Investigating Network Architectures for Body Sensor Networks

Anirudh Natarajan, Mehul Motani, Buddhika de Silva, Kok-Kiong Yap* & K. C. Chua
Department of Electrical & Computer Engineering, National University of Singapore
{elenatar,motani,eledsb}@nus.edu.sg, yapkke@stanford.edu, eleckc@nus.edu.sg

ABSTRACT

The choice of network architecture for body sensor networks is an important one because it significantly affects overall system design and performance. Current approaches use propagation models or specific medium access control protocols to study architectural choices. The issue with the first approach is that the models do not capture the effects of interference and fading. Further, the question of architecture can be raised without imposing a specific MAC protocol. In this paper, we first evaluate the star and multihop network topologies against design goals, such as power and delay efficiency. We then design experiments to investigate the behavior of electromagnetic propagation at 2.4 GHz through and around the human body. Along the way, we develop a novel visualization tool to aid in summarizing information across all pairs of nodes, thus providing a way to discern patterns in large data sets visually. Our results suggest that while a star architecture with nodes operating at low power levels might suffice in a cluttered indoor environment, nodes in an outdoor setting will have to operate at higher power levels or change to a multihop architecture to support acceptable packet delivery ratios. Through simple analysis, the potential increase in packet delivery ratio by switching to a multihop architecture is evaluated.

Categories and Subject Descriptors: C.2.0 [General]: Wireless Networks

General Terms: Experimentation, Human Factors, Performance, Measurement

Keywords: Body Sensor Networks, Network Architecture.

1. INTRODUCTION

Recent years have been marked by the rise of an important application, namely body sensor networks (BSN), for remote health monitoring and patient care. In a BSN, biomedical sensors monitor the physiological signals of the patient, such as electro-cardiogram (ECG), blood oxygen levels, blood pressure, etc. These signals are relayed to an access point, such as a PDA, which can process the data and make decisions, e.g., notifying healthcare professionals. As BSNs are a subset of Wireless Sensor Networks (WSN) with potentially high-rate, mission critical requirements [2] they must operate autonomously for extended periods of time without recharging or battery replacement and must meet stringent delay requirements.

A key factor that will determine the success or failure of BSNs is its ability to cope with the challenges of radio wave transmission around the human body. Humans are highly mobile giving rise to a dynamic, time-varying environment. Further, as shown in [13], the human body heavily attenuates radio wave transmission.

In this paper, we focus on the choice of network architecture, which plays a significant role in dealing with these issues. Network architecture is the logical organization of communication devices in the system. Common network architectures include star, mesh, ring and bus topologies. The selection of an architecture is influenced by the characteristics of the system under consideration, and can affect the performance of the system in many ways such as power consumption, ability to handle different traffic loads, robustness against node failure and choices of MAC protocol.

Current approaches concentrate on using propagation models or specific medium access control (MAC) protocols to study architectural choices. The issue with the first approach is that the models may not be completely accurate, in that they do not capture the effects of interference and fading. Further, the question of architecture can be raised without imposing a specific MAC protocol. In this paper, we approach the question from the perspective of a system engineer, i.e., by investigating network layer metrics such as Packet Delivery Ratio (PDR) and latency.

We contend that this will bring us a step closer to defining the correct network architecture for BSNs. Specifically, our contributions in this paper are:

- Identifying the design goals and evaluating the star and multihop network topologies against them.
- Designing and conducting two experiments to investigate the nature of transmission through and around the body in a high interference environment.
- Developing a novel visualization tool which provides a way to discern patterns in large data sets visually.
- Analyzing channel symmetry and PDR to provide insight about the channel.

*K.K. Yap is currently with Electrical Engineering, Stanford University. Most of this work was done while he was with the National University of Singapore.

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- By performing a simple optimization on the results obtained, we drive our understanding on which architecture is best for a BSN. We discovered that in rich scattering environments with significant multipath, star architecure will suffice. However, large gains can be reaped by switching to a multihop architecture in environments with low multipath.

2. RELATED WORK

There are many projects currently trying to implement BSNs, [16, 17, 15, 6, 1, 11]. CodeBlue [16] at Harvard University has developed devices that collect and transfer the heart rate, the oxygen saturation levels and EKG data to a device such as a laptop or PDA. HealthGear's BSN [11] uses an oximetry sensor to detect cases of sleep apnea. Ubimon [17] developed their own BSN node and are aiming to provide mobile monitoring using wearable and implantable sensors. Alarmnet [15] being developed at University of Virginia is also targeting remote healthcare monitoring.

