Modeling of Power Consumption and Fault Tolerance for Electronic Textiles

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Abstract

The developments in textile technology now enable the weaving of conductive wires into the fabrics. This allows the introduction of electronic components such as sensors, actuators and computational devices on the fabrics, creating electronic textiles (e-textiles). E-textiles can be either wearable or non-wearable. However, regardless of their form, e-textiles are placed in a tightly constrained design space requiring high computational performance, limited power consumption, and fault tolerance. The purpose of this research is to create simulation models for power consumption and fault behavior of e-textile applications. For the power consumption model, the power profile of the computational elements must be tracked dynamically based upon the power states of the e-textile components. For the fault behavior model, the physical nature of the e-textile and the faults developed can adversely affect the accuracy of results from the e-textile. Open and short circuit faults can disconnect or drain the battery respectively, affecting both battery life and the performance of the e-textile. This thesis describes the development of both of these models and their interfaces. It then presents simulation results of the performance of an acoustic beamforming e-textile in the presence and absence of faults, using those results to explore the battery life and fault tolerance of several battery configurations.

Dedicated to Guidance, Teamwork and Ingenuity
without which all ideas would not bear fruit.

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Chapter 1

1 Introduction

Electronic textiles (e-textiles) are fabrics with sensing and computing elements integrated on them. This is one of the major developments in the field of pervasive computing due to the fact that clothes are an integral part of the human life. Hence any computation performed on these clothes will easily integrate into current lifestyles. However, the answers to many issues regarding their development and deployment are not known. Their behavior in any environment (hostile or otherwise) remains unanswered. Power consumption, fault models, redundancy and performance are just some of the problems that must be studied. The solutions for these can be explored by a combination of hardware prototyping and simulation.

1.1 Motivation

E-textiles are in a transition from a few isolated computing and sensing elements on the fabric to a network of many computing and sensing elements distributed over the entire textile. Traditional distributed computing uses a high dedicated bandwidth, with little consideration for the power necessary to drive it. In comparison to this e-textiles are constricted by the bandwidth available. Furthermore they are either mobile or isolated from a permanent power source, and this puts a greater constraint on their power usage. Hence they are placed at a very tight position in the design space [2]. To understand the energy usage, it has to be measured for e-textile designs already available and estimated for future designs. This necessitates the creation of a power estimation tool that accurately follows the behavior of the computing elements in the real world and can determine the battery life of the e-textile. One contribution of this thesis aims to create a power estimation tool that is integrated into the simulation environment of the Virginia Tech E-Textiles Group.

Another area explored by this thesis is the operation of e-textiles in the presence of faults on the fabric itself. The fabric is the essential medium for any e-textile. The medium itself could have physical defects that are the result of the manufacturing process or of the environment they are exposed to. These defects could lead to short and open circuit conditions on the fabric, which would cause the services of the computing elements to be unavailable. Simulation was used to examine the behavior of an e-textile application when the fabric contains faults. There are two reasons for using simulation. First, it is difficult to use prototypes for determining their performance in the presence of faults. Second, the e-textiles technology is in its infancy; there are no widely deployed prototypes that would allow the collection of fault data. In particular, this thesis studies faults on power and ground lines and how those faults affect the placement of batteries on the e-textile.

1.2 Contribution of this Thesis

This thesis explores the possibility of creating simulation tools to monitor the operation of computing elements on e-textiles. The research contributes the following:

- It creates a simulation tool, called the *power tracker*, for estimation of power from various power-consuming elements on the e-textile, and verifies that tool using measurements from an existing e-textile prototype.

- It creates a first order battery capacity and placement model that allows estimation of the battery life of the e-textile.
- It simulates the performance of e-textiles in the presence of faults on the power and ground lines.
- It estimates the optimum placement on the e-textiles for purposes of redundancy and fault tolerance.
- Finally it contributes to the simulation framework to accommodate future designs. The simulation framework consists of the development of barebones elements that can be modified according to the application being developed. It also defines an interface for the transfer of information in a specific format between any computation block and the power tracker.

The contributions described in this thesis are a part of a larger design and simulation environment for e-textiles. In particular, the power estimation and fault tolerance tools were integrated into an existing simulation of an e-textile for finding the location of the sound source from acoustic beamforming. Acoustic beamforming determines the direction of arrival of sound from the difference in time of the arrival of sound at different microphones. However the tools were designed to be applicable to any e-textile application that would be simulated in the environment.

1.3 Thesis Organization

The thesis is organized in the following manner. Chapter 2 gives the background information regarding the work undertaken in this thesis. It introduces the concepts used in this thesis, the models referenced and the issues specific to e-textiles. Chapter 3 describes in detail the design of the battery and power tracker modules. It covers the present hardware design, test setup and analysis of the tracking technique employed. The physical modeling of the e-textile is explained in Chapter 4, particularly the issues regarding the topology and the introduction of faults. The simulation model is also explained. Chapter 5 verifies the results of the designs and presents the performance metrics used. Chapter 6 summarizes the goals achieved in this thesis and the avenues to pursue for future work.

Chapter 2

2 Background

This chapter introduces the concepts used in the design of this project and the work undertaken as part of the development of the thesis. The design methodology for pervasive computing incorporates previous developments of distributed computing and mobile computing. Electronic textiles (e-textiles) further propel the field of pervasive computing into a tighter design space. The design requirements and the resource utilizations to maximize the benefits of e-textiles are some of the topics explained in the following chapter. The chapter introduces e-textiles and the various design issues involved. It then discusses the power tracker and its need. The requirements for physical modeling are discussed along with the simulation development environment.

2.1 E-textiles

Fabrics that have electronics and interconnections woven into them are known as e-textiles [3]. E-textiles have risen into prominence because of the pervasive nature of fabrics in our environment. Fabrics and clothing are essential articles throughout the day, and hence they are designed to be comfortable for the wearer. This suits the development of systems on this media, which are unobtrusive to daily activities, and intelligent enough to fulfill the computing requirements. Our knowledge-based society demands integration of intelligence in pervasive forms and we believe that e-textiles is one way of achieving it.

In order to achieve this integration, the fabrics have to be woven with the necessary media for communication and power. The technology to manufacture fabrics is advanced enough to weave conductive wires in the fabric in necessary patterns. Sensors, actuators and computing elements can also be seamlessly integrated into these electronic fabrics. The added cost to the fabric is very less. Thus e-textiles offer a cheap and effective medium for development.

The world of e-textiles has developed across various form factors such as jackets that play music [5] and gloves that facilitate the transfer of data [9]. However the form factor may not be limited to fabrics that are always worn on the body. This leads to two broad areas of applications: the wearable and the non-wearable. Figure 1 is a prototype of a glove to detect the user's typing motion [4]. Figure 2 is the non-wearable fabric that performs beamforming [3].

Figure 1: The 'Ugly Glove' detects user's typing motion

Figure 2: Single Cluster Beamforming Fabric

The development of e-textiles has led to the introduction of other elements that are unobtrusive on the fabric. These include the batteries and speakers in the form of fibers. Piezoelectric strips are also considered to be important sensors because of their thin form factor and low power consumption [4]. They can generate a wide range of voltages contingent on the type of material and magnitude of applied stimulus. Other novel products include paper-batteries [10], smart watches [11] and gesture based input devices [12].

An important part of any electronic device is the availability of power. E-textiles are even more tightly constrained by power consumption than most mobile computing devices because large monolithic batteries would make the e-textiles too bulky to be considered clothing. They are still a long way from being autonomous in terms of self-power generation and self-sufficiency. In the present circumstances, a low power implementation is deemed necessary. The power needs to be evaluated regularly to determine the ability to carry out the operations on the fabric. This leads to the necessity of an element or elements to monitor the power and to also schedule the power across the different computing elements to achieve the necessary functionality. The scheduling will be distributed across the elements and not centralized. Unlike most currently available low power devices which have a single battery, e-textiles will likely have multiple batteries. These would be distributed throughout the system for fault tolerance. Now on one hand it is desirable to isolate the batteries from each other in the case of short circuits, to prevent the failure of one part to cause failure of the whole fabric. On the other hand, it is desirable to share the power between batteries, in case one battery is more heavily loaded than the others.

Another important problem is that all applications of e-textiles require some sort of knowledge regarding the physical location of elements on the system. These physical locations decide the accuracy of the results from the computing elements of an e-textile. For example the Acoustic

Source Finder Jacket [6] requires a definite placement of microphones on the shirt to determine the origin of sound.

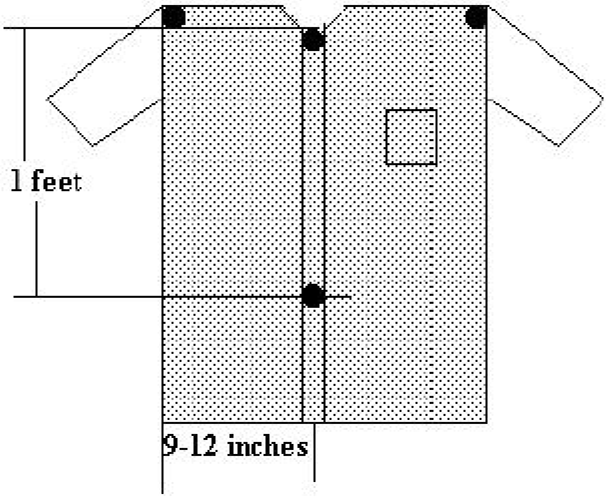

Figure 3: Placement of Microphones for Source Detection

Similarly the beamforming on the large acoustic beamforming fabric shown in figure 2 has microphones placed in a definite pattern for accuracy. However, it may not always be the case that these conditions are maintained. Hence, to determine the ways in which physical damage or wear and tear affects the operation, there is a need to model the physical features of the e-textile fabric. This is discussed in Chapter 4 in greater detail.

2.2 Power Management

The main source of power on the e-textiles fabrics is the batteries. Ignoring the form factor of the batteries, the energy provided and the duration of operation of these batteries is a major constraint on the e-textiles. The implementation and working states of the computing elements, sensors and other circuits decide the current being drawn from the batteries. This in turn dictates the rate of drain of the charge from the batteries, and hence the longevity of operation. The aim of this section is to explain the necessity of creation of tools to explore power management schemes. The first step in this direction is the creation of a power tracker which is discussed in Chapter 4. This section discusses the necessity of battery and power management and the basis for uniform design of components for lower power consumption. It talks about the selection and operation of the battery.

