Topology Selection Schema for Wireless Body Area Networks

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Abstract

Topology selection is an important part of Wireless Body Area Networks (BAN) development. It effects the operation of the entire network stack. For example a mesh topology requires all the nodes to have routing capability. In this paper we propose and illustrate a novel method of topology selection for BANs that we refer to as a topology selection schema. The schema identifies and compares a broad range of parameters that should be considered in topology selection such as the use case scenario, environmental conditions, device capacity, and traffic related parameters. The schema allows cross-matching of BANs to these parameters to assess the suitability of a wide range of topologies. The topology selection schema resulting from this work is intended to serve as a guideline for network planners, manufacturers, standardization bodies, and researchers in WBANs

Keywords: wireless sensor networks, body area networks, topology, network planning

1. Introduction

Developments in wireless sensor technology and device hardware have resulted in a wide range of new applications for Wireless Sensor Networks (WSN's) and Body Area Networks (BAN's). Examples include stationary and/or mobile sensors, such as environmental monitoring, surveillance and healthcare [1]. A new standard, the IEEE 802.15.6 [2], is currently being developed for the BAN. BAN's enable patient mobility in hospital and also increased functionality in home monitoring, which can lead to earlier discharge from hospital and the possibility of new alerting applications, such as can be seen in CodeBlue [3], MobiHealth [4].

The possible drawbacks, to the use of the wireless networks in these applications, must however be addressed. Radio links are time-variable, unstable and prone to errors. Furthermore, wireless BANs are not physically isolated from each other but share the same medium with other BANs, networks and devices. Such limitations make it necessary to employ the latest technologies to minimise those effects. However the use of those technologies is often restricted by the low specification of the BAN devices such as CPU, power, battery, memory and bandwidth that are a few orders of magnitude lower than corresponding ones for other systems such as WiFi or GSM. For example, a typical TCP/IP stack for an 8-bit node mustn't be bigger than a few kilobytes as otherwise it wouldn't fit into the ROM of a micro-controller. Therefore the proposed solutions must be tailored to effectively countermeasure the channel effects and satisfy the hardware constraints. A number of those drawbacks due to the limitations of the nodes can be overcome by a reduced Operating Systems (OS) such as Tiny OS [5] or Contiki [6] or a reduced TCP/IP stack.

A network topology refers to the logical connectivity of the nodes in the network. Selection of a network topology is often done explicitly for a given network, eg. a cluster topology for Zigbee. A good topology should facilitate development of a network stack (eg. protocols, techniques) that should be able to meet the QoS imposed by the users and their applications. For example, the 802.15.6 draft [2] proposes the use of two topologies: star and restricted tree. Use of the restricted tree topology is optional and it is important to determine when it is necessary to use this topology. The schema proposed here aims to facilitate this process by identifying and classifying a set of key parameters for use cases, radio performance, device nature and network traffic. The values of these parameters are then used for topology selection.

The remainder of the paper is structured as follows: Section II analyses the available topologies to be used in BAN's, section III discuss the network parameters that should be considered in topology selection and section IV describes the schema. Use of the schema is illustrated in section V and section VI presents future work and conclusions.

2. Network topologies

In this section we present the topologies available to be deployed for BANs [7]. We outline their features and their suitability for BAN applications. We consider five most commonly met topologies in the BANs: point-to-point, star, mesh, tree (cluster-based), tree-mesh hybrid (Fig. 1). The simplest topology is point-to-point. This topology is intended for a single link, for example, between a data collector and a sensor sending readings, such as a chest mounted sensor reporting to a hub device at the waist. The main advantage of this topology is simplicity often allowing the use of a simple or proprietary protocol rather than a full network stack, low-latency and high throughput due to lack of arbitration. The disadvantages include limited functionality, poor scalability and coverage.

