# To Hop or Not to Hop: Network Architecture for Body Sensor Networks

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***Abstract*— As Body Sensor Networks (BSNs) advance to fulfill the promise of continuous, non-intrusive, remote monitoring of patients, it is important that we achieve efficient communication between energy constrained on-body sensors. An important design choice which has significant impact on achieving this goal is the network architecture. Star architecture has been the natural choice for BSNs due to the short distances between the nodes. In this paper, we revisit this choice by quantitatively studying architecture choices using data from experiments conducted by deploying nodes operating at the $2.4\ GHz$ band on actual human volunteers. We compare the star and multihop architectures to highlight their respective performance characteristics. In particular, we use our data to construct multihop networks with routes that maximize end-to-end Packet Delivery Ratio (PDR) and routes that minimize the average number of retransmissions. Since BSNs span an entire spectrum of applications, each with its unique constraints and requirements, there is no solution that is optimal for all applications. Instead, we show the performance across a variety of metrics and the trade-offs that are achievable. We see that a multihop network minimizing retransmissions has several advantages including having better network lifetime as well as the lowest delay and energy consumption.**

## I. Introduction

With the growing population of the elderly [2], continuous, non-intrusive remote monitoring of patients provided by Body Sensor Networks (BSNs) will be crucial to prolong people's lives and improving their quality of life. BSNs involve deploying non-intrusive, energy-constrained sensors that monitor a patient's physiological signals continuously. These signals are transmitted to a gateway, usually a PDA or mobile phone. The gateway analyzes the data, evaluates the condition of the patient and then takes the necessary action. BSNs are capable of reacting to emergencies quickly and providing complete logs of the patient's condition.

There are several challenges that need to be overcome in implementing a BSN. One of these is achieving efficient communication between the sensor nodes and the gateway at all times. Several crucial performance metrics - packet delivery ratio (PDR), energy consumption, delay, network lifetime, etc. - are dependent on the design of the communication protocol between sensors and the gateway. In this regard, one of the parameters that has significant impacts is network architecture. Network architecture is the logical connection of communication between the various nodes in a network. Typically, star, multihop and cluster-based architectures are used in Wireless Sensor Networks (WSNs).

In this paper, we use data we have collected in experiments similar to those conducted in [1] to investigate the impact of network architecture on the following metrics.

- Packet Delivery Ratio (PDR) (Sec. V) is the probability of a packet reaching the destination from the source. This is an important metric as it reflects the reliability of communication.
- Average number of retransmissions (Sec. VI) is the number of times a packet has to be transmitted on average before it is received. This metric has significant implications for energy consumption and the delay incurred per packet.
- Network lifetime (Sec. VII) is defined as the time taken for the first node in the network to consume all its energy. Due to the non-intrusive nature of BSNs we aim to deploy as few nodes as possible, making this metric very important.

In addition, we inspect the impact of network architecture choice on an effect specific to BSNs - inter-user interference. Inter-user interference (Sec. VIII) is the interference due to the operation of other BSNs in the vicinity. This becomes especially important when several BSN users congregate in an area (for example, hospitals).

The network architectures evaluated in this paper are the star and multihop architecture. Star architecture is typically assumed for BSNs given the relatively small area over which the nodes are deployed. In this paper, we show that this solution has inadequacies especially for BSNs operating in dynamic, time-varying environments. One of the alternatives to star is a multihop architecture. In a multihop architecture, nodes have a choice to transmit data to the gateway or to other nodes in the network. This can provide robustness to adverse environmental conditions, but engineering such a network requires overcoming complexity. Among the several possible network configurations of multihop architecture we pick two in this paper. The networks we choose are a network with routes that maximize the end-to-end PDR of data transmission (referred to as a multihop-PDR network) and a network with routes that minimizes the end-to-end average number of retransmissions (referred to as a multihop-retransmission network).

In this paper, we will not propose a one-size-fits-all solution. Since BSNs span a set of diverse applications, this would be clearly unwise. For example, a BSN designed to sense heart arrhythmia cannot tolerate high latency, whereas a BSN monitoring body temperature levels will not have very stringent delay requirements. However, we do provide general guidelines that a network engineer can utilize to design a BSN. For example, if a BSN is supposed to operate in small room environments, then a star architecture has performance that is very close to that achievable by using a multihop network. However, if the BSN is to be deployed in open environments, multihop networks offer several advantages. If the BSN requires high end-to-end PDR, the multihop-PDR network can provide average PDR of $97.4\%$ compared to the $73.81\%$ achieved by a star architecture. If the BSN requires the low energy consumption and low delay, then the multihop-retransmissions network is the most favorable network. Further, we see that operating at higher power levels can increase inter-user interference but can, in select cases, reduce energy consumption.

Any BSN designer will have to confront the challenge of efficient communication between the sensors and the gateway. Seeing as network architecture is a crucial component of network design, our paper addresses an important topic. While the question of network architecture itself has not been given enough attention, the approach we follow - using data from real volunteers - is even more rare. Our contributions are as follows:

- We investigate the link layer behavior and highlight results that have significant impact on network architecture and other network design choices.
- Quantitatively evaluating the star and multihop architectures in various environments. Demonstrating from analysis on experiments conducted on real-life human volunteers, the characteristics of important performance metrics such as PDR, average number of retransmissions and network lifetime.
- We highlight and inspect the inter-user interference effect which is specific to BSNs.