The power tracker in the present system is the beginning of a complex power routing and scheduling algorithm that can be employed in e-textiles in the future. The power management schemes implemented by Benini et al in [8] are some possible algorithms. The balancing act between the insertion of additional power controlling elements and the power savings achieved, are all the more relevant in an e-textiles environment. The power levels used herein are at least three orders of magnitude lower (A laptop typically draws 1 Ampere average current from a 7.5 Ah battery, whereas the average current drawn in our present prototype is 56 mA from a 150 mAh battery). This leads to a tighter situation in terms of power management.

The e-textiles environment, however, offers some other advantages that are not present in conventional systems. This is the redundancy in the number of lines available for routing power. Thus, there is a flexibility offered for the use of alternate power lines in case of damage. Furthermore the physical locality of the battery is not much of a hindrance. Given the availability of power lines and their corresponding interconnection with associated batteries, it may be possible to change the power source as and when needed.

2.2.1 ACPI and Application in Present Design

The e-textile design environment being developed uses Ptolemy II [7]. The entities with functionality in this environment are called as *actors*. The actors available in Ptolemy are inadequate for designing the modules being used in the present prototypes. Hence a custom set of actors typically necessary for the development of an e-textile needs to be designed. The computation actors could have different states of activity, and these computation actors represent the devices consuming power. Hence an effective way to report the states of activity for the estimation of the power consumption is necessary. One part of the work of this research was the development of a standard interface between such actors and the power tracker.

This interface between actors and the power tracker closely follows the Advanced Configuration and Power Interface Specification (ACPI) standard [1]. The variety of intelligent devices being introduced for mobile computing prompted the industry to adopt a standard addressing protocol for managing the power (and hence operation) of the devices. ACPI simplifies the control of devices to operate at lower power consumption levels and to achieve the same performance levels prior to adoption of ACPI.

The benefits of a standard method to interface devices include

- Ability to design independently with the availability of necessary features
- Ability to control devices irrespective of their functionality. Thus a hard-drive appears the same as a Memory-Key to the OS. Their power states are all that it sees and all that it is concerned with.
- Ability to manage power states based on state tables for each device.

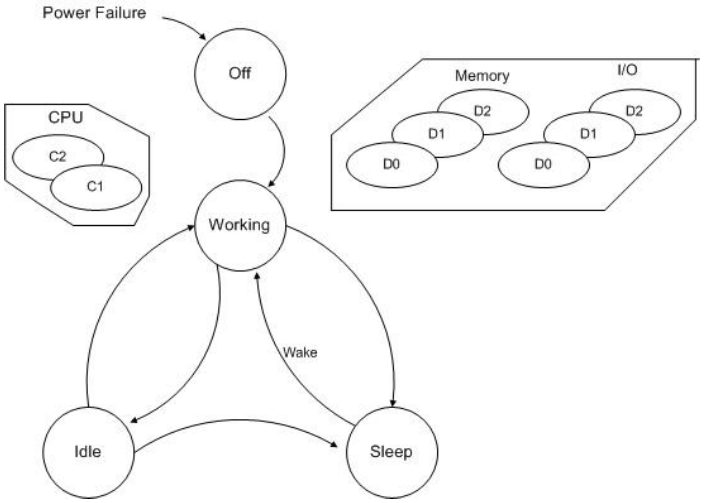

Figure 4: Example of a Power State Diagram for an ACPI Based System

Hence in an ACPI based system, three levels of power states are adopted (Figure 4). At the system level, the operational states of the system may include a Working, Idle and Sleep State (S0, S1, S2 etc). Within each state, the devices in the system i.e. the subsystems, can be in mode than one device power state (D0, D1, D2 etc). The CPU itself can also be in different power states depending upon the code it is running or the processes it is managing at that instant (C0, C1, C2 etc). The present system, for which the power tracker was designed, can also be split at the system level into a number of states. The device and CPU states do not exist at this level because of the absence of subsystems in our design.

The reasons for following ACPI are two-fold: First, ACPI was intended to give the operating system the ability to monitor the power states of hardware devices, which is the same problem, the power tracker intends to solve in simulation. Second, following the ACPI standard may allow the use of the ACPI compliant devices in e-textile hardware in the future.

The most important feature of interest in the ACPI model is the ability to control the power states via a series of tables. The entries in the table successively point to other tables and finally to the states available to transition. Hence the present design of a power tracker is based on a similar series of tables that are updated depending on the device being introduced into the simulation. This will lead to a uniform design practice and help in having a common methodology of measuring power. It should also ease the implementation of a distributed power manager.

2.2.2 Battery Modeling and Control in ACPI

The power management in an ACPI system also uses the information about the battery capacity to effectively increase the duration of operation. This necessitates the addition of intelligence to a battery, for it to report about its present battery level. Furthermore the OS should have an ability to determine levels of power at which to signal a warning and then to stop the working of the device.

The Remaining Battery Life can be calculated by

$$\text{Remaining Battery Life}\,[\text{h}] = \frac{\text{Battery Remaining Capacity}\,[\text{mAH}]}{\text{Battery Present Rate}\,[\text{mA}]}$$

The present design of the power tracker and battery model incorporates rate and capacity. However the present prototypes have no intelligence in the batteries. In addition these batteries are only discharging in the system, while in an ACPI battery charging may occur.

2.3 Physical Modeling and Visualization

The accuracy of the e-textile depends on the location and distance between the various sensors. As time progresses, it is possible that some of these sensors are removed from service due to defects being introduced on the fabric. Thus the accuracy of the system is affected. To prevent this, there is a need to have a robust placement arrangement which can tolerate these faults. Hence to arrive at this robustness, there is a special need to model the physical nature of e-textiles and to observe their accuracy in the presence of faults. This section deals modeling and visualization of the e-textile.

2.3.1 Necessity of Physical Modeling

The orientation and physical alignment of an electronic textile must be simulated because it allows:

- The ability to simulate physical faults on its deployment.
- The development of a fault tolerant model.
- Optimum placement of computing elements
- Distribution of elements both computing and non computing (e.g. sensors and actuators)

- Ability to visualize the targeted structure

2.4 Ptolemy Design Environment

Simulation is a major part of the development carried out to determine the feasibility and operation of an e-textiles application. The Ptolemy II design environment [7] has been selected for development purposes because of its open architecture, the ability to interface with different systems and the ability to operate in different computation domains. The computation domain decides how to deal with concurrency and time. Hence this allows us to create mixed-signal models such as the analog and digital behavior for the same embedded system environment. For e-textiles, the continuous domain can be used to model the physical environment and the physical phenomena, whereas the digital domain can model the computation.

The Ptolemy design environment consists of Actors. Each actor brings with itself some functionality to be implemented. The computation of the actor is controlled by a Director (analogous to shooting a movie). The director decides the domain of operation for the actors. The environment controls the interfacing across various actors and passes intermediate computed blocks called as Tokens to respective actors. Details about the environment and design within Ptolemy are covered in [7].

2.5 Target Application

The target application consists of 30-foot long e-textile with four acoustic beamforming clusters placed equidistantly, shown in Figure 5. Acoustic beamforming is an algorithm to determine the origin of a sound source from the phase shifted signals arriving to a uniformly placed cluster of microphones. Each cluster is identical in terms of hardware. The states of operation of each of the cluster are the same. However the working state at any particular time may be different. The data transfer between the clusters takes place in a cyclic manner. Only one cluster is connected to a display interface to determine the correctness of the results. Each of the clusters determines one particular direction of arrival (DOA) for the sound source, and passes this information to the cluster connected to the display interface. This final cluster now triangulates the results from all the nodes to arrive at one final DOA. The accuracy of the DOA can be improved by keeping a large distance between the clusters. However since the fabric has a limited length, the farthest two of the clusters can be used for best results.

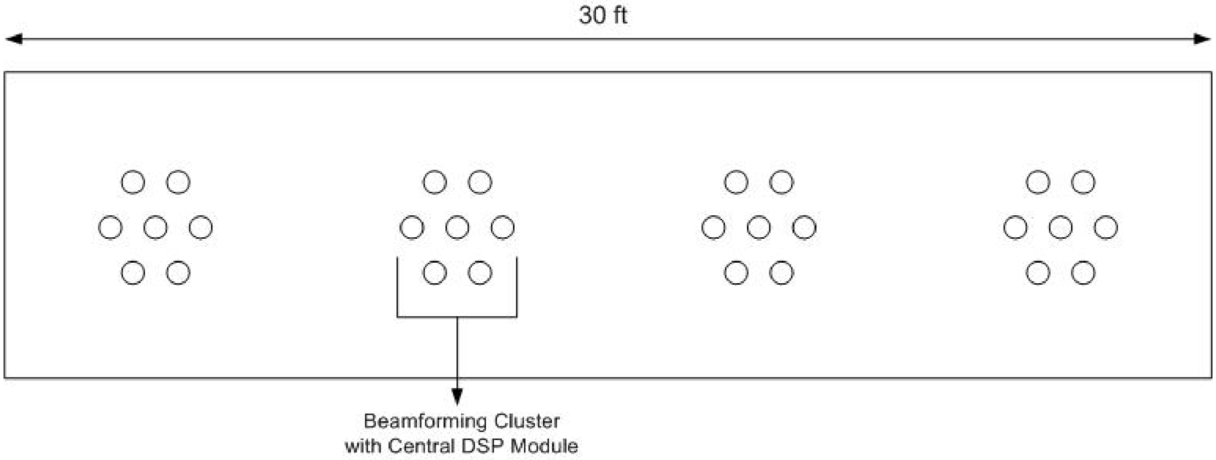

Figure 5: Beamforming Fabric Setup

Similarly the simulation environment in Ptolemy, for this application, consists of four identical modules in the Discrete Event (DE) domain. Additional modules are inserted depending on the functionality desired and data to be collected. The input data to the microphones is simulated and made available for further processing. Similarity is maintained in terms of the actual hardware and the simulation. The actors are designed in order to capture the different functionality of the system. Hence there is a separate actor that simulates the collection of the data from a virtual source, an actor that performs the computation on the collected data, an actor that tracks the power and another that defines the physical nature of the fabric under test. This thesis deals with the design of the actor for tracking power of the e-textile during its operation. The results of this thesis are for a particular application, i.e. the beamforming e-textile and in the presence of open-circuit and short-circuit faults. But this actor along with its interface is the basis for other actors that can be easily integrated into simulations of other applications.