Considerable work has also been done in investigating the nature of electromagnetic radiation at 2.4 GHz. Studies have obtained the dielectric constants of various tissue in the human body [4]. The energy absorption mechanism of biological bodies near antennas for frequencies above 300 MHz was studied in [8]. In [13] and [5], propagation models for RF communication in and around the human body are developed. Both groups simulate the models and find that their results match well with their respective experimental measurements. In [7], the radiation patterns and how it varies for differing body size and body posture is investigated through simulation.

First, these studies conduct experiments that approximate the human body through simulation. There is not a lot of data for experiments conducted on human volunteers. Secondly, for the purpose of deciding on networking issues such as architecture choice, one is not interested in modeling the channel at the physical layer, but rather in characterizing metrics such as PDR. The purpose of existing studies appears to be targeted at a physical layer understanding of electromagnetic radiation around the human body.

In terms of investigating the architecture, the literature concentrates on the system architecture. [10] and [12] are good examples. In [12], other than mentioning that sensors on the body have short range communication and the PDA has the capability for long range communication, the topic of how these sensors communicate between each other or to the PDA is not broached further.

To the best knowledge of the authors, there are very few studies investigating network architecture for BSN. [9] takes a look at network architecture and decide that from an energy consumption point of view, a multihop architecture is beneficial. Further, they claim that in some cases it is the only option available. [14] examines cluster based and tree-based network topologies from an energy consumption perspective by using certain MAC protocols. They found that the cluster-based topology works better. [3] develops the Wireless Autonomous Spanning Tree Protocol (WASP) protocol for multihop wireless body area networks which they analyze for throughput and delay performance. Note that in this paper we do not impose a MAC protocol, and would like to investigate which architecture is best suited to BSN, independent of the MAC protocol.

3. DESIGN GOALS AND CHOICES

An appropriate BSN architecture should be able to support a variety of sensors, which may be placed inside or on the body. The sensors will periodically monitor the user and relay the data to the PDA which processes the data and takes the necessary actions. Note that the system will need to have bidirectional communication between the sensors and the PDA which will allow the sensors to relay information to the PDA for analysis, and the PDA to actuate the sensors, should there be a need.

3.1 Design Goals

Network architecture and MAC protocols are tightly intertwined. In this context, the design considerations for a BSN should include:

1. Energy Consumption: In a mission critical application like BSN, it is vital that the nodes do not run out of energy. Therefore, the architecture must not require the nodes to expend excessive energy. Furthermore, in an ideal situation the energy consumption should be distributed over the entire network, rather than having a few nodes taking the brunt of the load.

2. Transmission Delay: Independent of traffic conditions, certain architectures will result in a larger delay. This is due to the number of hops the data has to go through before it reaches the sink.

3. Inter-User Interference: When users gather in a single place, the transmissions of the nodes of different users could interfere with each other. Since certain architectures will predispose some of the nodes to transmit with high power, they will increase such inter-user interference. Moreover, other extraneous interference sources can exist in the same band, such as WiFi and bluetooth. This phenomenon has been largely neglected in current literature.

4. Node Failure and Mobility: Node failure could happen for a number of reasons such as battery exhaustion. The sensors may also temporarily lose connectivity due to mobility of the users on which they are placed on.

We now consider two network topologies, namely star and multihop and evaluate them against our criteria. We have deliberately excluded the ring network topology from consideration, because it is inefficient in its energy consumption and causes excessive end-to-end delay.

3.2 Architecture Description and Comparison

A *star network* is one in which all nodes are directly connected to the sink. In the BSN case, the PDA is the sink to which all sensors talk. The PDA takes the necessary action based on the data it collects.

A *multi-hop network* is one where the nodes are connected to the access point possibly through other nodes. Note that, a multi-hop network is very general and also includes cluster-based network topology.