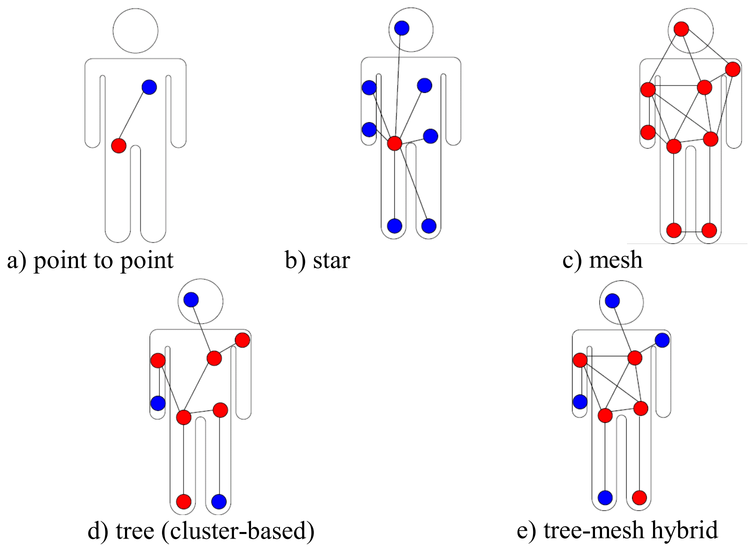

Figure 1. Topology classification

A topology in which all the nodes are connected through the central hub is a star topology. To date it has been the most common proposed and deployed topology for BANs. It is relatively simple with a potential to realize low latency and high bandwidth. Its disadvantages include single point of failure (the controller/hub failure causes outage of the entire network), limited scalability, and indirect communication between the leaf nodes. A topology with a full connectivity between the nodes is a mesh topology. Its benefits include being fault tolerant (self-healing) and self-organizing. The network with the mesh topology is highly scalable with optimal coverage. However running a routing protocol results in increased computation load, power consumption and overheard due to building and maintaining the routes [1]. The use of a mesh topology is a primary consideration in all the scenarios in which reliability and flexible communication is prioritized over energy efficiency and network longevity.

A tree topology has a top "root" node with a branch/leaf structure below. The connections between the nodes are hierarchically structured, meaning each node may be a child to an upper level node and a parent to a lower level node. A child can only communicate directly with its parent. Tree and tree-mesh hybrid topologies present an alternative to the mesh topology in cases where not all devices have full-functionality or simply do not have routing capability. The tree and tree-mesh topologies exhibit good coverage, fault tolerance, low latency and the potential to realize high bandwidth. However the parents may consume a lot of energy [7].

3. Discussion of the parameters to determine topology selection

We use the following parameter groupings to facilitate determination of a topology/ies for a given network.

3.1. Application scenario

We classify the scenario to stand alone BANs, global healthcare and pervasive network. The stand alone BANs comprise small devices in the close vicinity of the body that provide sensing and processing capabilities. In the simplest scenario the central node gathers and records readings such as ECG, EMG, blood flow, blood pressure over time for the subsequent offline interpretation in the clinics. The examples may include: monitoring elderly people at homes, cable free monitoring of vital signals in emergency case units, monitoring chronically ill patients in their daily situations [8].

Global healthcare connectivity can be thought of as a health care platform constituting sensors and a base station to provide a link to one or more medical centers. The main difference to the stand alone BANs is that the majority of the processing is shifted towards the medical center and is not done locally. The connections between the patient and the center may be bidirectional meaning the system can send an alarm or a reminder signal to a patient using for instance SMS services.

The most advanced scenario assumes pervasive networks combining ambient nodes integrated into a patient's environment and body nodes (wearable, implantable or swallawable) communicating with those ambient nodes. The concept assumes minimal interruption to the patient's life. The "invisible" ambient sensors are seamlessly deployed in the patient's environment, e.g. beds, chairs and are used by the wearable ones to provide the bridge connectivity to the healthcare centre or for the purposes of tracking location.

3.2. Radio propagation characteristics

A wireless link has numerous characteristics, relevant to topology selection, which can be summarized as follows:

- Small Scale Fading: In WBANs, the signal propagates from the transmitter to the receiver via different paths, each of which can involve reflection, diffraction, waveguiding and so on [9]. The different paths give rise to multiple attenuated, delayed, and phase-shifted echoes of the transmitted signal arriving at the receiver. Such fluctuations occur on a scale that is proportional to one wavelength and therefore are referred as to short-term fading [10].
- Large Scale Fading: Mean power, averaged over approximately ten times of the wavelength demonstrates fluctuations. These fluctuations have considered to happen on a large scale. For example for the transmitted signal carried on 2.4 GHz large-scale fading occurs at 12.5 cm. Hence this effect may be experienced for a person walking and having his/her sensor attached to the wrist. Large-scale fading often obeys lognormal distribution that is called shadowing [9].
- Pathloss: It's a reduction in power of an electromagnetic wave as it propagates through. Usually it is a reciprocal of the distance with power to 2-5 depending on the environment [10].
- Interference is another source of potential signal disruption. Generally it can be present in two forms: in- or out-system. In-system interference can be further divided into co- and adjacent channel interference [9], [10].

The schema groups these characteristics into the metric of a channel state, which can be classified *bad, medium* or *good.* For example a link where Line-Of-Sight (LOS) is possible, fading and interference are negligible, can be classified with a channel state of good.