Chapter 3

3 Battery and Power Management Modeling

To model the battery and to determine the power being used in the process of beamforming, the power being consumed by the hardware must be measured and made available to the battery model and power tracker. This element determines other parameters such as longevity of operation and the flexibility offered in terms of the form of the battery. This section describes the design process to implement a realistic power tracker and battery modules.

3.1 Present Hardware Design

The entire module is divided into a digital and an analog part. The Wake-up circuit, Digital Signal Processor (DSP), the Flash memory and the communications interface form the digital part. The microphones, analog signal processing components and the analog-to-digital (A/D) converter form the analog part.

DSP and FLASH:

The Analog Devices 2188M DSP [14] is the sole controller of this module. It was selected because of its low power dissipation in the IDLE mode (44mA), quick recovery from power-down mode (typically 200 CLKIN cycles), 256K on-chip RAM, EZ-ICE debugging interface, and a simple design environment.

The Flash memory is a 4Mbit low power module for accommodating the controlling and computing software.

A/DC:

The A/D 7888 is the interface between the analog and digital elements. This is a 12-bit 8-channel A/DC, with the ability to sample at 125 Kilo Samples per Second. This is a successive approximation register type of A/DC.

Analog Circuitry:

The microphones collect the acoustic signals and make it available to a signal conditioning block. This block is essentially an op-amp based circuit for amplifying the signal of importance and for reducing the noise in the signal. This is made available to the A/DC for digitization.

Wake-Up Circuit and Digital Communication:

The Wake-up circuitry is necessary to detect signal when the system has entered an idle state. The signal from the microphones above a particular level is used to wake up the circuit.

The modules are connected to each other for purposes of communication of results. This is represented by the Digital Communication block. This block can also wake up a module, if necessary.

3.2 Measurement Setup

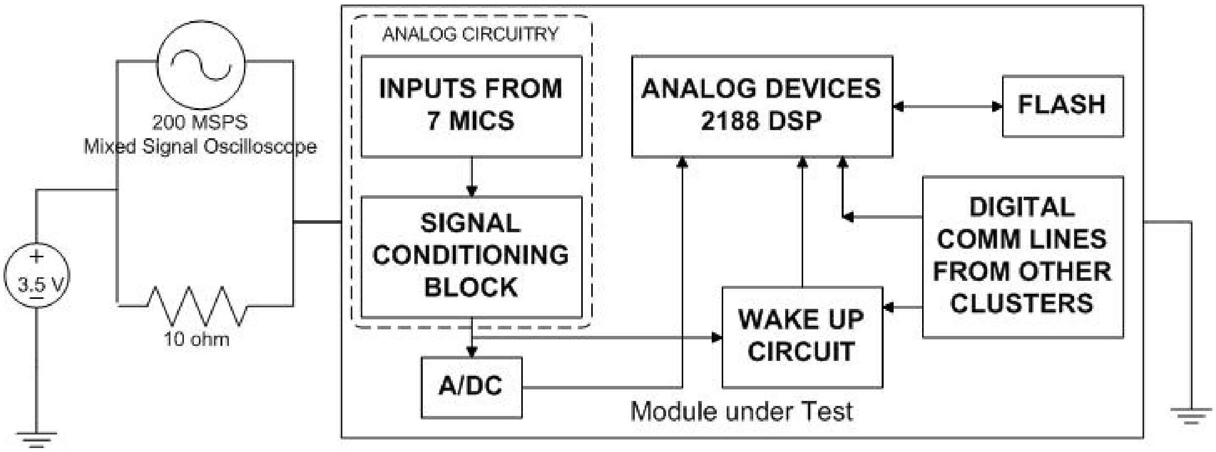

Figure 6: Setup for Power Measurement

The measurement of the power consumption was carried out with an Agilent mixed signal oscilloscope [13] capable of 200 Mega Samples per second (200 MSPS) as shown in Figure 6. The current drawn by the module was measured at different modes of operation. This was measured as the voltage across a 10 Ω 1W resistor, which was connected to the input of the voltage regulator for this module. The input voltage had to be increased to a larger value to accommodate for the drop across the resistor. Hence this input voltage is not the voltage to be considered for power measurements. The voltage used for all the calculations is the operating voltage of the module (typically 3.1V).

The general steps for measurement of power are as follows:

1. Identify the states of operation of the algorithm implemented in hardware and software.
2. Prepare the FLASH modules with necessary program. Only known state / states of operation are permitted.
3. Run the module in the above arrangement. Capture the data during the particular state of operation. This can be done over the GPIB or with data capture provided by the oscilloscope. The data capture technique was used in the present case.
4. Estimate the running average of the captured data. The running average of a signal is equivalent to filtering the high frequency components of a waveform.

The measured values on the hardware for sampling rate of 2048 are given in Table 1.

Power State	Average Current (mA)	Time (us)
MicSampling Alone	29.6	438
Beamforming	38.9	162800
Sending	0.1	48
Receiving	0.26	48

Table 1: Charge Consumed per state

3.3 Simulation Environment: Interface with Components

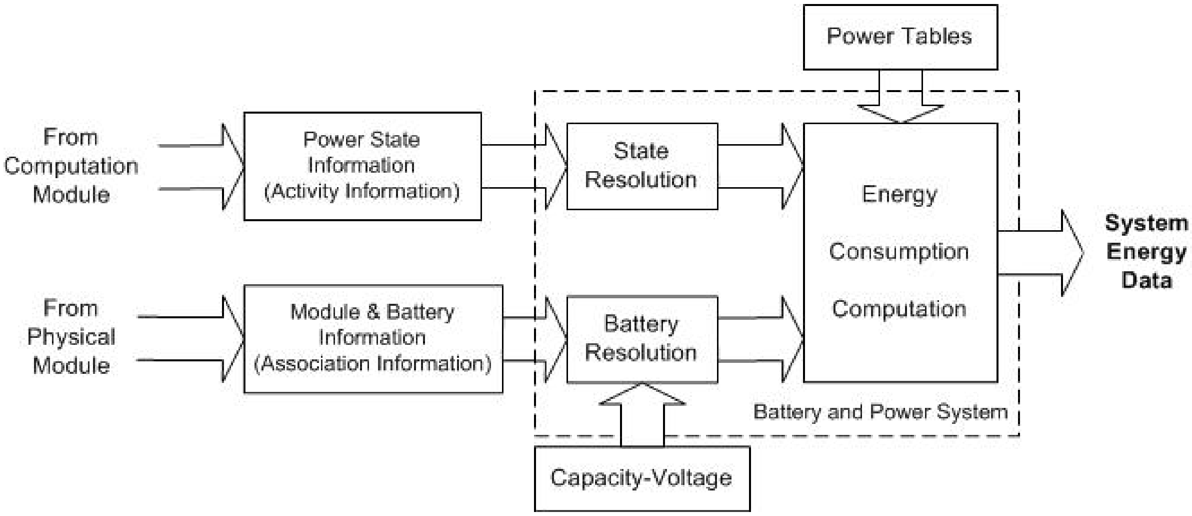

Figure 7: Block Diagram for Battery Model Creation

The battery model interfaces to the physical model (Chapter 4) and to the computation model. It uses the information from these two models and also its own independent information to decide the battery consumption during computation. It also aims to calculate the average current drawn and hence the longevity of operation possible. Each individual block is explained in the following paragraphs.

3.3.1 Power State Information:

The computation model has definite states of operation depending upon the design. The battery has to be informed about the present active state of operation. This is known as *Activity Information*. The Activity Information informs the battery regarding the state of operation and the parameters controlling the power consumption in that state. For example, a typical beamforming algorithm computation could use information from three or more sources and it could be run for a particular amount of time. Hence the number of sources and the time become parameters affecting the power value within a particular state. The Activity Information also includes the identification for a particular module to identify the battery associated with that module.

3.3.2 Module and Battery Information:

The placement of the modules and the battery/batteries on the fabric decide the association between the modules and the batteries. These are parameters in the Physical Model. This information is called as *Association Information*. Hence the modules and the battery/ies powering up the corresponding module on the fabric are sent to the battery model. The Association Information also indicates whether a particular module is out of service.

3.3.3 Battery Capacity and Voltage:

These are parameters of the battery model itself. They define the battery capacity in milliamp-hour (mAh) and the voltage in Volts. The number of capacity-voltage pairs should be identical to the number of batteries defined in the physical model.

3.3.4 Power Tables:

The power in the different states of operation depends on parameters within that state. This is collected from the prototype. The parameters are chosen at which operation of the modules is possible. For example the hardware can be run at a sampling rate of 2048, with seven microphones. The power values are collected for varying parameters, such as sampling rate, number of microphones and communication rate, and are then recorded in the tables. This part of the battery module is user dependent and will change for different computation modules.

3.3.5 Battery and State Resolution:

The Activity and Association Information is utilized to

1. Identify the computation module.
2. Identify if a computation module is active.
3. Identify the battery powering up the particular module.
4. Identify its state of operation.
5. Identify the capacity & voltage of the batteries

These tasks set the battery model up with the necessary parameters for further computation.

3.4 System Power Analysis

The system can be operated in two different setups. These are:

Case 1: One battery for the entire system.

Case 2: Multiple batteries of equal capacity for the system with the same total capacity as case 1.

Case 1 is the most general case in e-textiles. Case 2 arises from the need to circumvent the dependency on a single central battery. In case 2, the system is divided into subsystems. These subsystems can then be powered by individual batteries. Multiple subsystems could also be powered by a common battery. This section deals with the analysis of the entire system for measuring the power consumed during operation.

3.4.1 System-under-test Power State Diagram

The power states for the acoustic beamforming application are shown in figure 8.

