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A Resilient Smart Body Sensor Network Through Pyramid Interconnection

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ABSTRACT In the era of body monitoring revolution, wireless body sensor networks (WBSNs) have become an important area of research in many fields, such as health care, military, fitness, and body-interactive games. It consists of a number of tiny low capability sensors organized and deployed over the human body or any living being body. These sensors collect body vital signs data and send it to a base station (BS) for further processing and computations. In fact, gathering and collecting data in real time and communicating it with the station in a timely manner is a crucial feature in the WBSNs. Equally important, reducing the power consumption of these sensors will result in maximizing the battery life and reducing the interval time needed to recharge. Therefore, there are several architectures to gather and collect such data with efficient design. These designs vary from enhancing the distribution of sensors over the human body to the implementation of improved protocol-based communication architecture. In this paper, we propose a novel WBSN architecture through a pyramid interconnection that decreases the power consumption and data gathering delay and increases the resiliency of the system as opposed to the state-of-the-art models. A performance analysis that shows the superiority of our model is presented and discussed as well.

INDEX TERMS Hypercube interconnection, pyramid interconnection, star interconnection, wireless body sensor network.

I. INTRODUCTION

Wireless body sensor networks (WBSNs) are used in different aspects of our life, such as body measurement control and body activity monitoring for healthcare, gestures detection, face recognition for social networking and sometimes it is used in entertainment, such as interactive games. As a result, it is important to provide solid architectures and framework to design these applications of networks. Nowadays, wireless technology improvements led as well to the improvement of WBSN. Thus, it becomes more efficient to continuous monitoring the body and transmitting data to the BS in real time and timely manner [1], [2]. Moreover, these networks contain small sensors located over human body to sense and gather body vital signs. These devices have a limitation in the capabilities due their sizes that would be placed inside or outside the body [3]–[12]. Thus, reducing the power consumption and increasing sensor battery lifetime are also crucial factors that need to be considered in designing WBSNs.

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Several areas could be enhanced to provide better performance and reduction of node computation. For instance, effective programming and platforms used lead to overall enhancement of in WBSNs [13]–[15]. Thus using framework with proven algorithms for such network provide better performance and reduce complexity. On the other hand, data gathered from single sensor may not be efficient for some applications, therefore data gathered from multi sensors play major role in the enhancement of the network [16]–[18]. Therefore, gathering data from multi sensors need to be addressed to overcome nodes computation overhead and reduce network utilization. Nevertheless to say, these areas have a great impact on how data gathered and transmitted over the network.

WBSNs are a sub field of the wireless sensor networks, which inherit the main characteristics weakness of the wireless networks such as memory, power and computation limitation [19]–[25]. In addition, these devices placed inside or outside the body where it bring an extra constrain to its sizes as well as the size of its batteries. Thus, the efficiency in monitoring and gathering data become highly important factor in designing these networks to meet sensors capabilities and maximizing of battery life of these devices [26]–[29]. Moreover, the network topology is a major factor in designing WBSNs. In fact, power consumption and data transmission reduction affected by the topology of the network. Thus, better topology provide smooth data transition with less data conjunctions and high network throughput [30]–[32].

Network topology used in WBSNs vary based on proposed solutions. These topologies including Star, Mesh, hypercube [33] affect the network in many areas such as accuracy, efficiency and resiliency. The results of network efficiency and resiliency reflected on the solutions by providing less data gathering delay and reduce power consumption. As far to our knowledge, no one discussed the efficiency and resiliency of using pyramid network topology on WBSNs. Pyramid topology has a unique features resulting on better performance when used on WBSNs. For instance, the maximum number of vertex degree known as node degree which has a direct effect on the cost of each node computation will never exceed 9 in pyramid network. On the other hand, for star and hypercube networks it depend on the total number of nodes within the network. Similarly, the transmission phases for pyramid is less than hypercube which reduce the data transmission delay. These features make pyramid network superior and provide more resiliency, reliability and scalability for such networks and increase data accuracy and reduce transmission delay.

This paper proposes a new WBSN architecture that aims to decrease the power consumption and data gathering delay by reducing the data transmission phases to the base station and decreasing the node degree connections. Our proposed system is based on a pyramid backbone structure which provides more resiliency and reduces data gathering delay in comparison with other interconnections (such as star and hypercube). Pyramid network is a hierarchical structure that offers many features such as power efficiency, network resiliency. Moreover, it minimizes the delay that makes it suitable for critical applications such as health care and military [34]. The remainder of this paper is structured as follows: related works are presented in section 2. In section 3, we cover our network model and architecture. In section 4, we show the performance analysis of our system. Finally, the conclusion and future work are discussed in section 5.