## II. Related Work

Most of the work being conducted in BSNs is on developing non-intrusive sensors to record physiological data. Several groups, [3]–[6] have focused on this task and have achieved considerable success. The CodeBlue group at Harvard University, [3] have developed sensors that can sense heart rate, oxygen saturation and EKG data. The Ubimon group at Imperial College, [4] have developed a custom BSN mote that can be interfaced with sensors.

As mentioned, network architecture for BSNs has typically been assumed to be a star architecture. The argument is that due to short distances between nodes and the gateway, no relay nodes will be necessary. In fact, most of the work done is at the level of system architecture such as in [7] and [8]. In these cases, network architecture is hardly considered in detail. For example, [8] only mentions that the sensors will somehow communicate with the PDA which can conduct long range communication.

There are only a few studies that have investigated network architecture for BSN. Typically, these studies model the communication between nodes placed on the human body from radio wave communication models. A typical example is [9] which uses a simple radio-wave propagation model and identifies that from an energy consumption point of view, a multihop architecture is beneficial. Yet other studies use MAC protocols in conjunction with network architectures to evaluate them. [10] ascertains that a cluster-based architecture performs better than a tree based network. In a similar fashion, [11] analyzes multihop network architecture for throughput and delay by using their WASP protocol.

Our approach is significantly different from the studies identified as we use data from human volunteers as opposed to radio-wave propagation models. These models are tedious to use and need the environment to be specified to a very high degree. This is fraught with difficulty as the wrong specifications lead to wrong results.

One study using an approach similar to ours is [12] where the authors have collected data in the 433 $MHz$ range from a single volunteer in three environments. They use this data to look at the differences between the PDR of star and multihop architecture. Note that, our analysis in this paper considers a wider range of metrics than those in [12]. Further, our data set is in the popular 2.4 $GHz$ band.

## III. Link Layer Behavior and Network Architecture

In order to quantitatively investigate the effect of different architectures, we needed to collect data regarding the behavior of nodes on the human body. As we have mentioned earlier, most of the work done in this area is done by developing path loss models of the human body. However, using these path loss models to get link layer metrics needs a very high specification of the environment which is extremely difficult. Our previous work, [1], focused on capturing the characteristics of wireless communication between nodes placed on actual human volunteers in real environments. In this section, we detail the methodology behind an extended version of this experiment and some of the important results that have implications for network architecture.

### A. Experiment Design Choices

Our goal was to obtain data one would observe in the actual operation of a BSN. Therefore, we made the following design choices:

**Choice of environment**: To capture a wide range of environments in which we expect BANs to operate, we picked an office setting (our lab), residence environment (hall of an apartment) and an open space environment (roof top).

**Traffic model**: Nodes are scheduled to transmit such that they never transmit at the same time. This makes our data useful for TDMA schemes and providing a strict upper bound to the performance achieved by contention-based MACs. Further, low data rates in BANs [14] makes TDMA particularly attractive.

**Frequency range**: Our data is from the 2.4 $GHz$ range. This is a popular frequency band for on body sensors [3], [4], which makes our study important. Note that, while special bands exist for medical applications, such as the Medical Implant Communications Service and Wireless Medical Telemetry Service, these bands are highly regulated. They either require an authorized healthcare professional or are not allowed for home use, [13], which makes the unlicensed 2.4 $GHz$ band even more favorable.

**User movements**: Unlike in [12] we do not constrain our volunteers to certain positions. This is due to our goal of capturing performance closest to what is observed in the real-life operation of BANs. The only constraint on volunteers was that they do not leave the environment, in which the experiment was being conducted.

**Number of nodes**: We used 12 nodes in our experiment to cover a wide range of possible applications. Further, an application designer who wishes to use only a subset of nodes in her application can still use the empirical traces of communication between the subset of nodes.

### B. Experiment Description

12 CrossBow TelosB motes were placed on human volunteers as shown in Fig. 1. Node 10 was placed on the volunteer's back diametrically opposite node 9. The motes are placed such that batteries are closest to skin, with the antennas being further away.

Each of the 12 motes broadcast information to the rest of the network according to a schedule. First, node 1 would broadcast 40 packets, each at an interval of 200 $ms$ at the lowest power level available, $-25\ dBm$. The 11 nodes would be kept in receive mode and would listen for the packets transmitted by node 1 and store the IDs of the packets received and the RSSI at which they were received. Once this was finished node 1 would transmit another 40 packets at $-15\ dBm$ and then at $-10\ dBm$. Following this, node 2 would transmit the same number of packets at each of the three power levels and so on. After all 12 nodes had finished transmitting, node 1 would begin the cycle again.

Experiments were run on 14 different volunteers in 3 different environments with roughly 82 hours of data collected. The first environment was a cluttered lab environment with several reflective surfaces. The second environment was a home environment with large rooms and fewer reflective surfaces. An open roof environment, which would provide very little multipath, was the last environment in which the experiments were conducted.