We present a qualitative comparison of the different architectures in Tab. 1, deferring the quantitative evaluation to section 6. Of particular importance is the fact that nodes will generally transmit at lower power when using a multihop

Table 1: **Comparison of Different Architectures**

	Star Network	Multi-Hop Network
Energy Consumption	For nodes in close proximity to the PDA, the power used by them to transmit to the PDA will be low. The nodes further away, however, will consistently require more power to be able to transmit their information.	The nodes that are nearer to the PDA will have to spend more energy as they will have to forward not only their own information but also information from other nodes.
Transmission Delay	The star network presents the least possible delay present in transmission from any sensor to the PDA, as there is only a single direct link between them.	Dependent on how the network is configured. In terms of delay, the nodes closest to the PDA can get their information through quickly, without any intermediate relay.
Inter-User Interference	Sensors that are farther away from the PDA will have to transmit with higher power, increasing the amount of interference.	Since each node is only transmitting to its neighbor nodes, the energy of transmission is kept low and hence mitigates the effects of interference.
Node Failure and Mobility	Only the failed node will be affected and the rest of the network can perform as needed.	The part of the network that involves the failed node has to be reconfigured. Overheads are involved

network, rather than a star network. In terms of transmission delay, the star network performs well as there is only a single hop between all the nodes and the sink.

We now turn our attention to understanding the constraints of the system. The human body is known to be complex in its behavior with relation to the propagation of electromagnetic radiation. With different tissue possessing varying properties, it is non-trivial to model the human body. Furthermore, based on the current literature, one can not glean performance metrics that are of interest to the network engineer. In light of this, we decided to perform our own experiments, which are discussed in Secs. 4 and 5.

4. TRANSMITTING THROUGH THE BODY

Our first goal was to understand how impervious the human body is to transmissions in the 2.4 GHz band. While we can infer results from [5, 13, 7], our aim was to derive conclusions from empirical measurements in a real-world setting using actual sensor devices. All experiments were conducted with Crossbow TelosB motes, which uses the popular 802.15.4 compatible transceiver Chipcon CC2420, also used in the Imperial College BSN motes.

4.1 Methodology

We compared the human body to two other media, namely air and aluminum (which shields all radiation). We first realized that there are two ways in which transmissions can be propagated from one node to another, i.e., the line-of-sight (LOS) and reflected multipath. We note that the multipath phenomenon is heavily influenced by the environment. To ensure consistency, all our experiments were performed in the same rich scattering environment.

The setup of the experiment is as shown in Fig. 1. We programmed a mote as the transmitter and the other as a receiver. The transmitter would transmit 1000 packets at 10 ms intervals, at -25 dBm (lowest possible) and 0 dBm (highest possible) respectively.

The experiment is carried out by changing the materials of the LOS "obstacle" and enclosing boxes to investigate the propagation of EM waves. The enclosing boxes and LOS obstacle would impede the multipath and LOS components respectively. The materials used for the enclosing box were aluminum and perforated cardboard. Perforated cardboard is known to be a good medium, allowing all the radiation through with negligible attenuation. For the LOS obstacle, we had aluminum, air and the human body. With the aid of 3 volunteers, the experiment was repeated for all combinations of materials possible to ensure unbiased results.

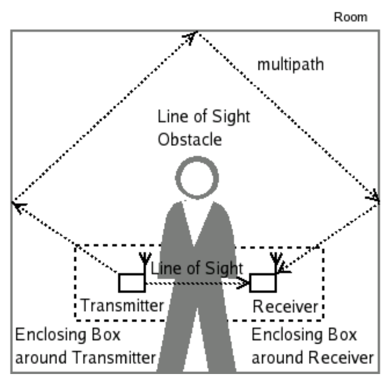

Figure 1: Setup of experiment investigating RF transmission through the human body

Table 2: Packet delivery ratio (PDR) for transmission through human body – The figures are for the highest/lowest power level.

		Material of Enclosing Box	
		Cardboard	Aluminum
Material of LOS Obstacle	Air	98.5 / 84.2	99.3 / 93.7
	Human Body	97.6 / 74.1	0 / 0
	Aluminum	96.2 / 88.8	0 / 0

4.2 Results

The results for the highest and lowest power levels are shown in Tab. 2. We observe that the human body behaves very similarly to aluminum, with regards to allowing radio transmission through. Note that when propagation is allowed via multipath, around the human body and aluminum sheet, a high percentage of packets get through (minimum of 74.08%). When the multipath was obstructed by aluminum, no packets got through even at the highest power level.