II. RELATED WORKS

Many papers in the literature reviews focus on the WBSNs as a whole system. These papers vary from enhancing the network topology, architecture, Medium Access Control (MAC) to intelligent sensor nodes. The main contributions of these articles are reflected on power consumption, data transmission rate or data delay rate. Authors [35]–[40] introduced several improvements to network performance and reduction in data transmission delay by several enhancements on MAC protocols, to illustrate an example is combining several protocols to take advantage of certain property from each protocol. For instance, Bou Dargham *et al.* [39] design a protocol that guarantee immediate and reliable transmission, where they designed a protocol that combine the high delay efficiency of DS-CDMA with high energy efficiency of DTDMA. As a result, this scheme outperform other schemes in terms of delay and packet drop percentage.

In other work, authors discussed different methods to enhance effectiveness of WBSNs applications. For instance, authors in [13], [14], [41] provide several studies to increase application performance and enhance network utilization. Giancarlo *et al.* [13] show the performance evaluation of using middle ware in developing WBSNs applications. As a result, they concluded that SPINE provide better performance than CodeBlue and Titan. On the other hand, Giancarlo *et al.* [41] propose BodyCloud, a SaaS multi-tier application-level architecture approach that supports the development and deployment of Cloud-assisted WBSNs applications. BodyCloud receives data from smart phone which used as base station, where body sensors sense and gather data then transmitted it to the smart phone.

Moreover, other authors introduced more enhancement to WBSNs by improving the architecture of proposed systems. Authors studied redesigning and implementation of modified network nodes to manage data transmission over the network. For instance, [42]–[44] improve the network by implementing multiprocessors architecture to the system. Similarly, other authors improve WBSNs by redesign the architecture of sensor nodes itself. In particular, Braojos Lopez, Ruben, and David Atienza [42] completely redesigned memory subsystem for sensors in combination with advanced code synchronization management in the system architecture. As a result, their modification improve the network by reduction in power consumption by up to 82%.

Khan and Pathan [12] provide state-of-the-art wireless body area sensor networks survey. In their study they tried to cover all possible areas of latest WBSNs solutions, specifically their communication architectures, applications, programming frameworks, security issues, and energy-efficient routing protocols. Authors provide a set of challenges that faces the use of these networks. For instance, placing sensors over body, energy consumption and using multi different sensors. They concluded that WBSNs are new technology and they have good possibility to enhance healthcare applications in the coming future. In addition, these networks would be powerful in their applications and they would directly affect the human healthcare by adding easiness to our daily life.

Kaur and Naveen Bilandi [45] studied several topologicals placement for WBSNs. Authors categories the sensor topologies to: Point to point, Star, Mesh, Tree and Tree-Mesh hybrid. Authors concluded that among all studied network topologies, Mesh and Tree mesh provide best performance for WBSNs. In addition, multi-hop topology (mesh, tree) is effective because of its low power consumption. However, the drawback of multi-hop topology in comparison with one hop topology is transmission has a higher delay. In addition, authors did not discuss other network topologies such as hypercube and pyramid.

Salayma *et al.* [46] suggested that the data carried by WBSNs are sensitivity and critical. Thus they provide a comprehensive study and investigation about the reliability and fault tolerance paradigms suggested for such networks. Authors argue that the increase of heterogeneity of networks, sensors, applications and communication technologies increase the challenges in reliability. In addition, they concluded that the majority of proposed systems for fault tolerance cover only on fault detection techniques. Proposed systems supposing that the only recovery approach is node isolation and replacement. This approach leads to increase of node delay in response, where a critical systems needs an instance node response.

It is noted that a very few works concentrate on improving the network topology. Zuhra *et al.* [25] provide a comprehensive survey in WBSNs routing protocols. They noted that, bus and ring topologies are not suitable due their limitation in scalability. Thus, the best topology that are widely used in WBSNs are star and mesh [46]. The main benefit for star topology is its property as nodes are directly connected with the base station. However, the drawback is the high power consumption as one node will be the bottle neck of the network. In the other hand, mesh networks are appropriate for multi hop networks for their excellent performance. Thus, this network has no single point of failure where the previous networks have. However, multi hop networks suffer from transmission delay but authors did not discuss this factor with other network topologies such as hypercube and pyramid.