### C. Results

The main metric we analyzed in our paper was the metric of Packet Delivery Ratio (PDR). The PDR between nodes $i$ and $j$, $PDR_{ij}$, is expressed as the percentage of packets transmitted by node $i$ and received by node $j$. Therefore, a PDR of 95% means that out of 100 packets transmitted, 95 were received. In addition, we define received PDR for node $j$ to be $E[PDR_{ij}]$ where the expectation is over all nodes $i$, $i \neq j$.

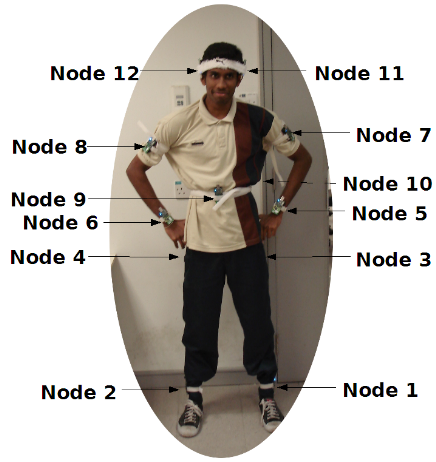


Fig. 1. Node ID and position on the body. Node 10 is on the volunteer's back.

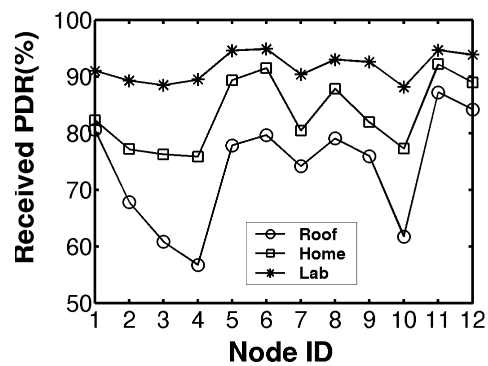


Fig. 2. Received PDR in different environments. Tx power: $-25dBm$.

Our preliminary result in [1] was that even at the highest power levels (0 $dBm$ using the CrossBow TelosB mote) no communication through the human body is possible. Therefore, any communication between the nodes must happen by radio waves reflecting off of surfaces in the environment. This would predict that nodes in the lab environment with the most reflective surfaces would receive the most packets and nodes in the roof environment the least.

This is the case as shown in Fig. 2 which shows the received PDR for each node. We realize that for applications operating in diverse, time-varying environments, star architecture is insufficient. In fact, for some of the links in the roof environment, the PDRs between the links at $-25\ dBm$ are lower than 60% for 46% of the experiments performed.

We also developed a visualization tool (Fig. 3) to help us discern important patterns from our data. In this figure, the $ij^{th}$ entry in the matrix represents the PDR between nodes $i$ and $j$. We identified that channel symmetry is seen to hold well between nodes placed on the human body. In fact, the difference in PDR between the forward and backward links between the nodes $i$ and $j$ is on average only 4.6%. This implies that if one were to implement a multihop arhitecture, the same routes could be used for the uplink and downlink communication with the gateway.

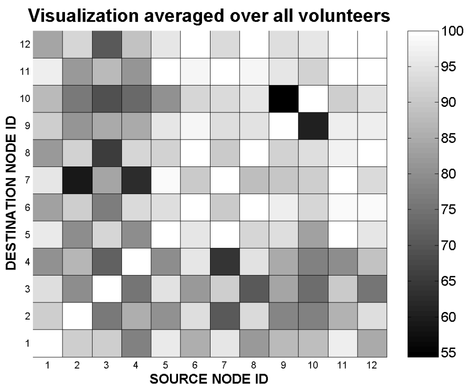


Fig. 3. Visualization with PDR averaged over all environments.

To investigate the changes in the PDR of the links over time, we use the notion of temporal variance. This is investigated by calculating the standard deviation of short-term PDR. Short-term PDR is the PDR of a link calculated over a 40 packet window of communication between a node pair. The sample standard deviation of short-term PDR for a link over the course of a whole experiment is the temporal variance of that link. Consider, for example, a link having 50% PDR for the whole experiment. If, over the course of this experiment, the short-term PDR was 50% consistently, this link would have zero temporal variance. On the other hand, if the short-term PDR switched between 0% and 100% alternatively, the temporal variance of this link is high.

Our data shows us that there is high variability in the performance of links over time, with links exhibiting a standard deviation of up to 40%. Further, the links that exhibit the highest temporal variance were seen to have an average PDR of 50% to 80%. This implies that an adaptive routing scheme might be necessary for a multihop architecture.

## IV. Network Architecture Choices

We consider two network architectures - star and multihop. In a star architecture, each node will communicate directly with the gateway. The complexity involved is significantly lower than in implementing a multihop architecture. However, this implies it will be unable to react to changes in the environment except by increasing the power level.

In a multihop architecture, nodes can communicate with the gateway through relay nodes. This also allows the network to adapt to changes in the environment and achieve better performance. However, this increases complexity as now each communication could involve coordinating several nodes. We must note though that the issue of complexity is not as significant as in other WSNs due to the small number of nodes in a BSN. Further, most sensor nodes in BSNs are low rate sensors, [14], except for electromyograph (EMG) sensors. The lower data rates and the periodic nature of sampling the physiological signals, imply that nodes can take turns sending the data without colliding with one another. This characteristic of most BSN traffic makes multihop even more feasible as contention-based MACs are not required.