This result re-affirms the conventional wisdom that *in vivo* sensors should not be transmitting at 2.4 GHz. We wish to remark that multipath propagation is heavily dependent on the surroundings and one cannot guarantee the PDR to be similar to the values obtained here.

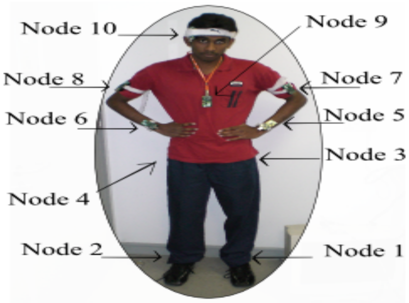

Figure 2: Node ID & Position on Body

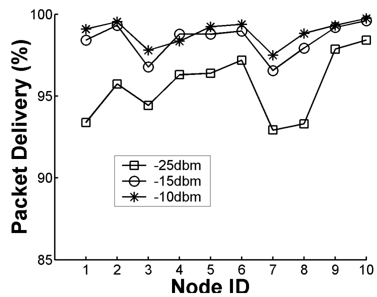

Figure 3: Packet delivery ratio (PDR) for received packets at every node

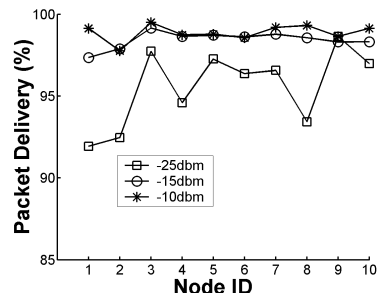

Figure 4: Packet delivery ratio for transmitted packets at every node

5. TRANSMITTING AROUND THE BODY

The previous experiment indicates that radio reception is heavily dependent on the existence of multipath components. In addition, it is clear that reception is also correlated with the position and orientation of the nodes on the human body. Therefore, we set out to understand how well nodes placed at different parts of the body would communicate with one another.

5.1 Methodology

To emulate the use of actual sensors, we placed motes in a variety of positions on volunteers, as shown in Fig. 2.

A computer controls and coordinates the actions of the motes on a volunteer, via an attached gateway mote. Once the volunteer has strapped on the sensors, the computer would synchronize these nodes and issue a command to start the experiment. Node 1 would then cycle through the three lowest power levels and broadcast 41 packets at each power level. Each packet contains the source node's id, current power level and a sequence number. All the other nodes record these items for packets received, in their memory. After 32 seconds, node 2 would repeat the actions of node 1 and all nodes do so in turn. The entire process is iterated 5 times before the experiment is concluded. The motes are then taken off the volunteer and the data is uploaded into a SQL database for analysis.

5.2 Results

5.2.1 Preliminary results

We look at Fig. 3 which captures the number of packets each node received from the other nodes over the course of the entire experiment, expressing it as a percentage of the total number of packets transmitted by the other nodes. The values are for the three lowest transmission power levels provided by the TelosB motes.

We observe that increase in power invariably improves the PDR, with a consistently lower value for node 1, 3 and 7. However, we note that the PDR is 93% even for the lowest power level. This signifies that even though the human body obstructs radio waves, the reception through multipath is sufficiently strong. This is a strong argument for the star architecture. Further, node 10 seems to have the highest received PDR, which makes it the best placement for the PDA from a networking point of view.

Table 3: Distribution of PDRs for Different Body Postures at the lowest power level

Packet Delivery Ratio (PDR)	Percentage of links (sitting)	Percentage of links(standing)
95%-100%	68.8%	80%
90%-95%	20%	10%
85%-90%	7.8%	8.8%
Below 85%	3.4%	1.2%

Fig. 4 shows the proportion of packets transmitted by each node that were received by other nodes. Once again, we observe that the lowest percentage of packets transmitted successfully is about 92%, even at the lowest power level. This again lends support to the adoption of star network topology for BSN.

For a star network to work, the gateway node has to be able to establish reliable communications with *every* other node. We therefore needed to take a closer look at the individual node pairs, as opposed to the average PDRs.