Rezvani and Ghorashi [47] proposed context aware and channel-based resource allocation. They designed a WBSN for healthcare based on star network topology and improve the performance by adaptive resource allocation. On their solution, they studied the fading traffic used by body sensor and divided it to cases depend on user's medical situation. First case for normal situations where the user in normal condition and no medical assistance is needed. Secondly, where the user in emergency case and need for medical assistance, therefore it tolerates to channel faults and provide the network with data that considered fading effects. Results have showed that network utilization and performance are improved. In addition changing the interval of the consecutive transmissions based on fading condition reduced the packet loss rate up to 60%.

Almogren [20] proposed Smart BodyNet, a design of the WBSN based on virtual hypercube interconnection. Author provide a new design architecture for the proposed as well as performance evaluation for the proposed system in comparison with star interconnection. The author concluded that, hypercube overcome star interconnection in term of energy efficient. In addition, the proposed system inherits the main advantage from a smart phone which easily integrated with smart world. Furthermore, smart phone has the ability to connect the two different networks on the proposed system. First network is the interconnect between body sensors and the smart phone for gathering body data. Second network is the connection between the smart phone and the Internet using its wireless LAN or using broadband cellular network technology (3g/4g).

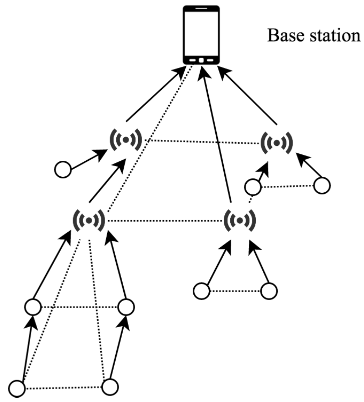


FIGURE 1. Pyramid interconnection nodes.

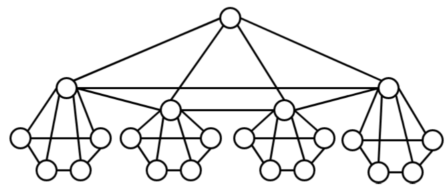


FIGURE 2. Communication tree transmission for pyramid interconnection.

III. THE PROPOSED ARCHITECTURE (PIN)

Pyramid Interconnection Network (PIN) is a hierarchical structure composed of 4-ary tree and meshes [48] distributed over the layers with one node at the root and each layer having four times the nodes in the previous layer as depicted in figure 1. For n-layer pyramid interconnection network (denoted as $PM[n]$) total number of nodes calculated as [49]:

$$\sum_{i=0}^{n} 4^i \text{ which equals to } \frac{4^{n+1}-1}{3} \text{ ISNs}. \quad (1)$$

The quality of data gathered from nodes affected by several factors such as the resiliency of the network and data gathering delay. Thus, in each layer of the pyramid, nodes are connected horizontally to other nodes in the same mesh through edges called mesh-edges. This connectivity provides the pyramid with resiliency that missing in star interconnection when edge node die where its adjacent node handle the traffic instead. In addition, nodes also connected vertically with its parent and children via layer-edges, where pyramid interconnection has less layers than hypercube interconnection. These connections increase the network resiliency and decrease the data gathering delay which result of improving data accuracy. In addition, These connections can be represented as tree interconnection as depicted in figure 2.

Sorting on a pyramid cannot be significantly faster than on a 2D mesh. However, routing data can be faster by the added links compared with a 2D mesh. To route from any node to any other node, we can simply route upward to the

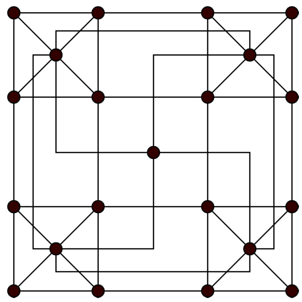


FIGURE 3. 2D layout transmission for pyramid interconnection.