3.3. Device parameters

The properties of the device such as location of the devices, power source, expected lifetime, and transmit power have a significant impact on topology consideration.

The devices may be placed in-body (implantable, swallowable devices), on-body or off-body [11]. It is important to note that their location and environment imparts various requirements on them. For example, implantable devices must be small and ideally have a lifetime of years. Devices mounted on the body may be bigger and what is most important are battery powered and can be easily recharged or replaced when depleted. Off body devices can be mains powered, battery powered or scavengers. If the devices are battery powered and it is not feasible to change the batteries (for example implantable), then their lifetime is determined by the longevity of the batteries. In this case it is key that the communication protocol is energy efficient. The expected lifetime can be expressed in days, months or even years. For example a soluble thermometer for measuring a temperature of a diver for the time he/she is in the water needs only to operate for maximum of a few hours.

Another important parameter associated with the devices is transmit power. Transmit power determines the communication range of devices. The higher the power the higher probability the communication is established and maintained. However higher transmit power shortens device lifetime and must remain compliant with the SAR (Specific Absorption Ratio) regulations. As such, on and especially in body devices' transmit power must be tailored for the application.

The topology selection schema classifies these device parameters, according to the device's processing and power capabilities. It uses the values *heavy-duty* (performs functions for other devices, e.g. routers, hubs), *medium-duty* (performs limited processing on behalf of other devices) and *low-duty* (performs for itself only).

It is worth to note here that the Zigbee standard follows similar device categorization namely full-function device (FFD) and reduced-function device (RFD). The first ones can serve as the coordinator of a personal area network, whereas the second type is meant to be extremely rudimentary that can only communicate with coordinators.

3.4. Traffic/network parameters

We consider that relevant traffic and network parameters in the context of topology selection are: the flow of the traffic, the pattern of the traffic, quality of transmission and the ability to accept new members of the network (association). An important traffic parameter in a BAN is the direction of flow in which data is generated by the devices. It may either originate in the nodes (or hubs) and be passed onto the network or it may be bidirectional communication, e.g. the hub receives an alert from a glucose sensor and sends a command to a node that triggers the pumping of insulin or sends a report to the nurse over an access network (eg. WiFi, GSM).

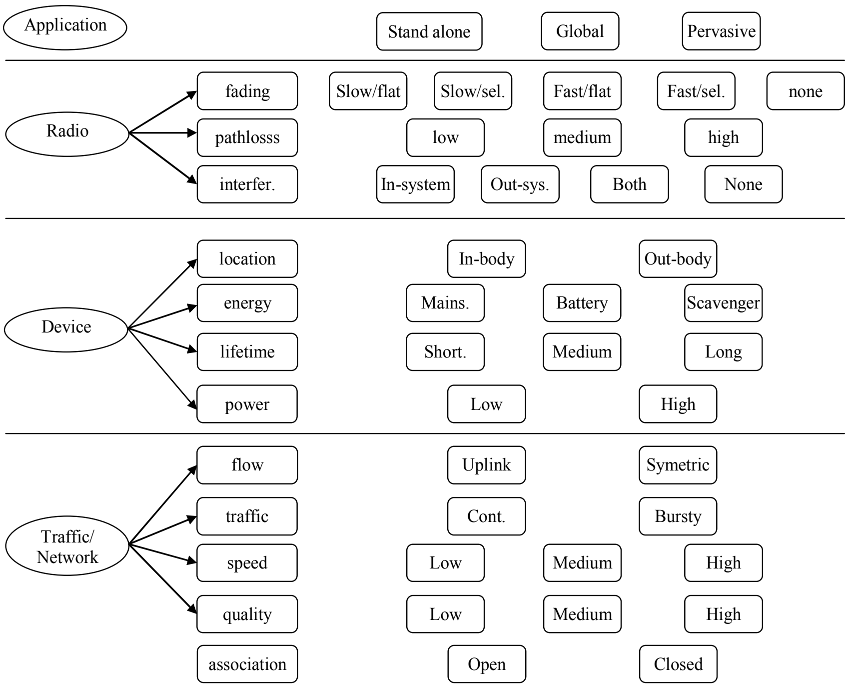

Figure 2. Key WBAN Parameters for Topology Selection

Traffic on the BANs may take various patterns. Many of the BAN devices are event-based (eg. an event occurs, such as an increased blood pressure, and the signals are sent to the controller) and hence they generate data irregularly. Other applications such as ECG/EKG/EMG take the measurements on a regular and/or continuous basis. Traffic generated by video or voice streamers produce data on a continuous basis. Various devices may use different transfer speeds to accommodate the needs of the applications running on top of them. Thus the BAN should support wide transfer speeds ranging from a few bits per second to a few mega bits per second. A network related parameter that is particularly important in a wireless environment is the reliability of the link. A Bit Error Rate (BER) of 10e-5 or better is considered acceptable for most of the BAN applications [9].