Tab. 3 shows the distribution of the PDRs for the lowest power level. We note that even at the lowest power level, most of the node pairs have good connections with PDRs of 90% or greater. To test out the effect of different postures on the quality of the link between the various nodes, we also asked the volunteer to move around and engage in mild activity during the experiment. The results show that in this case the communication actually improves implying that the star network architecture might work well regardless of the posture of the user.

To understand the channel better, we developed a visualization tool that allowed us to discern patterns.

5.2.2 Visualization Tool

For N nodes, the visualization is an N by N matrix, where the color of the ij^{th} square ($i \neq j$) corresponds to the PDR for packets broadcasted from node i and received by node j. The PDR between a node and itself is assumed to be 100%. Fig. 5 shows the visualization for the experiment with the volunteer sitting in a closed room. The graded color strip to the right of the matrix depicts the mapping between colors and PDRs. The visualization enables us to discern information about channel symmetry and highlights unreliable node pairs.

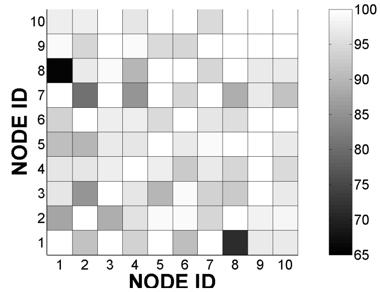

Figure 5: Visualization for packet delivery ratio between specific nodes at power level -25 dBm with volunteer sitting in a room

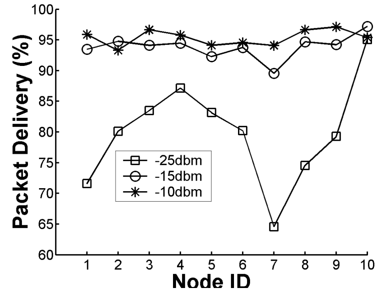

Figure 6: Packet delivery ratio for received packets at every node with volunteer on a roof top

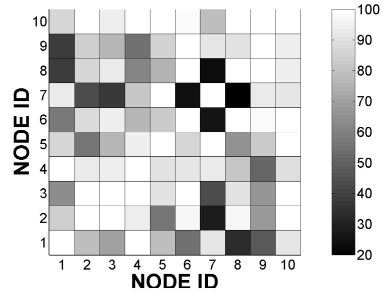

Figure 7: Visualization for packet delivery ratio between specific nodes at power level -25 dBm with volunteer on a roof top

First, we notice from Fig. 5 that there is no obvious correlation between PDR and the distance between the nodes on the body. For example, one would expect that nodes 1 and 2, which are placed at the ankles, would have the poor PDR with node 10, which is placed at the head. However, they both have high PDRs (above 96%) with node 10.

We also note that there seems to be a checkerboard pattern in Fig. 5. This implies that even (odd) numbered nodes can communicate more reliably with even (odd) nodes than with odd (even) nodes. Consider the row for node 1. Nodes 3,5 and 7 which are all on the same side of the body as node 1 (the left side) have high PDR. This prompted us to look at the PDRs between nodes on the same side of the body and on opposite sides of the body. The 12 node pairs on the left side of the body (between nodes 1,3,5,7) had an average PDR of 97.1% and the node pairs on the right (between nodes 2,4,6,8) had an average of 96.5%. The average PDR between opposite node pairs, where one node was on the left side and one on the right, fell to 89%. This is explained best by the fact that the body blocks the line of sight for nodes on opposite sides of the body. These observations tell us that node position (right or left side of the body) is important and should be taken into account.

We note that the curves for transmission, Fig. 4, are not the same as the ones for receiving, Fig. 3, both in terms of their values and in their trends. For example, while we saw a dip at power level 3 for the received PDR, we see a spike for node 3 in the transmitted PDR. While this indicates that the channel is not strictly symmetric, it is not severely asymmetric. We use the difference between the ij^{th} and the ji^{th} entry as a measure of the difference in the channel for the two nodes. The average absolute value (over all node pairs) of the differences, is 3.5%. When compared with the PDRs seen for the nodes (above 90%), this is relatively small.

5.2.3 Importance of Multipath

To verify that multipath played a key role in achieving reliable reception, we repeated our experiments on an open roof top, with far fewer reflective surfaces. The received PDR for this experiment shown in Fig. 6 presents an intriguing picture. Firstly, as expected the reduction of multipath causes a significant drop in received packets at -25 dBm. Further, in a closed room, the benefit of increasing the power level from lowest to the one above is around 5% (from Fig. 3). However, in the roof top environment, the results in Fig. 6 indicate a 15% average benefit by operating at the second lowest power level. Note that the inter-user interference would also increase by increasing the power level.