There are several possible options with regards to how a multihop network architecture can be configured. Before the network configurations are considered, we first define certain variables.

Let there be N nodes in a network and the links between the nodes in this network be denoted by $1, 2, ..., L$, where $L = N(N-1)$. Then $p_l$ denotes the PDR of the link. For any route $r$ between nodes $i$ and $j$ consisting of multiple links $l$, the end-to-end PDR between nodes $i$ and $j$ is then defined as $PDR_{ij}^r = \prod_{l \in r} p_l$.

We concentrate on 2 instantiations of multihop networks - a network optimized for the highest PDR and a network optimized for the lowest average number of retransmissions.

- Optimizing for the highest end-to-end PDR: The end-to-end PDR is a measure of how reliably one is able to send a packet from the source to the destination. To find the route that maximizes the PDR between any pair of nodes $i$ and $j$, we aim to find the route such that $PDR_{ij} = \max_r PDR_{ij}^r = \max_r \prod_{l \in r} p_l$. This is equivalent to $\min_r \frac{1}{\prod_{l \in r} p_l}$. By some simple manipulation we see that we can use Dijkstra's algorithm on a graph where the weight of a link is denoted by $\log \frac{1}{p_l}$ to find the optimal routes. We will refer to this architecture as the multihop-PDR network.
- Optimizing for the lowest average number of retransmissions: The average number of retransmission metric achieved by hop-by-hop retransmission, is an important metric that presents a lower bound for both the energy consumption and communication delay. For a link $l$ with PDR $p_l$, the average number of retransmissions for any packet sent on that link is given by $\frac{1}{p_l}$. To pick routes that reduce the number of retransmissions, we use Dijkstra's algorithm to find $\min_r \sum_{l \in r} \frac{1}{p_l}$. We will refer to this architecture as the multihop-retransmission network.

Note that, over a single hop minimizing the average number of retransmissions is equivalent to maximizing the PDR of that link. However, in the multihop scenario the case is not the same. For example, suppose that the direct link between nodes $i$ and $j$ has a PDR of 50% and therefore has average number of retransmissions of 2. Further, consider that the PDR between a third node, node $k$ with both nodes $i$ and $j$ is 90%. If packets being transmitted to node $j$ is being routed through node $k$ then the end-to-end PDR for this route will be 81% and the average number of retransmissions will be 2.22. Clearly, it is seen that optimizing for PDR and average number of retransmissions produces different results.

The evaluation of the network architectures was conducted as follows. From the data for an experiment, the routes for the multihop-PDR and multihop-retransmissions network were determined. Then the metrics (PDR and average number of retransmissions, for example) were computed for each source and destination pair. After performing this for every experiment, the values of the metrics are averaged over all the experiments, weighted by the number of packets transmitted in that experiment.

We inspect the results of this analysis in the rest of the paper. We first investigate the impact on PDR of the different network architectures.

## V. Packet Delivery Ratio (PDR)

PDR, which is the probability of a successful transmission, is an important metric in most WSNs. As explained earlier, we measure it by observing the end-to-end PDR. We first inspect the effects of the different network architectures on PDR in the lab environment in Fig. 4. Note that the lab environment has the most number of reflective surfaces and receives the highest proportion of packets among the three environments.

### A. Impact of the Environment

As can be seen, in the lab environment, even at the lowest power level, the direct links between the nodes already achieve received PDR mostly above 90%. Note that, if the multihop-PDR network is used, one can achieve a PDR of above 95%. However, it must be noted that using the multihop-PDR network there are several routes that have as many as 4 or 5 hops (average of 2.57 hops per route). This significantly increases the overhead in configuring and maintaining the network. Therefore, we impose a limit of 2 hops per route and then find routes that maximise end-to-end PDR. This network has an average of 1.67 hops per route. This would significantly limit the overheads involved and as can be seen from Fig. 4, the performance achieved is very close to that achieved by multihop-PDR network. Note also that the multihop-retransmissions network presents an improvement over star architecture.

One might argue that PDRs of close to 90% are sufficient for the running of a BSN. However, if we are to implement a continous monitoring BSN it must operate in diverse, time-varying environments including open spaces. Fig. 5 shows the impacts of the various network architectures on a BSN operating in a roof-top. We notice that a star architecture is insufficient here. The average received PDR for the nodes placed in the pockets (nodes 3 and 4) is close to 60%. This will not suffice for applications requiring high data rates. However, we observe that the optimal multihop-PDR network can provide average received PDR for most nodes at about 96%, with the lowest being 93%. As with the experiments in the lab environment, there were routes of 4 and 5 hops (average of 2.69 hops per route). Imposing a 2-hop limit on the length of a route (average of 1.74 hops per route), we notice that the PDR is still significantly improved with all nodes receiving almost 90% PDR or more.

Finally, we also observe that the multihop-retransmission network improves the PDR significantly to above 80% (PDR of 86.42% averaged over all nodes). While this is lower than the gains made by the multihop-PDR network, it was noticed that there were significantly fewer hops in this network (average of 1.02 hops per route in the lab, average of 1.21 hops per route in the roof). Further, as explained in Sec. VI, this network represents the lowest energy consumption per packet being transmitted in the network.