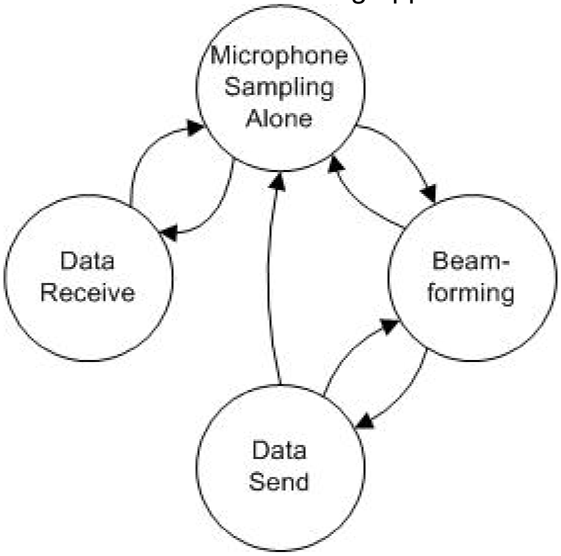

Figure 8: Power State Diagram

For the beamforming application, the system is always in a state of microphone sampling (micsampling). After each node has collected 512 bytes of data, it performs a beamforming on the collected data. Besides this communication occurs whenever there is sufficient data in the memory (i.e. just before the memory is filled up). Data receiving takes place if the requested data is available or if data has to be transferred to another node. Thus the sending and receiving of data is quite random.

From the present hardware prototype, the design parameters include:

Capacity of the battery C = 150 mAh

Voltage of the battery V = 9V

Sampling Rate = 2048 Hz

Hence each simulation cycle = 1/2048 seconds of real time

3.4.2 Analysis of Different Setups

Since there are 4 nodes in the current beamforming prototype,

Let subscripts 0,1,2,3 stand for nodes 0,1,2,3 respectively. Nodes are the computation modules.

m = Microphone Sampling state

b = Beamforming state

s = Sending state

r = Receiving state

If a simulation runs for 'x' simulation cycles then we have:

x_m = # of times only microphone sampling state is reached = x

x_b = # of times beamforming state is reached.

x_s = # of times sending state is reached.

x_r = # of times receiving state is reached.

Also t_m, t_b, t_s, t_r are the times spent in each of the corresponding states, and i_m, i_b, i_s, i_r are the currents in each of those states.

In hardware, after every 512 microphone sampling cycles, one beamforming cycle is run. Hence

x_b = Quotient (x_m / 512). …………………………………… (Eqn 1)

x_r and x_s are random because of the communication protocol employed. The nodes are receiving requests for transmission of data. This transmission proceeds only if the node ID is the same as the one from whom the data is being requested. If not, the request is retransmitted to the next node following it. Similarly the information requested is transmitted to the next node and so on, until it reaches its correct destination.

The current drawn versus time graphs for each of the states involved can be obtained from the setup described in Section 3.2.

Figure 9 is the current drawn during microphone sampling. It is seen that t_m = time for one cycle of this periodic waveform.

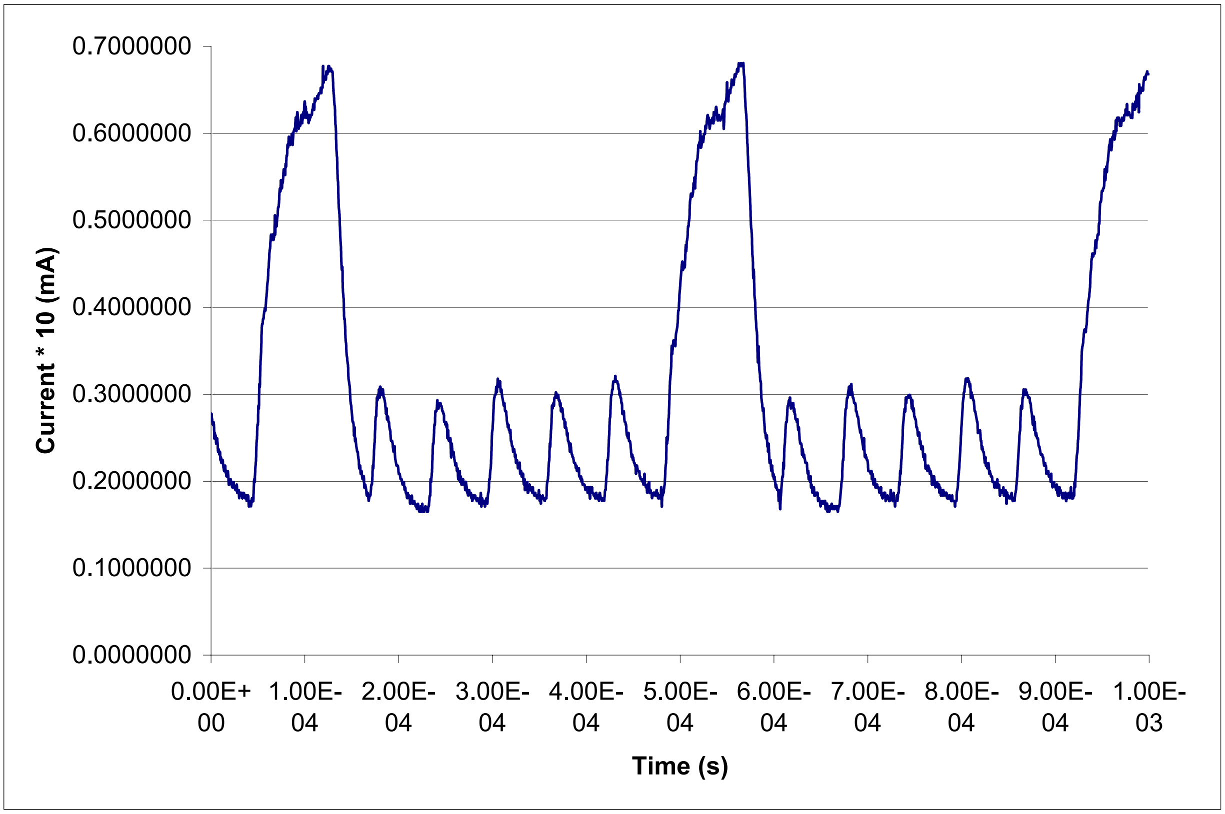

Figure 9: Current Drawn in Mic. Sampling

The graph of the current drawn during the Receiving state has a similar shape as figure 9 but it has a higher average value.

Figure 10 is the plot of the current drawn by the prototype during the state of beamforming. Once beamforming is finished it returns to the microphone sampling only state. During Beamforming Microphone sampling is also being carried out.

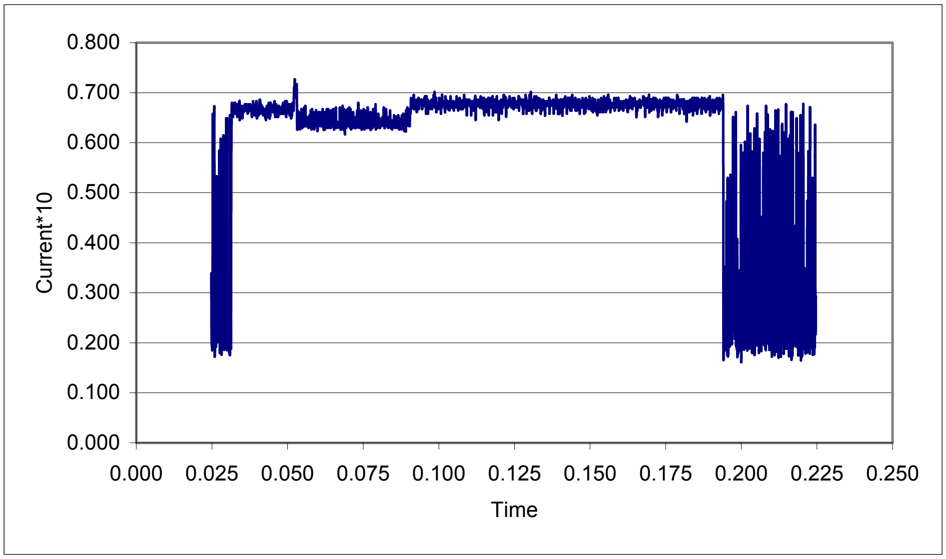

Figure 10: Current Drawn by Beamforming

From figure 10 t_b = time for which beamforming is active.

The current plot for the Sending state is similar in shape to figure 10, however this Sending state plot has a higher average current. However the Sending state is achieved by setting a flag bit in hardware, which by itself occurs in a very very small time period. For this design it is assumed that it takes 1/10th of the simulation cycle time

The charge consumed by Node 0, over a length of time will be

$$C0 = x_{m0} * t_{m0} * i_{m0} + x_{b0} * t_{b0} * i_{b0} + x_{s0} * t_{s0} * i_{s0} + x_{r0} * t_{r0} * i_{r0} \text{ .... (eqn 2)}$$

Similar equations can be written for Nodes 1, 2, 3.

Hence charge consumed over time for entire fabric

$$C = C0 + C1 + C2 + C3 \text{ .... (eqn 3)}$$

However this charge may be drawn from the same or multiple independent batteries. Depending on the number of batteries per node, three different configurations have been selected for analysis

Configuration 1: All four nodes are powered by the same battery. Hence in the case that battery is completely discharged,

$$C = C0 + C1 + C2 + C3 \quad \text{(eqn 4)}$$

Configuration 2: Two of the four nodes are powered by the same battery; the other two nodes are powered by another battery. Hence in the case that battery is completely discharged,

$$C_{00} = C0 + C1 \quad \text{(eqn 5)}$$

$$C_{01} = C2 + C3 \quad \text{(eqn 6)}$$

For the sake of comparison of different configurations, it is assumed that

$$C = C_{00} + C_{01} \quad \text{(eqn 7)}$$

It is also assumed that C_{00} and C_{01} are equal.

Configuration 3: Each of the nodes is powered by an independent battery. Again the total battery capacity of the application is assumed to be C. Each of the batteries is ¼ the capacity of C.

3.5 Design Flow

The information received from the battery and state resolution is utilized to compute the energy being used by the e-textile. This energy is also attributed to each of the batteries on the e-textile and hence the remaining battery capacity is estimated. This estimation depends upon the accuracy in simulation of the computation module to the actual hardware. Based on these factors the longevity of operation of the e-textiles application can be estimated. The steps of operation of this module include:

1. Identify the module being used
2. Identify the state/s of operation of the module.
3. Use the Power Tables to estimate the energy being consumed.
4. Estimate the battery capacity remaining after this operation.
5. Estimate the average current drawn in the lifetime of operation of the e-textiles.