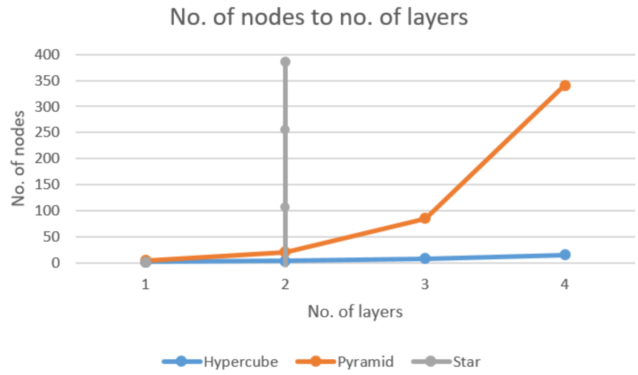


FIGURE 4. Number of nodes incremental to number of layer for each network.

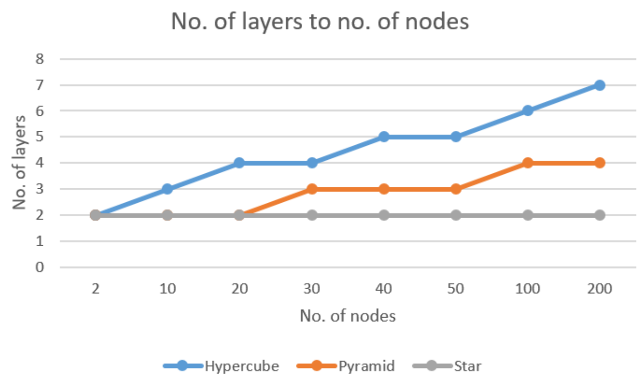


FIGURE 5. Number of layers to the number of nodes for each network.

apex and then downward to the target node. This will archive a good performance as long as the number of data is decent, otherwise a congestion probability will increase at the top of the pyramid which entail an increase in delays [50]. Figure 3 depicts 2D layout transmission for pyramid interconnection.

In addition, pyramid networks have the following features that support their superiority and make them better to be used in WBSNs than other topologies such as star and hypercube:

- Network degree ranges from three to nine and will never exceed nine [34].
- Number of layers equal to $\frac{(4^{n+1}-1)}{3}$.
- Number of nodes increase exponential to the number of layers.

The first feature is the network degree which is the node number of edges to other nodes. When a degree is high it makes the network more reliable and reduce the data transmission delay. However, if the degree is huge, it will produce negative impact on the network. For instance, a network with high degree is more probability to be vulnerable to security attack [51]. Similarly, high network degree increases the complexity of the network as it generate multiple links for each node [52]. Thus, star and hypercube networks degree are depend on the number of nodes within the network. As a result, as number of nodes increased, the network complexity and security risk both increased. Therefore, pyramid network become better choice, whenever the number of node increased the network degree never exceeded nine.

The second feature is the transmission phases; where it is represented by the number of layer in each network. When a node sends a data over the network, it passes each layer using network hub. These hubs increase the data transmission delay when the number of hubs increased. For star network it is fixed to number two of layers where it better for small scale number of nodes, however when the number increased it will make a significant impact on the base station. On the other hand, the hypercube network has $log_2 \ N$ layer, therefore, the number of layers increased with small incremental in number of nodes. However, pyramid network provide is better choice as the number of layer is small even in the number of nodes increased with high rate. Figure 5 describe the number of nodes incremental when the number of layer increased.

The third feature is the number of nodes to the number of layers for each network. This feature represents the maximum number of nodes for number of layers in the network. For the star network, the number of nodes is not related to number of layer as star network layer is fixed to two. On the other hand, hypercube network maximum number of nodes is equal to 2^n where n is number of layer. Similarly, for pyramid network, the maximum number of nodes is equal to $\frac{(4^{n+1}-1)}{3}$. This shows that for the same number of layers, pyramid supports more nodes than hypecube network.

These features make pyramid networks more reliable and provide better performance for WBSNs. In fact, it also reduces power consumption and node computation. Therefore using pyramid network interconnection increase WBSNs efficiency and effectiveness.

As a result, our proposed system architecture is based on pyramid interconnection. We show the different levels of communications and routing and the architecture of the proposed system. Figure 6 describes a typical architecture of our system, it separated into three tiers:

1) Tier 1: The Intelligent Sensor Nodes (ISNs) presented in white circles. They are responsible for monitoring, measuring, and gathering data from the body area. It uses the pyramid master nodes (donated in signal icon) to exchange these data with other ISNs and/or transmit it to the BS. Master nodes are nodes that connected directly to the BS, thus their degree are four

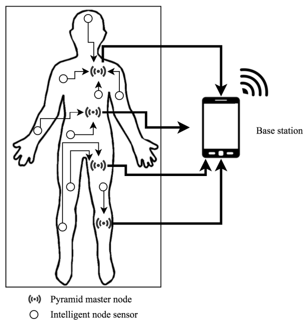


FIGURE 6. High level of intelligent sensors over body.