### B. Increasing the Power Level

The situation with a star architecture can definitely be remedied by increasing the power level. This has other consequences on energy consumption and inter-user interference that we discuss in Secs. VI-B and VIII. However, from the point of view of PDR, increasing the power has significant impact on the performance of the network as shown in Fig. 6. Averaged over all environments, there is almost a 9% increase achievable by increasing the power level from the lowest power level to the second lowest power level. In particular, for the lab environment, increasing the transmission power from the lowest power level (Fig. 4) to the second lowest power level, means that all the nodes received PDR of greater than 96% on average. This increase is even more significant in the roof situation, where the nodes experience PDRs of 85% and above (as compared to PDRs as low as 55% at the lowest power level). It is also noticed that, regardless of environment, at the higher transmission power levels, multihop-PDR networks have received PDRs close to 99%.

**Summary:** In this section, we explored the impact of the network architecture on end-to-end PDR. We note that there are significant performance gains to be achieved, by using a multihop-PDR network, even if there is a 2-hop limit imposed on the network. Further, increasing the power level can allow star networks to achieve higher PDR in open environments. We also noted that a multihop-retransmissions network achieves moderate improvements, compared to multihop-PDR, over the star architecture in open environments. Therefore, if a BSN requires very high end-to-end PDR and the BSN is to operate in a variety of environments, then the multihop-PDR network should be used. However, if the complexity or overhead in engineering the multihop-PDR network is too high, a star network with higher power or a multihop-retransmission network can be used.

We now look at the impact of network architecture on average number of retransmissions.

## VI. Average Number of Retransmissions

The average number of retransmissions for a link is the reciprocal of the PDR of that link. However, the end-to-end average number of retransmissions is not the reciprocal of the end-to-end PDR for a route with multiple hops as shown in Sec. IV. It represents the number of times, on average, a packet must be sent before it is received. In this section, we explore the impact of the different network architectures on this metric. We first consider the importance of this metric to BSNs.

Average number of retransmission is an extremely important metric for most WSNs. This is due to the fact that radio communication is the most energy consuming component of a sensor device, usually consuming orders of magnitude more current than other processing needs. Given this constraint, we see that the greater the number of times a packet is transmitted, the consumption of energy increases. It also follows that if a packet has to be transmitted multiple times before it is received, the delay will increase. Note that minimizing the

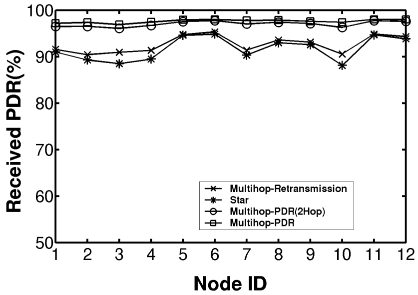


Fig. 4. Received PDR with different network architectures. Lab environment. Tx power: $-25$ $dBm$.

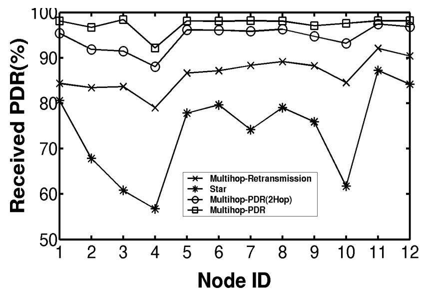


Fig. 5. Received PDR with different network architectures. Roof environment. Tx power: $-25$ $dBm$.

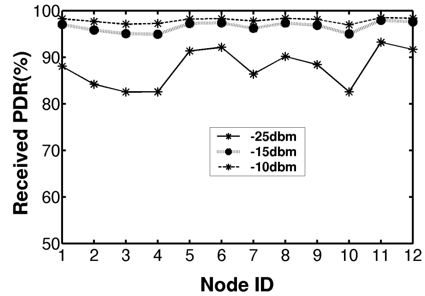


Fig. 6. Received PDR with star architecture at different power levels. All environments.

average number of retransmissions for each packet, implies that we reduces the amount of time for which the communication channel is occupied. This reduces the opportunity for interference from transmissions of other networks.

From the network architectures, that we have chosen to evaluate, we can expect that the multihop-retransmissions network will perform the best, as this network chooses the optimal routes for average number of retransmissions. Further, we also expect that the multihop-PDR network might have poor performance in this metric. The reason is, as we have noted, that several routes have hop lengths of 4 or 5 hops. Since the minimum value for average number of retransmissions is 1, for these routes the average number of retransmissions will have a minimum value of 4 or 5. A single hop link would need to have a PDR of less than $25\%$ to have similar average number of retransmissions.

### *A. Impact of the Environment and Power Level*

We now inspect the performance of the various network architectures in the lab environment. In Fig. 7, the x-axis is the node ID of the nodes sending the packets and the y-axis is the average number of retransmission over their links with all other nodes. As expected, on average, the multihop-PDR network has the worst performance in this metric. This highlights that, despite the gains that these networks present in terms of reliability, they significantly increase the overall energy consumption of the network and the delay incurred by each packet. We also notice that the multihop-retransmissions network does not present much of an improvement over the star architecture in most cases. Therefore, in the closed room lab environment, star network architecture could suffice. It must be noted that node 7 has particularly bad performance, and this highlights the inflexibility of the star architecture.