6. Estimate the lifetime of the battery before draining completely.

The first order battery model is assumed. The reduction of the voltage, as the charge capacity reduces, is assumed to be linear. The chemistry of the operation of the battery decides the model of discharge of the battery [16]. For the purposes of accommodating batteries of different working principles the power estimation model has to be modified with respect to its operational equations. The present model is based on the linear discharge effect observed in the batteries available in the consumer market [15]. For accommodating the models of different batteries, the discharge equation needs to be modified. Within each battery simulation design module, there exists one function that accesses the stored charge data. This function can be written according to the discharge profile of the battery, to determine the charge consumed in a particular state. Hence this design allows for modeling of batteries with higher order discharge equations.

Chapter 4

4 Physical Modeling

E-textiles applications can be of many shapes and sizes. The behavior of an e-textile when deployed cannot be predicted before hand. Hence some sort of simulation is necessary to determine the behavior of the e-textile material considering ideal conditions. This chapter deals with one such design to model the e-textile material. This chapter explains the model parameters that are used to describe the physical properties of the e-textile including its size, shape, placement of batteries and other components, the placement of power and ground lines, the faults on the fabric, and the connection between the sub-fabrics. This model has been used on the beamforming textile to determine its operation in the presence (and absence) of faults.

4.1 Design Parameters

The present design models the 30 foot long e-textile, made up of multiple beamforming clusters, described in Chapter 2.5. This is a rectangle with multiple power and ground lines running along its x-dimension. Computing clusters are introduced on these at regular intervals and in predetermined patterns. This information is necessary for modeling the e-textile material. The design parameters introduced in this section help in the modeling of the beamforming fabric and are general enough to describe all e-textile applications.

4.1.1 Shape and Dimensions

The default shape assumed in the design is a rectangle. For the beamforming application this shape is sufficient. E-textiles cannot be generalized into one particular shape or even into regular polygons. Hence this shape is a starting point for the development of other complex shapes.

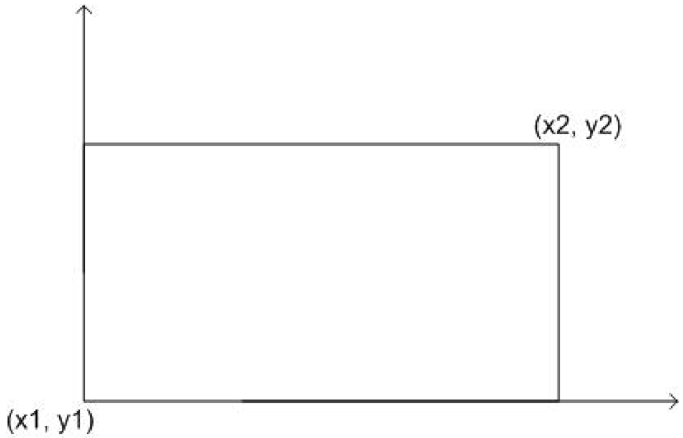

Figure 11: Shape and Dimension of e-textile under development

Furthermore the present operation is considered to be approximately in two dimensions. Wearable e-textiles will have more complex shapes because of the movement of the body. For example a shirt can be assumed to be a collection of rectangles sewed at their edges. But even then each rectangle will be oriented independently in a three-dimensional space.

Hence for our definition we use rectangular co-ordinates, in a two dimensional system. The area of interest can then be simulated.

4.1.2 Line Density

In the absence of the ability to transfer power over a wireless medium, power and ground lines would be the predominant wires in an e-textile. Their number would depend on the application being developed and the redundancy to be provided. The density and placement of these lines will decide the fault tolerance and the cost of the fabric as a whole. Figure 12 is a representation of two fabrics with different densities of power and ground line pairs.

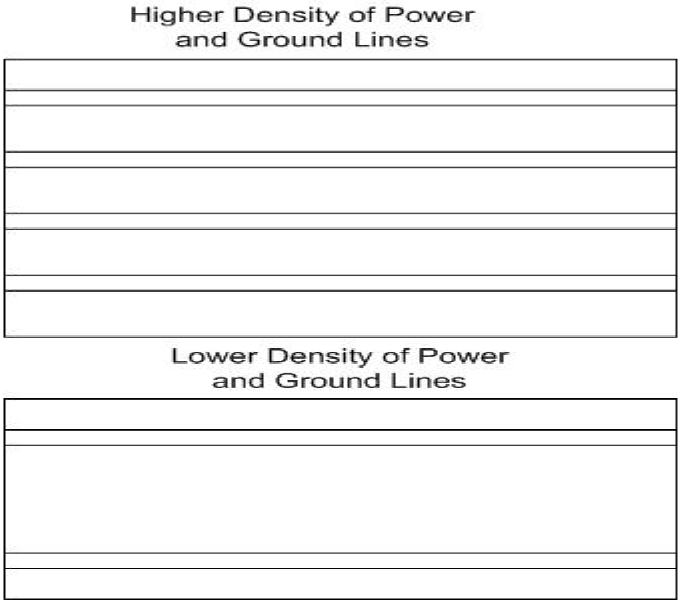

Figure 12: Power and Ground Line Density

Power and ground lines are assumed to be an inseparable pair for design purposes. Although it is possible that a computing element is closer to power and ground lines from different pairs, the present simulator routes the power through only the pair that is closest. The separation of power and ground lines depends upon the density of wires on the fabric, as shown in Figure 12.

4.1.3 Locality of Elements on the Fabric

The elements on the fabric include the batteries and the circuit boards. The power and ground pairs are powered by the battery closest to that pair. The locations of the circuit boards on the fabric decide the power-ground pair closest to it, and hence the battery that supplies power to this board.

The e-textile can be powered up by a single source or by multiple sources. The number of batteries used decides the power lines that they will be feeding into, and hence the computation modules they will be powering up. The battery model development section (Chapter 3) talks more about the locality of elements and the implications of that locality.

4.1.4 Introduction of Faults

The present simulation was developed with respect to the beamforming fabric. This fabric will be spread on the ground for detecting the approach of vehicles towards it. Hence it is necessary to introduce the faults in the simulation that could have an effect on the accuracy of the system. The faults introduced can cause the shorting of ground and power lines, or instead cause the circuit to be open-circuit. This can have an adverse effect on the battery and hence and longevity of operation of the fabric. Faults can turn off a part of the e-textile, and hence robust algorithms are needed that give accurate results in the presence of such faults.

The faults on the fabric can themselves have very complex shapes and impact. However this has been simplified in the present simulation. A typical probability for the occurrence of open and short circuits is adopted. A set of location of faults was generated randomly and this set was repeated for different configurations of the e-textile. Once an e-textile has been deployed and a better model for the fault rates and types has been developed, the present random generation can be replaced by a more deterministic model.

The time of occurrence of the fault has also been considered. At the particular time instance of a fault, a particular portion of the fabric is removed from the main fabric. Depending upon the instantaneous fault value (short or open circuit), e-textile modules may be removed from service.

4.1.5 Joining Ability

The beamforming fabric being developed can be broken down into sub-fabrics. These sub-fabrics can be independently powered.

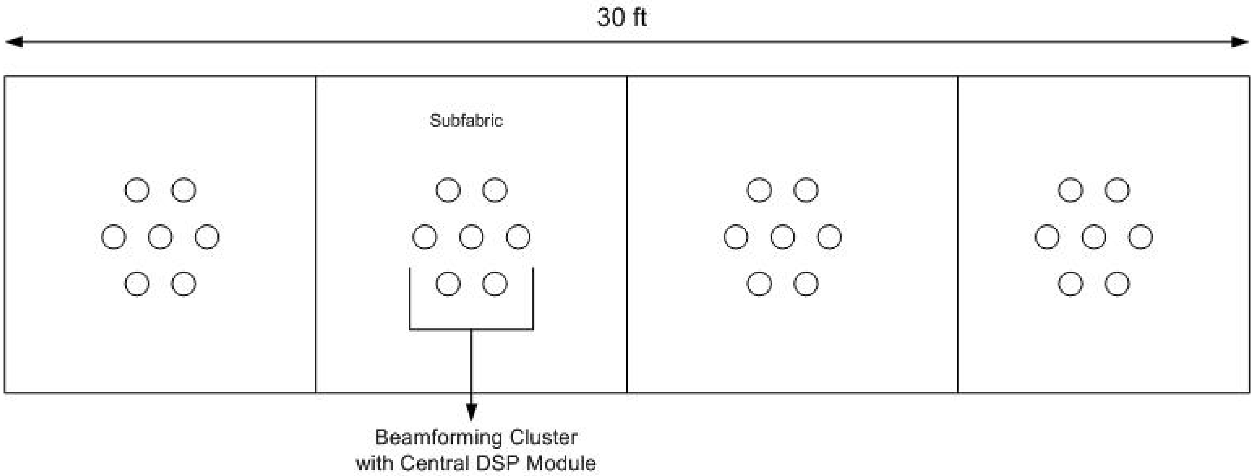

Figure 13: Sub-fabrics connected to form one large fabric

These sub-fabrics can also be connected in a variety of configurations depending upon the batteries used. Hence one battery can power all four sub-fabrics, or two batteries can power one pair each, or each sub-fabric can have their own individual battery. Hence to address this need, the fabrics should have some way to communicate the information to one another. Alternatively there can be an additional actor in the simulation, which combines the data from all these devices. This is also necessary in the Ptolemy Design Environment as loops are nearly impossible to implement without introducing delays into the simulation. Ptolemy has no provision to exchange information in both directions.

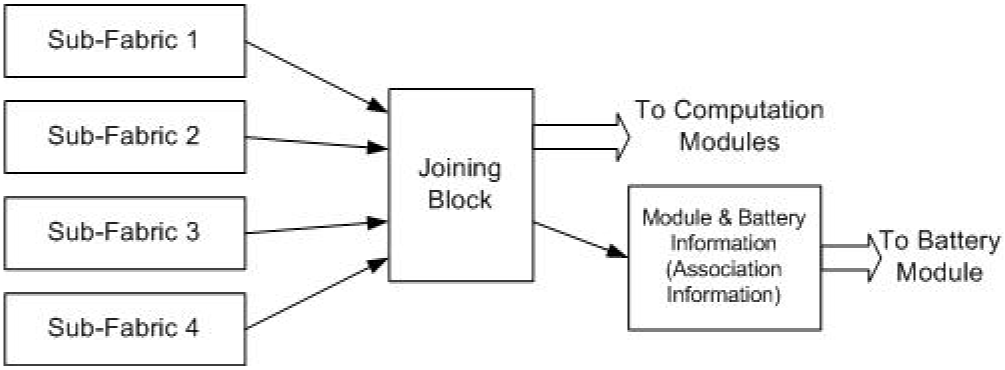

Figure 14: Joining block to combine fabrics

Thus an additional actor was designed for the simulation, which provided this functionality of combining other sub-fabric elements in the simulation. This is shown in Figure 14, where the outputs from all the fabrics are combined by the Joining Block. The various configurations between the sub-fabrics can be defined within this Joining Block

4.2 Simulation Environment

In our simulation environment, the physical structure of the fabric is defined with an actor. The actor decides the activity or inactivity of various computing elements depending on the various parameters entered into the actor. It also decides whether physical damage to the fabric results in loss of computing elements or parts thereof.