Automatic association is the ability of the network to accept new members. The network may be called open if it allows new devices to join the network, or closed in which case the network, once formed, limits the admittance of new members or doesn't accept them at all.

The topology selection schema classifies these parameters as the QoS demands of the applications, *high resource demand*, *medium resource demand* and *low resource demand*.

4. Topology selection schema

The schema is based on reducing the groups of parameters presented in Fig. 2 for use in mapping to the characteristics of particular topologies. Fig. 3 shows the reduction of these parameters into a concise set which can be used more easily to identify the suitability of topologies for a given use scenarios.

Table I shows the mapping of this set of metrics to topologies in order of preference (most preferable are leftmost). The process of deriving the most preferable topologies from a given set of parameters is somehow subjective but nevertheless is accomplished through the following steps:

1) Eliminate topologies that are unlikely to meet the requirement in a parameter group, e.g. there is no need to use a mesh for a low duty devices. The characteristics of the remaining topologies relevant for those parameter groupings are then used to determine the order of preference, e.g. mesh is the most preferable and point to point is the least preferable in a bad radio environment, given their respective fault tolerance.
2) Parameter groups are prioritized with *Application scenario* having the highest and *Traffic parameters* the lowest priority.

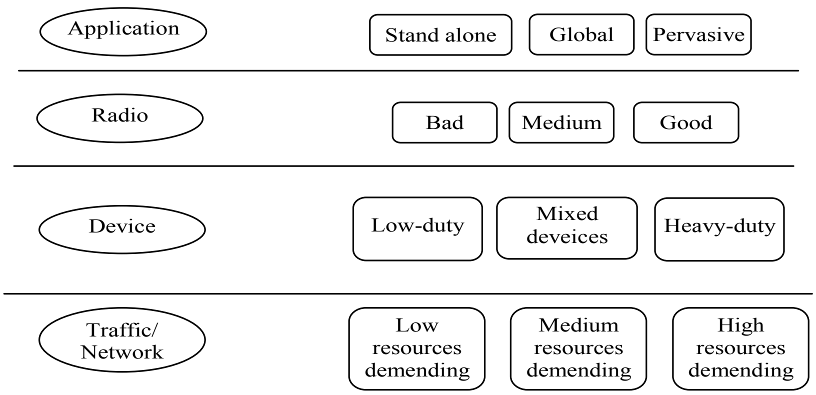

Figure 3. Encapsulation of the fine grained parameters into the states of the .

As an example, consider a scenario where a network is composed of sensors taking emergency body readings in a highly variable wireless environment, and all the devices have extensive processing capabilities with batteries that can be charged regularly. In this case the schema defines the application as *Standalone*, the radio as *Bad*, the device as *Heavy Duty* and the traffic/network as *High Resource Demanding* as per Figure 3. From Table I, we can see that the *Radio, Device and Traffic parameters* suggest *mesh* to be the preferred choice, with the *Application scenario* suggesting *star* with *mesh* included as the least preferable. Even though the *Application scenario* is treated as the highest priority parameter and suggests *star*, the preference of the other three parameters for *mesh* means that the topology to be selected would be *mesh* or *hybrid tree-mesh*.

TABLE I. BEST SUITED TOPOLOGIES FOLLOWING PARAMETER ANALYSIS

Parameters	Values	Preferences on topologies				
Application scenario	Global	Star	Tree	Mesh	Hybrid	
	Pervasive	Hybrid	Mesh	P2P		
	Stand alone	Star	P2P	Tree	Hybrid	Mesh
Radio parameters	Bad	Mesh	Hybrid	Tree	Star	P2P
	Medium	Mesh	Hybrid	Tree	Star	P2P
	Good	Star	P2P	Tree	Hybrid	Mesh
Device parameters	Non-	Star	P2P			
	Mixed	Hybrid	Tree	Star	P2P	
	Heavy duty	Mesh	Hybrid	Tree	Star	P2P
Traffic/ network parameters	Low resource demanding	P2P	Star	Tree	Hybrid	Mesh
	Medium resource demanding	Tree	Hybrid	Mesh	Star	P2P
	High resource demanding	Mesh	Hybrid	Tree	Star	P2P

5. Validation of the topology schema

We have used the proposed topology schema to consider the topology to use in a number of scenarios including a sportsman exercising in the gym (Fig. 4.1), fell-down accident report from on body sensors to off the body network (Fig. 4.2), and audio entertainment BAN comprising a mobile, an mp3 file storage and headset (Fig. 4.3). We will show the analysis of the sportsman scenario to derive the key parameters, and the use of the parameters to select the topology.