Fig. 8 shows the scenario in the roof environment. We notice that the performance of the star network in this situation is mostly poor. Several nodes have average number of retransmissions of 5 and above, only node 1 has performance close to that of the multihop-retransmission network, which is the optimal network for this metric. Note that, the only way to amend the situation for the star architecture is to increase the power. In comparison, the multihop-PDR network, even though it might use many hops to establish communication between the nodes, it selects high PDR links and can achieve sufficiently less number of retransmissions. The 2-hop limited multihop-PDR network performs even better, as expected.

By design, the multihop-retransmissions network performs the best and it typically uses only two hops for the routes (average of 1.21 hops in the roof and 1.02 in the lab). Seeing that delay performance is crucial for BSNs, this architecture produces favorable results. This, combined with the PDR results in Fig. 5, points toward the multihop-retransmissions architecture as the favorable choice.

As noted before, due to the added complexity of configuring a multihop network, one might still want to persist with a star architecture. To examine the performance in this case, we inspect the impact of power increases on a star architecture operating in a roof environment in Fig. 9. As can be seen, invariably, increasing the power improves the performance of the star architecture. Further, we observe that at $-15$ $dBm$, the performance the metric is almost constantly at a value of 1, which is the minimum achievable.

### *B. Energy Consumption*

While our discussion, in this section on average number of retransmissions, has direct implications for delay performance, this is not so for energy consumption. Particularly, while average number of retransmissions, and hence delay, decrease with increasing transmission power, this might not be the case for energy consumption. Energy consumption is investigated by observing the product of the average number of retransmissions with the power consumed at each transmission power level. Clearly, this is a device specific metric. For the TelosB using the CC2420 radio, [15], the situation in the roof environment is shown in Fig. 10. Note that, we only show the star and multihop-retransmissions network here, and the energy consumption is on a log base 2 scale.

Interestingly, we notice that, for star architecture, the best solution for many nodes is to operate at $-10$ $dBm$. This highlights that, in some environments operating at higher power levels might reduce the energy consumed per packet. The multihop-retransmissions network provides the similar performance at all power levels with $-15$ $dBm$, consuming the least energy. In the lab scenario, our data suggests that regardless of network architectures, operating at $-25$ $dBm$ consumes the least energy. This highlights that the choice of power level is one that might need to be adaptive, from an energy consumption point of view.

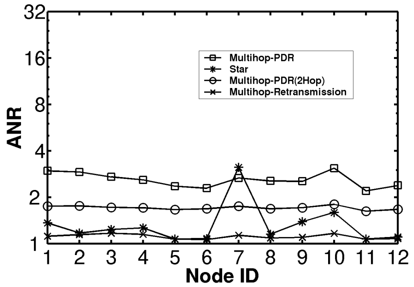


Fig. 7. Average number of retransmissions (ANR) (log base 2 scale) for different architectures. Lab environment. Tx power: $-25\ dBm$

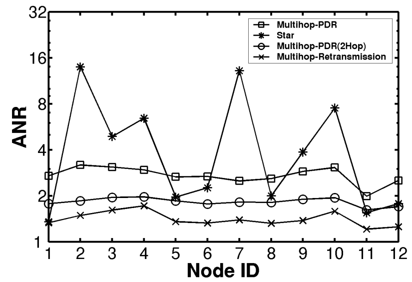


Fig. 8. Average number of retransmissions (ANR) (log base 2 scale) for different architectures. Roof environment. Tx power: $-25\ dBm$

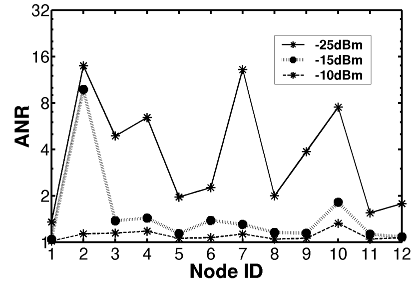


Fig. 9. Average number of retransmissions (ANR) (log base 2 scale) for star architecture at different power levels. Roof environment.

**Summary:** From this section, we see that multihop-retransmission network presents the minimum average number of retransmissions achievable in a multihop network. While the star architecture has similar performance in the closed room lab environment, for the same power level the multihop-retransmissions network is significantly better in open environments. If a BSN designer wishes to design a network that uses the least energy, or one with the least delay, then the multihop-retransmissions network is the best choice. Note that, star architecture can reduce the average number of retransmissions by increasing the power level, and in some cases this can also reduce the energy consumption. We now proceed to inspect another key metric for BSNs, network lifetime.

## VII. Network Lifetime

Network lifetime is a very important metric for WSNs, and is even more so in a BSN setting. We define network lifetime to be the time taken for the first node in the network to die. To understand the importance of this metric, note that in a BSN, each node typically senses a specific mode of data. Therefore, the death of a single node usually means the loss of that modality of data. Even in BSN applications, where this is not the case (motion detection BSNs can be made completely out of accelerometers, for example), since the nodes are being deployed on humans, we wish to put in as few nodes as possible, in order to be non-intrusive.

We assume that each node in the network generates the same number of packets. As noted, BSNs are a diverse set of applications, and the assumption of equal data rates does not hold for all BSNs. Despite this assumption, the approach taken, still allows us to achieve insight into the impact of architectures on network lifetime.