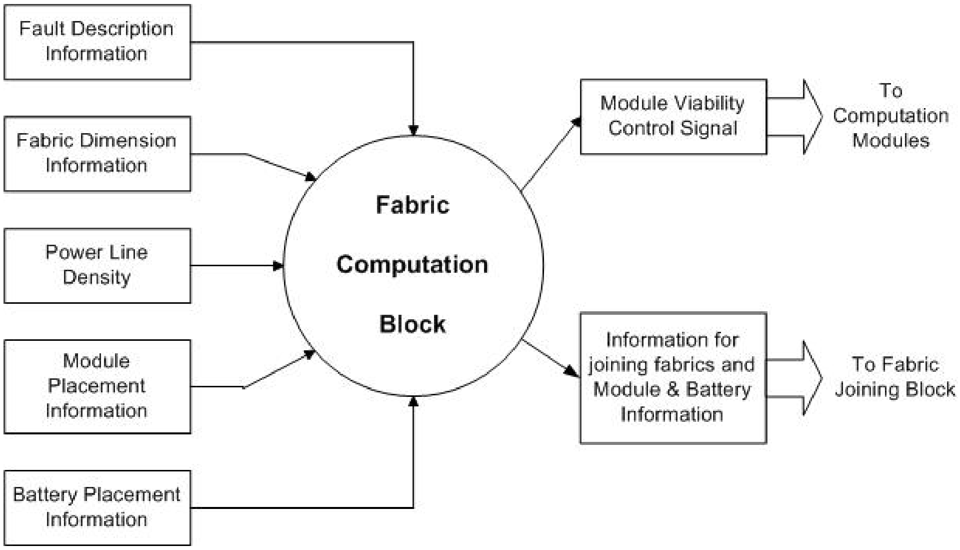

Figure 15: Block diagram for physical model creation

The blocks in the Physical model of the fabric are related to the design parameters mentioned in Chapter 4. The *Fabric Dimension Information* is the input for defining the shape of the fabric. The present simulation was developed for the beamforming fabric and hence takes in the upper right hand and lower left hand corners to simulate a rectangular fabric. The *Fault Description Information* is the block providing the ability to select a fault type and location. The *Power Line Density* decides the placement of power and ground lines on the fabric. The *Module Placement Information* decides the placement of the various computing and non-computing elements on the fabric. It also provides an identity to each fabric. Finally the *Battery Placement Information* selects the battery for the system and decides the location of the battery on the fabric.

The inputs are then used to generate patterns for passing information to the other blocks in the simulation. The faults on the fabric are used to decide whether a computation module is active or not. The inputs also decide the operation for a subset of the modules on the fabric (Chapter 2.5).

The association of batteries and modules on the fabric is needed by the Battery Model (Chapter 3). This association string is called as *Association Information*. It gives the information regarding the battery, the computation modules and whether they are still in a working condition.

The *Module Viability Control* signal controls the operation of the computation blocks in the simulation. This signal has to be manipulated into a control signal contingent to the relation of the various modules to each other. For example, in our beamforming case, the microphones can be either seven or five in number. Hence this selection has to be made depending on the implementation.

The fabrics need to be joined in order to simulate multiple fabrics having a common battery. The necessary information is passed to the joining block, which combines the information across different fabrics and across same or different batteries.

Chapter 5

5 Results and Conclusion

This chapter presents the simulation results for the power tracker and e-textile fault models described in chapters 3 and 4. The research involved the design of a battery and power tracker module. This chapter begins with an analysis of the results from the power tracker. It then explains the different configurations with the sub-fabrics and the corresponding power consumption profiles. Finally the effects of faults on the accuracy of the e-textile are presented.

5.1 Power tracker results

The power tracker was tested for 5 minutes of real time. No faults were introduced in order to validate the working of the battery and power tracker module alone. Using the power tracker alone allows a designer to estimate the power consumption of an e-textile application and can be used to evaluate the quality of distributed power management schemes for e-textiles

In this setup all the nodes are switched ON with no particular control on their working. Hence the accuracy of the e-textile is not the point of interest here but the performance of the power tracker model to accurately track the power is evaluated.

	Charge Consumed (mAh) MicSampling	Charge Consumed (mAh) BeamForming	Charge Consumed (mAh) Sending	Charge Consumed (mAh) Receiving	Total Charge Consumed Per Cluster (mAh)	Charge Consumed per Battery (mAh)	Power Remaining Simulation (mAh)	Average Current mA
One Battery Supplying 4 nodes								
Node 0	1.7271490	1.6487402	0.0000349	0.0016720	3.3775962	13.5104941	136.48692	207.700
Node 1	1.7271490	1.6487402	0.0000505	0.0016786	3.3776184			
Node 2	1.7271490	1.6487402	0.0000712	0.0016775	3.3776380			
Node 3	1.7271490	1.6487402	0.0000775	0.0016748	3.3776416			
Two Batteries Supplying 4 Nodes								
Node 0	1.7271490	1.6487402	0.0000349	0.0016720	3.3775962	6.7552146	68.8664	103.8
Node 1	1.7271490	1.6487402	0.0000505	0.0016786	3.3776184			
Node 2	1.7271490	1.6487402	0.0000712	0.0016775	3.3776380	6.7552795	68.8662	103.9
Node 3	1.7271490	1.6487402	0.0000775	0.0016748	3.3776416			
Four Batteries Supplying 4 Nodes								
Node 0	1.7271490	1.6487402	0.0000349	0.0016720	3.3775962	3.3775962	33.78651	51.925
Node 1	1.7271490	1.6487402	0.0000505	0.0016786	3.3776184	3.3776184	33.7864	51.925
Node 2	1.7271490	1.6487402	0.0000712	0.0016775	3.3776380	3.3776380	33.78644	51.925
Node 3	1.7271490	1.6487402	0.0000775	0.0016748	3.3776416	3.3776416	33.78641	51.925

Table 2: Power Tracker results for a run of approx 5 minutes

Table 2 gives the results for the average current and power for a run of approximately 5 minutes. The average current obtained from the measurement setup of chapter 3.2 is 56 mA per node. Hence there is an error of approx 4 mA or 7.1% error. It also tracks the power consumption in terms of the charge consumed by the node. The corresponding configuration of the system decides the power available to the system. This validates the working of the battery and power tracker.

5.2 Physical Analysis

The operation of the e-textile can be affected by the battery configuration employed in the e-textile. The operation of the e-textile was tested for the accuracy depending upon the fault introduced in the system. The faults in the e-textile can either short the power and ground lines, or can leave frayed open ends. The discharge of the battery in both these faults was captured. The accuracy of the system was also noted for the detected direction of arrival (DOA) of an approaching vehicle. These have been performed in simulation only. The accuracy will be discussed in Chapter 5.3. The basic setup remains the same in chapters 5.2 and 5.3.

Three configurations have been used for the system. Each configuration uses four fabrics that may or may not be connected to each other, i.e. their communication lines are always connected to each other but their power and ground lines may or may not be connected to each other. The total charge capacity of the system has been held constant across all the configurations. The dimensions of each fabric are 8 feet x 2.34 feet. Each fabric has two pairs of power and ground lines. Similarly on each fabric, there is a central computing element with six microphones around it and one central microphone. Faults cause one or more microphone devices to shut off, or cause the disruption of power to the central computing element. The battery discharge profiles were recorded for different configurations for a run of at least five minutes of real time. These are explained in the following sections.

For all the figures of the fabric :

- ‘ ◊ ‘ is a working element,
- ‘ × ‘ indicates a non-working element,
- ‘□’ is the battery
- long dash line is the fault
- short dash lines are the power and ground lines

5.2.1 Configuration 1: One Single Battery for the Four Fabrics

In the first configuration a single battery powers up the entire e-textile. However this battery is also the central focal point whose damage will cause the biggest loss in computation. Similarly a short circuit in one of the fabrics can cause the battery to be drained out completely, disrupting the operation of the other circuits.

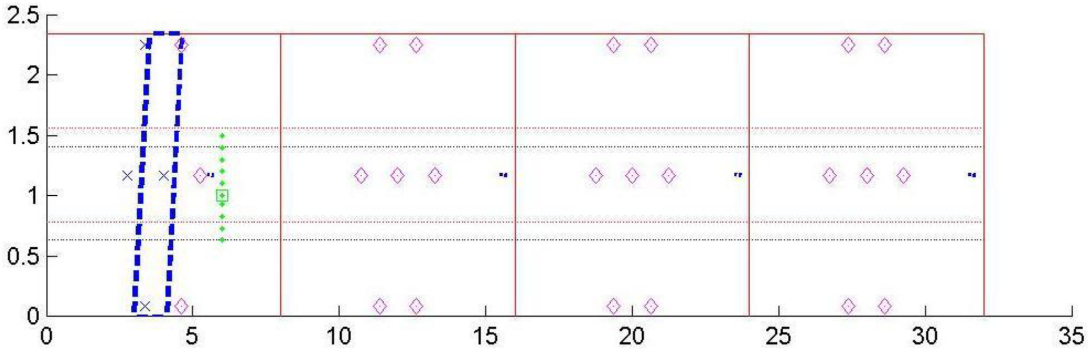

Figure 16: Simulated fabric with single battery and an open-circuit fault

Figure 16 is the representation of the system with a single battery obtained from the simulation. A fault is introduced into the system, to represent a wheel rolling over the e-textile, shown by the dashed line. Figure 16 also gives the elements that are active and those that are inactive. In the first case an open circuit fault is simulated. As a result the only particular area on the left hand side of the fault is inactivated. The remaining three fabrics are still being powered up. The battery gets drained at a slower rate compared to its operation for four fabrics. Figure 16 is the charge left after the computation time.