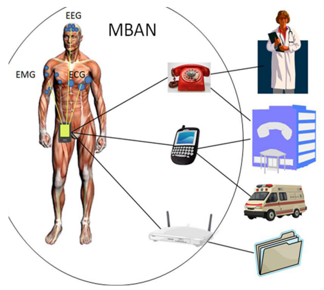

Fig. 4.1. Centralized monitoring of EEG, EMG and ECG

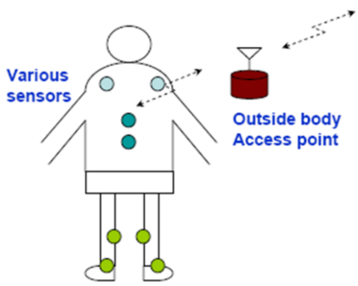

Fig. 4.2. Fall-down accident report BAN employment

Fig. 4.3. Audio entertainment BAN

The sportsman's sensors (EEG, ECG, EMG) report readings to the sports healthcare centre for collection and offline interpretation. A PDA device mounted at the hip of the sportsman bridges the BAN with the healthcare centre, hence this is a *Global Healthcare*

In terms of the Radio Parameters, the sportsman's running and exercising causes vast fluctuations in the received signal strength and assuming the use of DSSS transmission (for instance being used in 802.15.4 network), fading is slow to medium and selective. The pathloss would be low to medium, as the sensors are mounted at the upper part of the body (torso and head) and the hub at the hip. Interference will be both in-system (cross talk of the nodes) and out-system (may arise from WiFi in the gym). This results in a classification of *Bad* for the Radio Parameters.

For the Device Parameters, the location is out of body, the energy supply is a (rechargeable) battery that should last for the short lifetime of the session. The transmit power would be set to the maximum and there is no need for its control. This results in a classification of the Device as *Medium Duty*.

Finally, the Traffic and Network parameters are classified as *Medium*, as the flow direction is uplink, the generation of traffic is continuous with a medium transfer speed. The error rate and reliability would be medium as a BER of 10e-6 should suffice. The Automatic association would be open as new devices can easily join the network.

Applying the Schema as per Table I, results in the choice of *star, hybrid* and *tree* topologies in that order of preference (note that mesh is not suggested for a medium duty device as routing is CPU resource hungry).

Similar analyses for the fall-down accident and entertainment audio system were performed. A fall detection BAN may comprise tilt sensors for monitoring the fall-down accident, foot detectors for counting the steps, breathing sensors for monitoring respiration, movement sensors for monitoring activities. All the sensors report the readings to off the body sensor networks integrated into the patient's environment. An audio system may be made of mp3 file storage, an audio streamer and headphones. A mobile or mp3 player may act as a mp3 audio streamer that reads files wirelessly from a portable mp3 storage and plays them to the headphones. The parameter values and resultant topology choices are shown in Table II.

TABLE II PARAMETER VALUES AND RESULTANT TOPOLOGIES FOR THE OTHER EXAMPLES

Example	Application scenario	Radio parameters	Device parameters	Traffic parameters	Topologies
Sportsman	Global	Bad	Medium duty	Medium	Star, hybrid, tree
Fell-down accident report	Pervasive	Medium	Heavy duty	Low	Mesh tree-mesh hybrid
Audio streaming	Stand-alone	Medium	Heavy duty	High	Tree, mesh

6. Conclusions

The paper presents a topology schema selection that aims to facilitate the selection of the topologies for use in wireless sensor networks with particular application to wireless body area networks. We have demonstrated that topology selection should be carefully chosen as it has a major impact on the communication stack for the wireless sensor network. For example a network operating under a star topology removes the need for routing simplifying the development process of the network layers. If reliability on the BAN is prioritized over low power consumption and longevity then a mesh topology should be in the first place following a star topology.

We have emphasized that in order to provide a comprehensive topology consideration a wide range of parameters should be taken into account such as device limitations, operating environment, use case scenarios and network/traffic related parameters. Even though the presented schema is subjective it has been shown to be of use in a number of BAN scenarios.

Future work will include applying a weighing algorithm in the second step where different topologies are selected in each of the parameter groupings. It is also planned to develop an automation tool to facilitate the analysis.

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