We calculate network lifetime as follows. Given a gateway $g$, the energy cost of node $i$ transmitting a packet at power $P$ directly to node $g$ is given by $\frac{P}{PDR_{ig}}$. This is the product of the power consumption per packet with the average number of retransmissions used for sending packets from node $i$ to $g$. Given a star network architecture, an equal number of packets being generated by each node $i$, and all nodes beginning with the same energy, then the node whose battery will die first is the node for which $\min_i \frac{PDR_{ig}}{P}$.

For a multihop network, we must consider the cost of packets being routed through each node too. Note that we do not consider the cost of processing the routed data, as radio communication is the biggest consumer of energy. Further, in the multihop-PDR and multihop-retransmissions networks, for a certain gateway $g$, node $i$ only communicates with node $j$, regardless of the source of the packets that node $i$ is now sending. Therefore, given that the number of nodes sending packets to node $i$ is $n_i$, i.e. the in-degree of node $i$, and that node $i$ forwards to node $j$, the network lifetime is calculated as $\min_i \frac{PDR_{ij}}{(n_i+1)P}$.

### A. Results

Fig. 11 compares the different network architectures on their performance for network lifetime. The figure shows the network lifetime of the network, given that the node $i$ on the x-axis is the gateway. Note that in this figure, all power levels are $-25\ dBm$.

In terms of network lifetime, the multihop-PDR network is the worst performer. As noted before, several routes of 4 to 5 hops were present in this configuration. As a result, nodes will have high routing cost. This is the reason for the poor performance of multihop-PDR. We also note that, the 2-hop limited multihop-PDR network has a minor performance gain.

The star architecture has significantly better performance, with double the lifetime achievable in many cases. The best performing network architecture for network lifetime is the multihop-retransmission network. However, note that since we have not looked for the network that optimizes network lifetime, we do not know the maximum network lifetime achievable. In this paper, we only wish to compare between the network architectures outlined in Sec. IV.

We now observe the impact of increasing the power level on network lifetime. Note that, since we are considering the product of power consumed and the average number of retransmission, we could have a case where increasing the power level increases network lifetime. This will occur if the decrease in average number of retransmissions offsets the increase in the power consumed. Since this metric is device specific, we investigate with the power consumption data for the TelosB mote which was the mote used in our experiments.

Fig. 12 compares the performance of the star architecture and the multihop-retransmission architecture, operating at the three different power levels. We see that especially for star architecture, network lifetime, on average, increases with increase in power, from $-25\ dBm$ to $-15 dBm$. However, increasing the power further does not improve the network

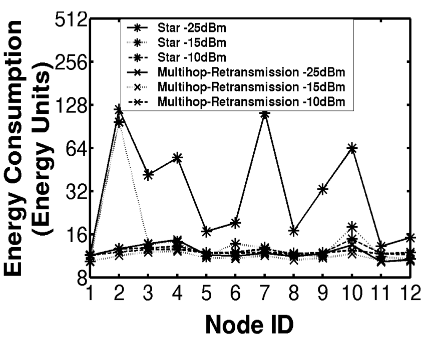


Fig. 10. Energy consumption for star and multihop-retransmissions architectures at different power levels.

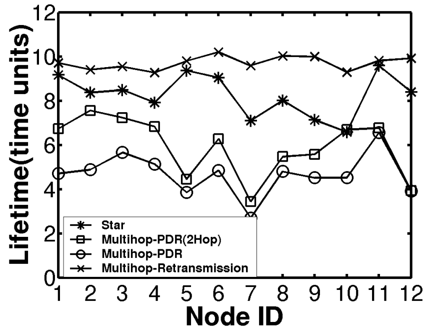


Fig. 11. Network lifetime for different network architectures. All environments. Tx power: $-25$ $dBm$

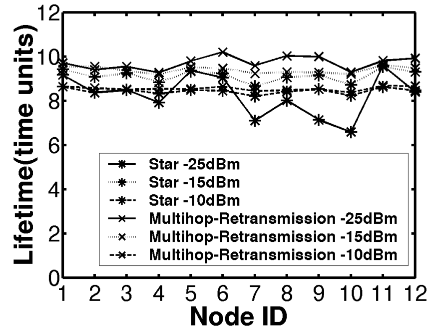


Fig. 12. Network lifetime for different network architectures at different power levels. All environments

lifetime. Note that, these results only hold for the TelosB motes and need to be calculated independently for each device. We also note from our figure, that network lifetime for the multihop-retransmission network is roughly equal over the lowest two power levels, and begins to reduce as power increases beyond that.

**Summary:** From this section, we have identified that the multihop-PDR network has the worst network lifetime performance among the networks we consider. To increase network lifetime, a BSN designer should choose to use a multihop-retransmission network operating at the lowest power level. We now inspect inter-user interference in BSNs.

## VIII. Inter-User Interference

Inter-user interference is defined as the interference of communication in one BSN with the communication of another BSN. Since BSNs can be deployed on mobile humans, who can congregate in a single area, it is important that we consider the impact of many BSNs operating together. Interference, due to many BSNs working in the same vicinity, can degrade the performance of the networks. The performance of certain BSN applications could therefore crucially hinge on how the network is able to cope with inter-user interference.