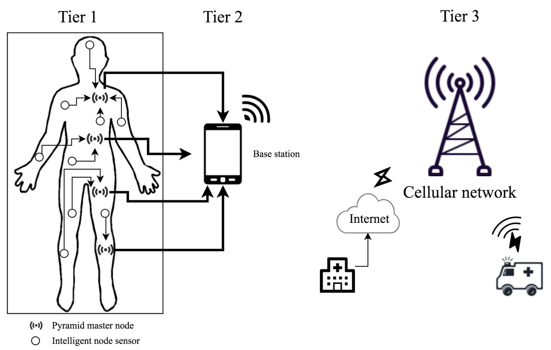


FIGURE 7. The proposed architecture and tiers levels.

in the pyramid networks. These nodes receives all data from other nodes within WBSNs then send them to BS.

2) Tier 2: The BS is presented in a mobile phone icon. It is responsible for receiving data from pyramid master nodes. BS is working as a gateway to efficiently exchange gathered data with remote parties using Tier 3 as depicted in figure 7.
3) Tier 3: The communication network that responsible for transmitting data to remote parties. Thus, mobile phone in tier 2 will link two separate networks. First network is the WBSN which is a pyramid master node with the collection of ISNs. Second network is the Internet that used to distribute the collected data to remote parties.

Figure 7 depicts the proposed architecture with the tiers levels as mentioned above. It illustrates the three tiers in the proposed system and other parties that interact with it. In fact this architecture can be expanded to have multi WBSNs, so that the BS become the master node of the network.

IV. PERFORMANCE EVALUATION

In this proposed architecture, we expand our previous architecture based on hypercube (Smart BodyNet) by using pyramid topology. In addition, we compare it with others architectures based on star topology that used in other solutions such as CodeBlue and Titan. Our criteria for evaluating our solution with others are based on power consumption,

TABLE 1. Comparison of main feature in pyramid, hypercube and star architectures.

Features	Pyramid	Hypercube	Star
Simplicity	Yes	Yes	Yes
Redundant paths	Yes	Yes	No
Routing between Sensors	Yes	Yes	No
Broadcast of Sensors	Yes	Yes	No
Scalability	Yes	Yes	No
Energy efficiency	Yes	Yes	Yes
Node mobility	Yes	Yes	Partial
Network degree [51], [54]	9	$log_2 N$	$N-1$
No. of layers	$\frac{log_2(3N+1)}{2}$	$log_2 N$	2
Number of nodes	$\frac{(4^{n+1}-1)}{3}$	2^n	N+1

data gathering delay and the features that pyramid networks overcome other network topologies. In the beginning we show the main features that supported by our proposed architecture in comparison with other architectures. Table 1 illustrate these features.

Moreover, we compare our proposed architecture with others in term of power consumption. Nodes in WBSNs consume energy based on the following formula [20]:

$$P_{Tx}(k,d) = E_{elec} \times k + E_{amp} \times k \times d^{\alpha},$$
$$P_{Rx}(k) = E_{elec} \times k, \tag{2}$$

$P_{Tx}(k,d)$, is the energy consumed by sensor to send k-bits long packet over distance d. Similarly, $P_{Rx}(k)$ is the power consumed by sensor to receive same packet size. Each node is consuming certain amount of energy from receiving data and re transmitting it again to next phase. Total energy consumption for pyramid network is represented by formula 3.

$$P_{Tx}^{pyramid}(k,d) = (\frac{(4^{n+1}-1)}{3} - 1)T \tag{3}$$

The hypercube networks master node degree is three, therefore it consumes more energy than pyramid network. This leads the hypercube to consume more power and, as a result, the network lifetime is decreased.