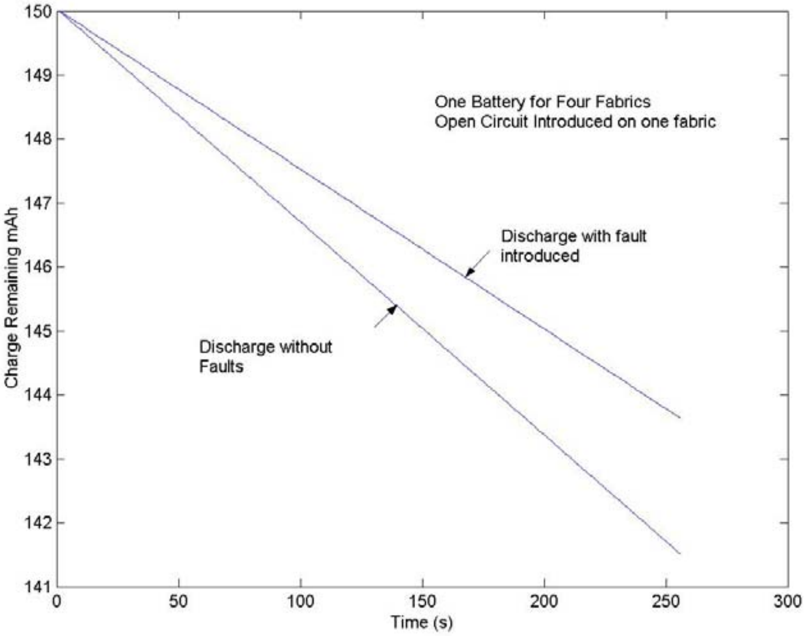

Figure 17: Battery Charge remaining after an open circuit fault has been introduced

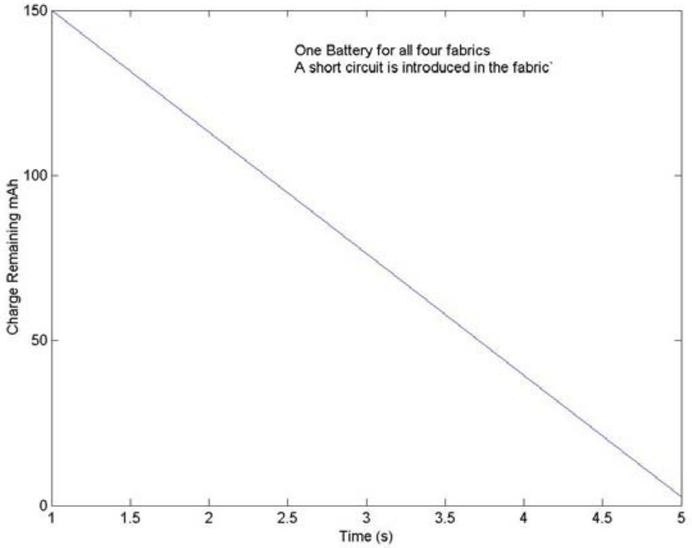

Figure 18: Battery discharged due to short circuit

Figure 18 shows that the battery charge in the circuit reaches the lowest possible value in a very short time and is held constant from that point onwards. The time scale for Figures 17 and 18 is vastly different because Figure 18 has a short circuit introduced that rapidly reduced the charge of the battery, whereas Figure 17 is the normal operation of the battery. Hence it is observed that a short circuit on any part of the fabric will cause the working of the entire e-textile application to stop. Hence a central battery is the critical point of the e-textile, and can bring down the operation of the e-textiles.

5.2.2 Configuration 2: Two Batteries for Each Pair of Fabrics

The central battery was observed to be the critical point. Hence in the next step, the battery was divided into two batteries. The total charge available to the e-textile was kept the same as in the single battery case. Each battery supplied power to two fabrics. The power and ground lines between these two pairs were isolated from each other. Figure 19 has two batteries as against a single one in Figure 16. In Figure 19, one battery powers the two fabrics on the left and the second battery powers the two fabrics on the right.

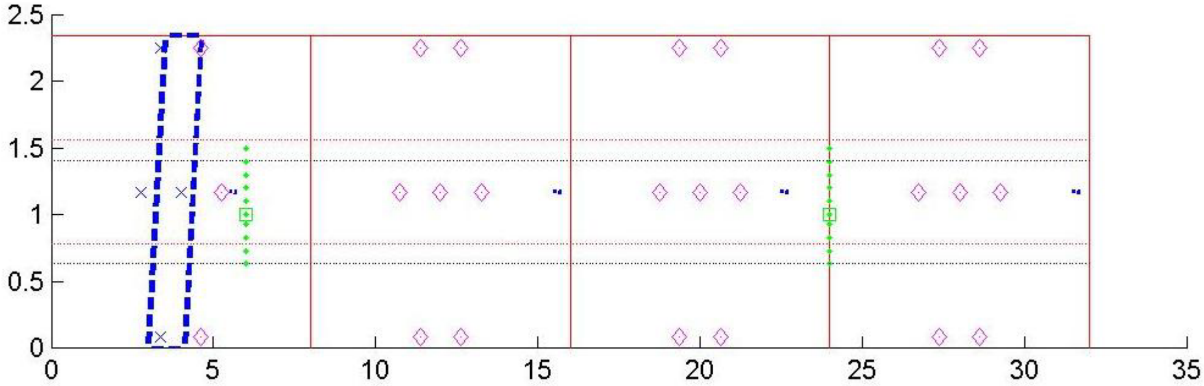

Figure 19: Configuration with one battery for each pair. The two fabrics on the right are connected to each other but not to the two fabrics on the left. An open circuit fault is introduced.

An open circuit fault was introduced in the circuit (Figure 19). This fault can potentially be on the battery itself, leading to the collapse of that particular pair of fabrics. For analysis purposes, the fault was introduced such that one fabric from a pair was disabled. Hence in the present scenario, one pair of fabrics is working as usual, whereas the other pair has only one active fabric. Hence the battery discharge profiles from these two pairs will be different and can be seen in Figure 20.

One of the batteries will obviously get discharged much faster than the other. However until the time it discharges, the e-textile can still function and give results. The accuracy depends on the fabric on which the fault was introduced.

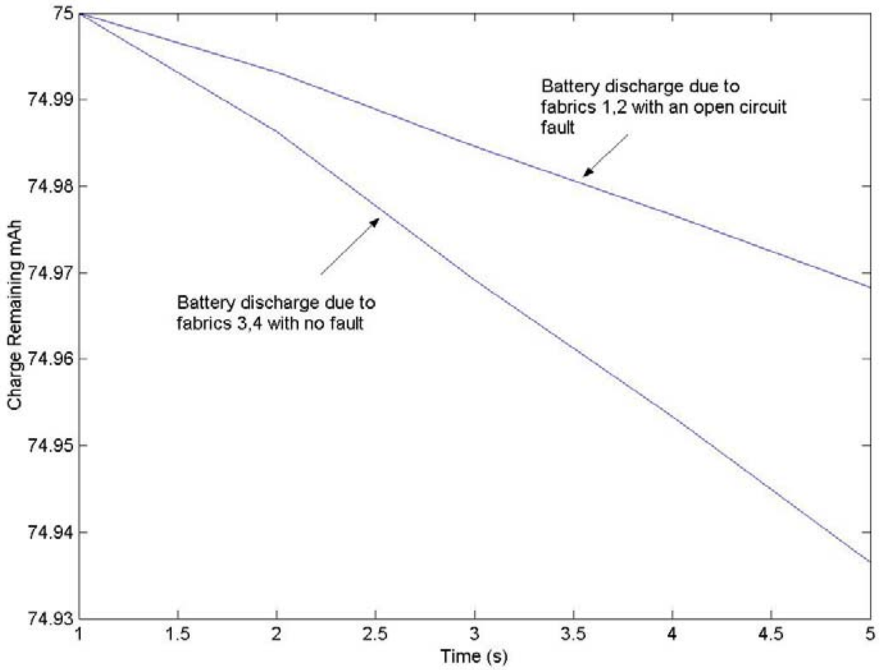

Figure 20: Battery discharge from the two pairs of fabrics from figure 19.

For the second test, a short circuit was introduced in one pair. This caused the total failure of that pair as shown in Figure 21, with the pair on the right removed from service. The introduced fault simulates a random bullet pattern.

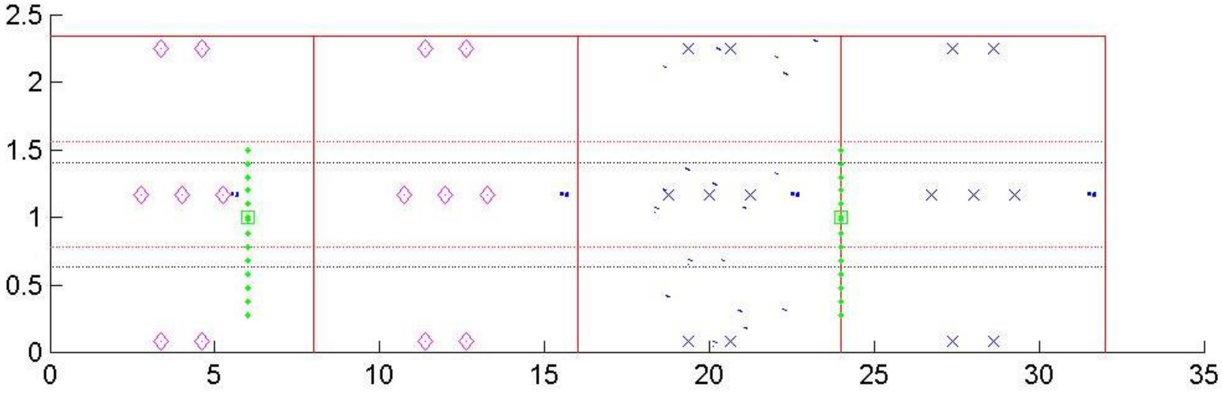

Figure 21: Short circuit introduced on right pair

Hence now one of the batteries is expected to discharge much before the other battery. The results obtained from this fabric will depend upon the working fabric pair.

