4(3N+1) = \frac{\log_2(3N+1)}{2}$$

More topological properties of the pyramid network were investigated in [12-13]. Such attractive topological properties of the pyramid have motivated us to use it as a virtual backbone for the WSN and propose a new data gathering scheme that utilizes such features.

4 PYRAMID-BASED DATA GATHERING SCHEME

The data gathering is an essential task in wireless sensors networks. The sensed data must be gathered and transmitted to the base station efficiently in term of power consumption and delay. Power efficient methods must be employed for data gathering and aggregation in order to achieve long network lifetimes as the WSN consists of low-cost nodes with limited battery power. Moreover, such methods need to have minimum delay as it is mostly used for critical applications that require such promptness. The data gathering usually occurs through several communication rounds. In each round of communication each of the sensor nodes typically has data to send to the base station, so it is essential to minimize the total energy consumed by the system as well as the delay resulting in each round.

We propose to use the pyramid network as a virtual backbone, overlay network, built on top of the WSN network. Nodes in the pyramid network correspond to sensors that are connected by virtual links, each of which corresponds to a physical wireless link reached by the omni-directional antenna. The new scheme collects data from sensor nodes to the BS through the communication tree of the pyramid as shown in Fig. 4. It also shortens

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communication delay by parallel transmission and replaces dead nodes through reconfiguration.

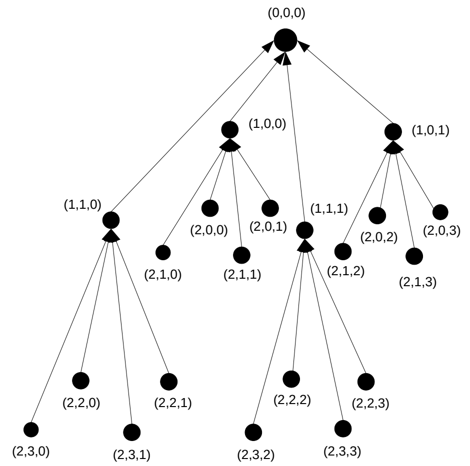

Fig. 4. Communication Tree for the Pyramid based Scheme with PM[2].

The virtual backbone is constructed using top down fashion starting from the BS which looks for four nodes within its transmission range and make them its children. Afterwards, it assigns them addresses forming the 1st layer. Such nodes will in turn construct the next layers recursively.

Some of the physical sensors are mapped to the nodes in the virtual pyramid and the data is transmitted from nodes at lower layers, high numbered, to nodes at upper layers in stages until it arrives to the base station in layer number zero. Fig.5. illustrates the construction of the virtual backbone and the mapping between the virtual backbone and physical WSN.

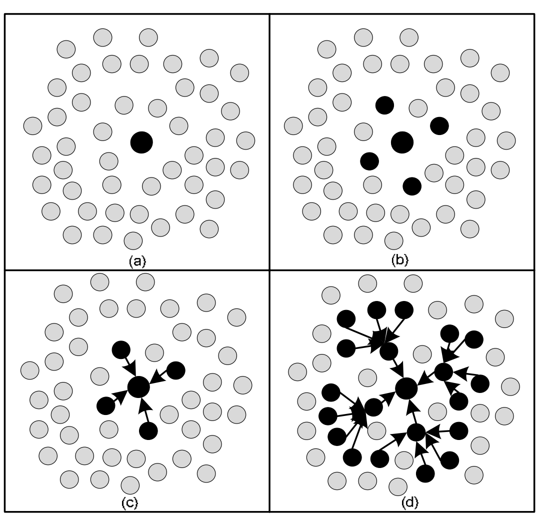

Fig. 5. Constructing the virtual pyramid backbone (a) The 0th layer (BS) (b) The 1st layer nodes (c) Constructing the 1nd layer (d) The 2nd layer.

Fig.6. shows the data transmission which takes three phases corresponding to the layers of the pyramid and equals to the height of its communication tree. The phases are shown between brackets on the figure.

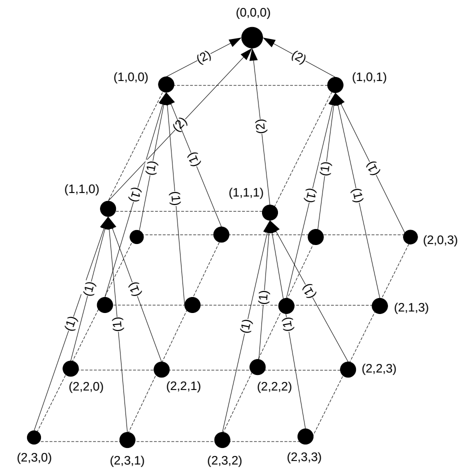

Fig. 6. Data Gathering for the pyramid based Scheme with PM[2].