Network architecture has impacts on inter-user interference in two ways. Firstly, increasing the power, at which the network operates, could have significant impact on the amount of interference, that other networks have to deal with. Secondly, if every packet is transmitted over multiple hops, or has to transmitted multiple times before it is received, the channel is utilized more, and there is more chance that interference will occur.

We inspect the impact of increasing power through simulation. Using TOSSIM, we set up a simulation environment, where we have the 12 node network from our experiment with the data from the experiments. An interfering node, that broadcasts a packet over a certain interval is then introduced. The power and the rate at which the packets are transmitted are modified.

### A. Impact of Inter-user Interference on PDR

We inspect the PDR averaged over all links on the y-axis, and the interval between the interference packets on the x-axis. The different curves show the power at which the interfering

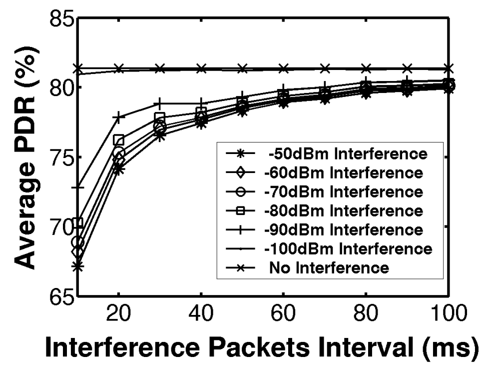


Fig. 13. Impact of various RSSI on PDR in the network

nodes transmit. From Fig. 13, we can see that increasing the power, or the rate of the interference, clearly reduces the average PDR. Note that, the rate seems more important, as even at higher power levels at a low rate of interference, there is not much impact. The high RSSI values ($-50$ $dBm$) were observed in cases where we transmitted information at $-10$ $dBm$ in our experiments. This shows the problem with using a star network architecture operating at higher power levels.

As mentioned in Sec. VI, the greater the average number of retransmissions, the greater the possibility of interference. This is due to the fact that each packet has to be sent on average more times before it is received, therefore utilizing the channel for longer period. For a given power level, the multihop-retransmission network minimizes the average number of retransmissions, and will utilize the channel the least amount of time. In the lab environment, the star architecture does not significantly increase the channel utilization, with average number of retransmissions averaged over all node pairs of $1.38$, compared to $1.11$ achieved by the multihop-retransmission network. But in the roof case, as seen in from Fig. 8, a multihop-retransmission network has significant improvement. Averaged over all node pairs in the roof environment at $-25$ $dBm$, the multihop-retransmission network has $1.41$ average number of retransmissions, as compared to the star network with average number of retransmissions of $5.05$. This implies that for each packet, the star network will have $3.5$ times more channel utilization, when compared to the optimal choice. Therefore, from an inter-user interference point of view, the multihop-retransmission network is preferable.

If a star architecture is still used, one option can be to increase the power level. And at $-10$ $dBm$, the star network can achieve average number of retransmissions of 1.11, averaged over all node pairs in the roof environment. As mentioned in this section, an increase in power level impacts the transmissions of the other networks adversely. Further, using the highest power level, as seen from Fig. 10, is not the best decision from an energy consumption point of view.

Note also that the multihop-PDR architecture significantly increases the average number of retransmissions compared to the multihop-retransmission network, therefore increasing the chance for inter-user interference. This is especially the case in the lab environment, where the multihop-PDR architecture has average number of retransmissions over all nodes of 2.60 at $-25$ $dBm$. In the roof environment, the performance of multihop-PDR is better than star (2.73 average number of retransmissions averaged over all node pairs), but utilizing the channel almost twice as much as the multihop-retransmission network.

**Summary:** We can conclude that, in a close room environment, the star architecture utilizes the channel almost as little as the multihop-retransmission network, but in open environments at lower power levels, it significantly deviates from the optimal achievable. This can be rectified by increasing the power, which however has the adverse effects of increased energy consumption, and higher impact on communications of other networks.

## IX. CONCLUSION

In this paper, we have looked at the impact of network architectures using a quantitative approach. In particular, we inspected two network architectures, the star and multihop architectures. Further, we looked at two configurations of multihop architecture, the multihop-PDR network (maximizes end to end reliability) and the multihop-retransmissions network (minimizes end-to-end average number of retransmissions). Our approach is to use data, that we have gathered from experiments conducted on actual human volunteers in various environments, to observe the impact of various network architectures.

We found that the multihop-PDR network produces very high end-to-end PDR, but it increases the energy consumed and the delay incurred for transmission. Further, the networks with 4 and 5 hops significantly increase overheads. The star architecture, while sufficient from the PDR, average number of retransmissions and network lifetime perspective in closed room environments, has bad performance in open space environments. This highlights the inflexibility in the star architecture, that could degrade network performance. The multihop-retransmissions network has several advantages. It uses the least amount of energy per packet, increases the network lifetime, and reduces delay the most. Even from a PDR perspective, it improves PDR over the star network architecture in the roof environment. Finally, since there are not many hops, the complexity and overheads are kept low.

In this paper, we have highlighted several important performance characteristics of different network architectures. A designer can use our analysis, in conjunction with the demands of her application, to decide on which architecture is to be used. In future work, one of our main goals is to analyze more data sets from experiments in different environments. In addition, we aim to understand how the links are to be chosen during the operation of the network.

## ACKNOWLEDGMENTS

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