Fig. 7 (which has a different color to PDR mapping from Fig. 5) depicts the visualization for the roof top environment. Interestingly, while it exhibits a large number of dark spots(40% of the node pairs have packet delivery ratio less than 85%), every row and column has at least two white blocks, indicating that every node has one good neighbor. This observation would mean that one can use a multi-hop architecture to efficiently reach the access point. The next section verifies this claim.

6. BENEFITS OF MULTIHOP

We qualitatively argued in Sec. 3 that multihop architecture has lower transmission power and higher delay when compared to star. We now build a quantitative argument using experimental measurements, demonstrating the gains that can be achieved in PDR by using multihop architecture.

The question we will answer is as follows. Given two arbitrary nodes i and j, where $i \neq j$ and i is transmitting to j, what is the most reliable manner to do so in terms of PDR? Specifically, we construct the most reliable route from i to j. Note that if it is best to transmit directly, a route of a single hop will be given. To do so, we denote the PDR of the single hop link l as p_l. The PDR of a route r from i to j is then given by $PDR^r_{ij} = \prod_{l \in r} p_l$. We then maximize the PDR across all routes r from i to j, i.e., $PDR_{ij} = \max_r PDR^r_{ij}$. This optimal route also gives the least number of expected retransmissions required to transmit from i to j.

Fig. 8 shows the improvement when using the optimal routes. The x-axis denotes node id of the sink and the y-axis is the PDR of the optimal routes to the sink averaged over the remaining nodes, i.e., $E_{i \neq j}\left[PDR_{ij}\right]$. In the roof top case, even with a transmission power of -25 dBm, the received PDR at all nodes was now above 96%! Further, using the optimal routes and averaging over all the node pair combinations we achieved an 18.1% increase in PDR over the direct links. This clearly shows a significant performance improvement. While of a smaller magnitude, an improvement was noted in the room environment too.

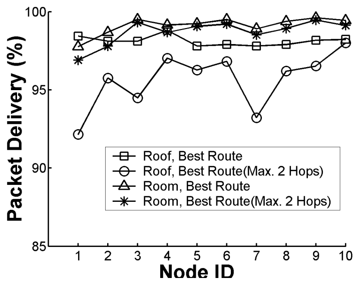

Figure 8: Received packet delivery ratio using optimal routes. Power is -25dBm for all curves

As noted earlier, multihop architecture has overheads involved in network operation. The optimal routes obtained in some cases (for roof and room environments) could be several hops long, leading to a potential increase in complexity. To keep the overheads low, we computed the optimal routes constrained to a maximum of 2 hops. Despite this constraint we notice in Fig. 8 that we can achieve received PDRs of greater than 92% for both the environments. This certainly is a strong argument for the use of a multihop architecture.

7. ARCHITECTURAL IMPLICATIONS

In this paper, our first step was to identify the primary design goals that the architecture could influence, namely power and delay efficiency. Reviewing the star and multihop network topologies, we concluded that while star is best for delay efficiency, nodes that are far away from the sink could run out of energy quickly.

When we ran experiments in the closed room environment, where multipath was a significant factor, even at the lowest power levels most nodes could communicate with each other in excess of 80% PDR. This certainly lends credence to our belief that a star architecture would be sufficient for the purpose of a BSN in a rich scattering environment such as those seen in hospital rooms. In the roof top, the case was significantly different with low PDRs for many links.

In both cases we found in Sec. 6 that by switching to a multihop architecture one stands to gain many benefits. This was especially true in the case of the roof top with the improvements achieved significantly bettering the PDR obtained when using higher power levels. In this paper, we have identified quantifiable potential that exists in using a multihop architecture. However, reaching this potential while balancing against other concerns such as complexity will be dependent on the MAC protocol.

In this paper, we have taken an exploratory foray into picking the best network architecture for a BSN. However, we realize that there is much more work to do. We plan to run the experiment on different people with different body shapes. We also intend to delve into the issue of inter-user interference as this will play an important role in choice of the right architecture.

Acknowledgments

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