5 THE PERFORMANCE EVALUATION

The scheme will be evaluated from power consumption and delay points of view. We will unify them and compare networks with the same number of nodes N.

A. *The power consumption*

We will evaluate the power consumption for our proposed scheme and compare it with the hypercube based scheme. Assuming the first order radio model introduced earlier, we will derive the power consumption in the following lemmas.

Lemma 3:

The total power consumption for the hypercube based scheme with Q_n is $E^{Q_n}(k,d) = (2^n - 1)\gamma$

Where $\gamma = 2(E_{elec} \times k) + (E_{amp} \times k \times d^{\alpha})$

Proof:

The total power consumed is the sum of power consumed for transmitting and receiving by all nodes:

$$E^{Q_n}(k,d) = E_{TX}^{Q_n}(k,d) + E_{RX}^{Q_n}(k)$$

Since the number of transmitting nodes and receiving nodes are $\sum_{i=0}^{i=n-1} 2^i = 1 + 2 + \cdots + 2^{n-1} = (2^n - 1)$

$$E_{TX}^{Q_n}(k,d) = (2^n - 1)\,(E_{elec} \times k + E_{amp} \times k \times d^{\alpha})$$

$$E_{RX}^{Q_n}(k) = (2^n - 1)\,(E_{elec} \times k)$$

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That leads to:

$$E^{Q_n}(k,d) = (2^n - 1)\gamma$$

Lemma 4:

The total power consumption for the pyramid based scheme with $PM[n]$ is:

$$E^{PM[n]}(k,d) = \left(\frac{4^{n+1}-1}{3} - 1\right)\gamma$$

Where $\gamma = 2(E_{elec} \times k) + (E_{amp} \times k \times d^{\alpha})$

Proof:

The total power consumed is the sum of power consumed for transmitting and receiving by all nodes.

$$E^{PM[n]}(k,d) = E_{TX}^{PM[n]}(k,d) + E_{RX}^{PM[n]}(k)$$

Since each node will send to its parent (except the root in layer zero)

$$E_{TX}^{PM[n]}(k,d) = \left(\frac{4^{n+1}-1}{3} - 1\right)(E_{elec} \times k + E_{amp} \times k \times d^{\alpha})$$

Also each node will receive from all of its four children (except nodes on layer n).

$$E_{RX}^{PM[n]}(k) = 4 \times \left(\frac{4^{n+1}-1}{3} - 4^n\right)(E_{elec} \times k)$$

So,

$$E_{RX}^{PM[n]}(k) = \left(\frac{4^{n+1}-1}{3} - 1\right)(E_{elec} \times k)$$

That leads to:

$$E^{PM[n]}(k,d) = \left(\frac{4^{n+1}-1}{3} - 1\right)\gamma$$

Lemma 5:

The pyramid based scheme and the hypercube based scheme, of similar size, consume the same power.

Proof

To compare the power consumption for both schemes we need to unify them and compare them with respect to the same number of nodes.

The hypercube Q_n has $N = 2^n$ nodes. Using lemma 3, the total power consumed for a hypercube based scheme with N nodes is:

$$E^{Q_n}(k,d) = (2^n - 1)\gamma = (N-1)\gamma$$

Similarly, from lemma 1, the pyramid PM[n] has $N = \frac{4^{n+1}-1}{3}$ nodes. Using lemma 4, the total power consumed for a pyramid based scheme with N nodes is:

$$E^{PM[n]}(k,d) = \left(\frac{4^{n+1}-1}{3} - 1\right)\gamma = (N-1)\gamma$$

So the average total power consumption for the hypercube based and the pyramid based schemes, when unified to have the same number of nodes N, is the same and equals to $(N-1)\gamma$.

B. Delay Analysis

The data gathering and aggregation is a very critical task especially in real time systems. So, the process needs to take place with minimum delay and fast propagation time. Moreover, the delay for every data gathering scheme is directly proportional to the height of its communication tree and the transmission phases.