Similarly total energy consumption for hypercube network is represented by formula 4.

$$P_{Tx}^{hypercube}(k,d) = (2^n - 1)T \tag{4}$$

Finally, star networks total energy consumption for star network is represented by formula 5.

$$P_{Tx}^{star}(k,d) = ((n+1) - 1)T \tag{5}$$

However, these represent the total power consumption during network life. Thus the total nodes living over time is vary depend on the network architecture and the number of transmission phases. In figure 8 we present the energy consumption and nodes living during network life. Within first quart of time, 77% and 67% of star and pyramid network nodes are a life respectively. However, only 44% of hypercube network nodes are a life. It is important to say that, first nodes to die are BS and master nodes, thus to

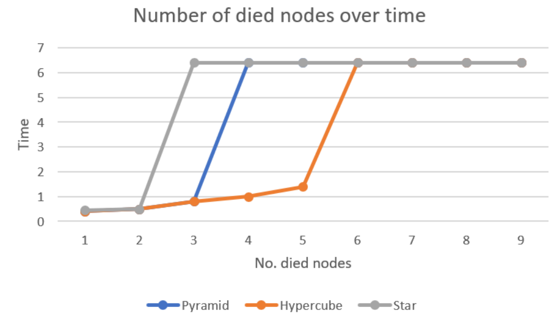
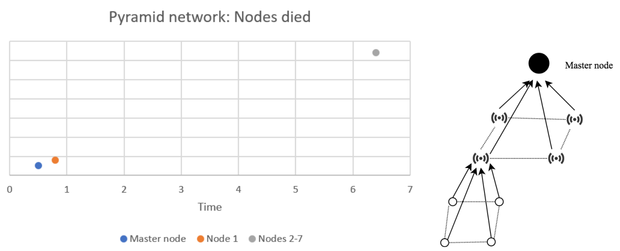
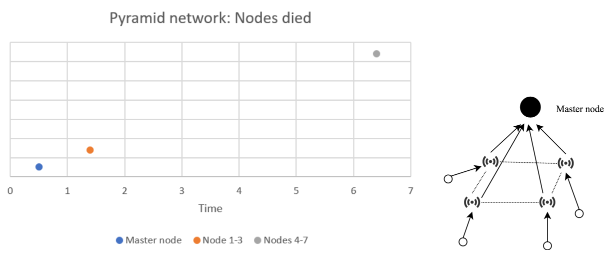


FIGURE 8. Number of dies nodes during network life.



(a) (b)

FIGURE 9. Nodes life time when organized as pyramid shape. (a) Power consumption over time. (b) Nodes organized in pyramid shape.



(a) (b)

FIGURE 10. Common figure caption. (a) Power consumption over time. (b) Nodes organized in balance.

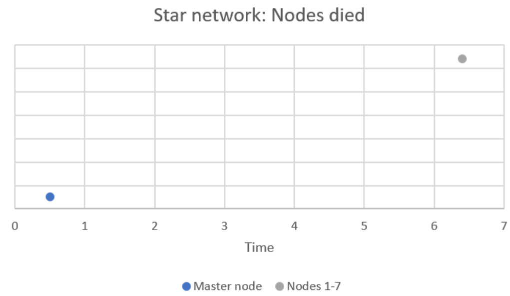


FIGURE 11. Nodes life time when reorganized balance nodes.

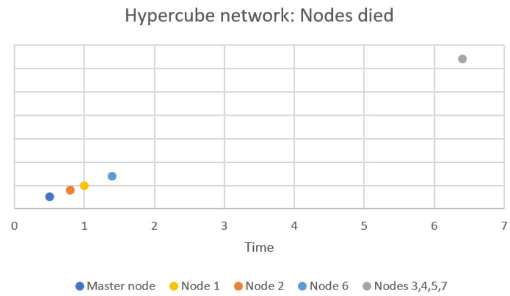


FIGURE 12. Nodes power consumption over time for hypercube network.

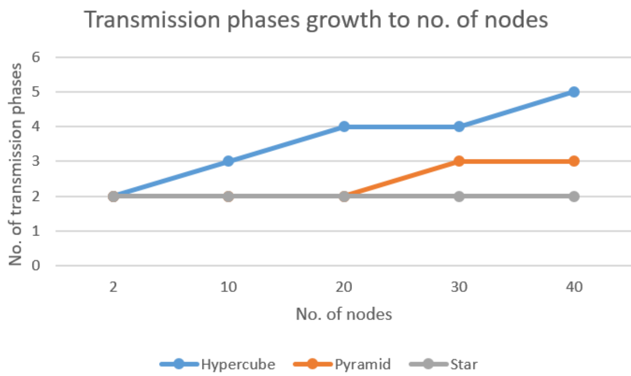


FIGURE 13. Transmission phases increased by number of nodes growth.

increase network life it is better to reduce sensors capability and increase the BS and master nodes capability.