Looking at the communication trees for both the hypercube based and the pyramid based schemes in Fig. 2 and Fig. 4 respectively, the data gathering starts from the leaves and moves upwards towards the roo

The communication tree for a hypercube based scheme with Q_n has $N = 2^n$ nodes, $n+1$ levels, and height of n maximum hops. One the other hand, the communication tree for a pyramid based scheme with PM[n] has $N = \frac{4^{n+1}-1}{3}$ nodes, n +1 layers, and height of n maximum hops. So, the height of the tree is the number of the hops from the leaves to the root and is equal to number of levels, or layers, minus one which corresponds to the number of transmission phases for such scheme. To do a proper comparison between the two schemes, we need to compute the heights of the communication trees as a function of network size. i.e. the number of nodes N. When the hypercube based scheme has N nodes the height of the communication tree HQ^N is defined as:

$$HQ^N = \log_2 N$$

So for instance, a hypercube based scheme with 64 nodes would have a communication tree of height 5 and that is the number of transmission phases needed for such network. When the pyramid based scheme has N nodes, lemma 2 can be used to define the height of the communication tree HP^N as:

$$HP^N = \frac{\log_2(3N+1)}{2} - 1$$

For instance, a pyramid based scheme with 85 nodes would have a communication tree of height 3 so the scheme needs 3 transmission phases for such

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network. It is apparent that the number of transmission phases needed for the pyramid based scheme is much smaller than that of the hypercube based scheme which will lead to smaller delay in favor of our proposed scheme. In general, for different sizes of networks, Fig. 7 shows the transmission phases for both the hypercube based scheme and the pyramid based scheme. The number of transmission phases is of great importance, since the delay is proportional to such transmission phases. In other words, having more hops or more phases would incur higher delay.

The energy efficiency and delay should not be considered on isolation since there is a tradeoff between energy spent per packet and delay. Therefore, the $Energy\ x\ delay$ metric is appropriate and has been widely used in the literature to compare data gathering schemes [7].

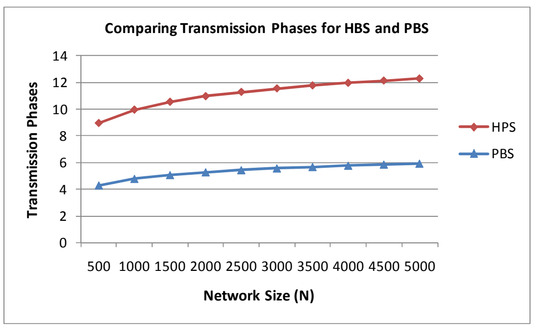

Fig. 4. Comparing the delay for Hypercube Based (HPS) and Pyramid Based (PBS) Schemes.

Lemma 5 showed that our proposed pyramid based scheme and the hypercube based scheme consume the same power. On the other hand, the proposed scheme has much less transmission phases, compared to the hypercube based scheme, leading to minimum delay. Consequently, using the $Energy\ x\ delay$ metric we conclude that our proposed scheme has much better performance since it provides lower delay without incurring any additional power consumption. Moreover, the construction and maintenance of the virtual pyramid backbone has much lower overhead compared to that of the virtual hypercube backbone. This is due to the fact that each node in the pyramid is connected to at most 9 neighbors regardless of the size of the pyramid. However, in the virtual hypercube backbone each node has n neighbors where n is the dimension of the underlying hypercube is.

6 CONCLUSION

We have used the pyramid topology as a virtual backbone for wireless sensor networks and proposed a novel pyramid based scheme for data gathering in WSNs. Furthermore, we provided an efficient mechanism to construct such virtual backbone. The proposed scheme is power efficient and with minimum delay leading to longer network lifetime and more effectiveness especially for critical applications. Moreover, the scheme provides scalability, efficiency and fault tolerance. We have analyzed the performance of our scheme and conducted a comparative study with other schemes proposed recently in the literature and concluded the superiority of our proposed pyramid based data gathering scheme.

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AUTHOR PROFILE:

Abdullah Al-Dhelaan, has received BS in Statistics (Hon) from King Saud University, on 1982, and the MS and Ph.D. in Computer Science from Oregon State University on 1986 and 1989 respectively. He is currently Associate Professor of Computer Science, Chairman of the join Ph.D. program, and Director General for the Center for International Collaboration and Visiting Professors, College of Computer and Information Sciences, King Saud University, Riyadh, Saudi Arabia. He has guest edited several special issues for the Telecommunication Journal (Springer) , and the International Journal for Computers and their applications (ISCA). Moreover, he is currently on the editorial boards of several journals such and Computer Network (Elsevier) and The International Journal of Computers and their applications. His current research interest includes: Mobile Ad Hoc Networks, Sensor Networks, Cognitive Networks, Network Security, and High Performance Computing.