As a result, both number of transmission layers and the degree of master node and other nodes make different power consumption. In figure 9 we show the power consumption for all nodes in pyramid network where it show that all load was on the master node and the node with higher degree as depicted in figure 9(b). We reorganized nodes to balance power load on the each node on the network as depicted in figure 10(b).. Thus instead of connected four nodes to one node we connected one node to each node on the edge. As a result, we highly recommended when number of nodes in pyramid network is less than the total number of nodes for n layer to balance nodes on each node edge.

Similarly figure 11 and figure 12 show the power consumption for all nodes for star and hypercube receptively. Thus to have better power utilization it is better to balance between the number of master node and other nodes degree and the number of transmission layers.

In the other respective, number of transmission layers or phases play a major role in network data gathering delay. When number of phases increased it leads to increase data gathering delay. However, when number of layer decreased and number of nodes increased it leads to increase the overhead on the master nodes. For each networks interconnections, figure 13 show the transmission phases incremental in comparison with nodes growth. Star interconnection has constant transmission phase which is just two phases, where it lead to poor resiliency and had huge impact on its master node as it will handle all data gathered by all nodes.

As a result, the data gathering delay is affected by transmission phases and number of nodes connected to base station. Star and hypercube based transmission phases calculated as above by $O(N)$ and $O(log_2 N)$ respectively. On the other hand, the transmission phases for our proposed system is calculated

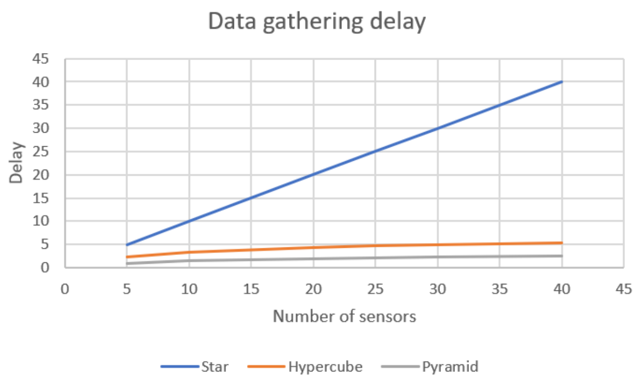


FIGURE 14. Data gathering delay chart.

by $O(\frac{log_2(3N-1)}{2} - 1)$. We show the Data gathering delay for star, hypercube and pyramid based architectures in figure 14. As a result, pyramid based architectures provide better data gathering than star and hypercube.

All above results have been simulated using omnet++ 5.4 installed on Windows Subsystem for Linux (WSL) on Windows 10 Home edition 64-bit. Hardware configuration equipped with a 2.0-GHz Intel Core i7-4510U processor (4 CPUs) with 8 GB of RAM; a 128 GB SSD; and a shared Intel HD Graphics GPU. Our experiment designed for 8 sensor nodes with following properties for each data processed (sent or received) cost 0.1 *ms* delay and 0.8 *watt* energy and startup power is 100 *watts*. For BS, it has following properties for each data processed (sent or received) cost 0.05 *ms* delay and 0.8 *watt* energy and startup power is 150 *watts*.

V. CONCLUSION AND FUTURE WORK

This research extends our previous work which was based on the virtual hypercube interconnection. We propose a novel architecture for the WBSNs which is based on the pyramid interconnection where we achieved great results. The proposed architecture provides an efficient data collection approach to accomplish this considering the type of network design challenges. The performance of our proposed system is validated and compared to our previous system, namely smart BodyNet, in addition to other popular systems based on star WBSN topology. The results show that the pyramid topology is more energy efficient as compared to the star and hypercube topologies. In the other hand, our proposed system is more efficient in term of data gathering delay than star and hypercube topologies. Equally important, we show the benefit from using pyramid network to increase the system resiliency, scalability and reliability. In addition, in our proposed system we gain the interoperability, portability, mobility and intelligence from smart phone that can be easily integrated with the surrounding smarter world. As a future work, we would investigate the possibilities of securing the group communications in our system to enhance the feasibility of the WBSNs.

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