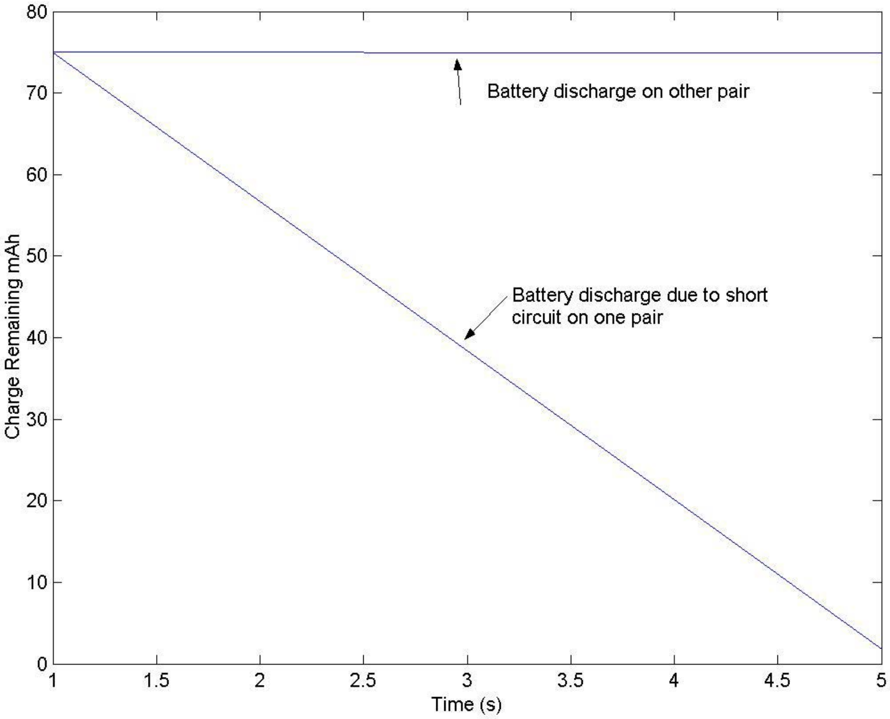

Figure 22: Battery discharge for short circuit on one pair

5.2.3 Configuration 3: Individual Batteries for the Fabrics

Another configuration has independent batteries for each fabric. No connections exist between the power and ground lines across different fabrics. Figure 23 is one representation of this configuration. The charge available to the e-textile is again the same as in the single battery configurations.

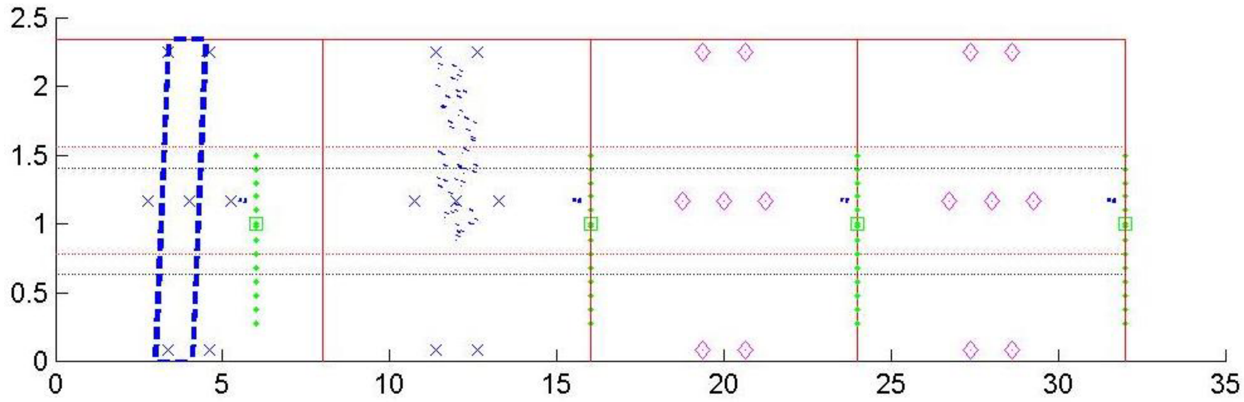

Figure 23: Four independent fabrics with four individual batteries. Each fabric is isolated from each other.

Two faults were introduced in the fabric simultaneously as well as at different instants. The battery discharge graph when the faults are introduced at different instants is as shown in Figure 24. One of the fabrics first goes out of service, but the remaining three can still be potentially used for beamforming. After some more time another battery is short circuited, resulting in the second line heading to the zero mark. The remaining two fabrics can still continue their operation irrespective of the damaged fabrics.

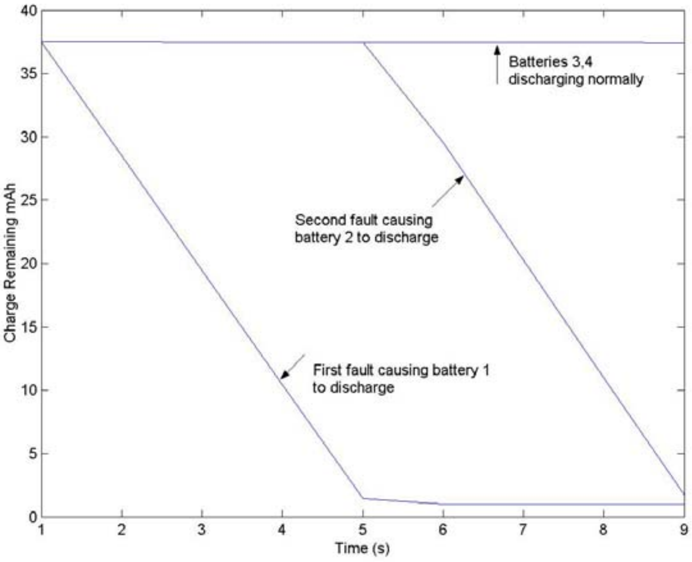

Figure 24: Battery Discharge for Faults Introduced at Different Time Instants

Faults were also introduced simultaneously. This led two fabrics to be unavailable for computation. Figure 25 gives the discharge graph for this case.

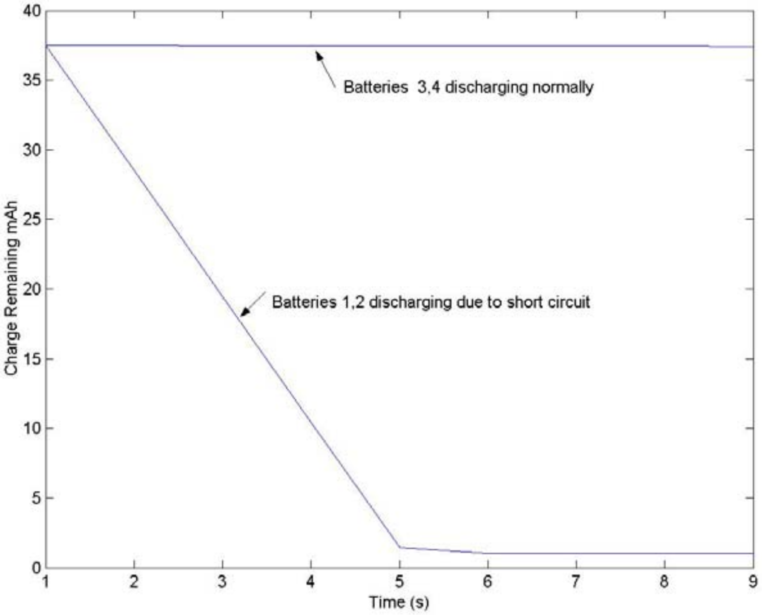

Figure 25: Battery Discharge when faults are introduced simultaneously on two fabrics

The time value needs to be divided by 3.5. This was done to capture different execution times.

This configuration allows for a more robust system than the previous two configurations. In this case only single fabrics are affected. The accuracy of the e-textile may get sacrificed but it could still lead to approximate results that can satisfy the requirements. Such a system will need to be turned off when the results do not give sufficient accuracy. But this e-textile configuration has a much longer lifetime than other configurations in the presence of faults.

5.3 Faults and its Effects on Accuracy

The three configurations for analyses were introduced in Section 5.3. The function of the beamforming array is to resolve the DOA from all the four clusters. The accuracy of the current beamforming fabric can be improved by using the data from the farthest fabrics. However in the event of faults this inter-fabric distance is decreased. Thus although there is a fabric with working nodes, the results from these nodes would not be useful. These effects were studied and the results are presented in this section.

The analysis has been carried out for short circuit faults. The current sampling rate of 2048 samples/sec will give best results if the speed of the sound source is small (<40 feet/sec) at a small radial distance (<100 ft) from the fabric. The beamforming algorithm gives good results for DOA between 45 and 135 degrees. Hence we assume throughout that the sound source is moving between angles 45 and 135 degrees at a radial distance of 60 ft. The fabrics have been numbered 0 to 3 from the left to right. The speed of the sound source is 7.85 feet/sec, so that it covers the circular path in a time span of 12 seconds.

Table 3 gives the results for each configuration from the previous section 5.2. The 'start time' is the point at which two nodes are selected for beamforming. The 'stop time' is the time when this same pair stops working due to a fault, and the next possible set of fabrics start operating. In configuration 1, the battery is the central critical element. Hence when a short circuit fault develops after 12 seconds, the e-textile is rendered useless. The accuracy of the system is the best, but its fault tolerance is very poor.

	Starting (s)	**Ending (s)**	**Nodes**	**mean error**	**std deviation**	**maximum error**
Config 1	0	12	0,3	3.7	4.588	10.057
Config 2	1	6	0,3	3.8814	4.443	10.0574
	6	12	0,1	7.39	8.69	15.6
Config 3	1	2	0,3	2.9293	3.42	5.8399
	2	4	1,3	3.4926	3.5835	7.9277
	5	12	2,3	11.15	11.92	27.806

Table 3: Analysis results for sound source moving at 7.85 feet/sec

On the other hand configuration 3 is more robust. Even if Node 0 is rendered useless, it can still give results that are quite accurate as the standard deviation is approximately the same. But if it loses one more node, then the readings lose their accuracy. It is an improvement over configuration 1, being able to continue giving results even after the fault occurs.

Configuration 2 is very similar to configuration 1. Loss of any node results in poor accuracy. However it is marginally better as redundancy of nodes allows the e-textile to function. Hence if accuracy is not of great importance to the e-textile, it can still collect data. Thus configuration 2 is better than configuration 1 but worse than configuration 3 in terms of accuracy.

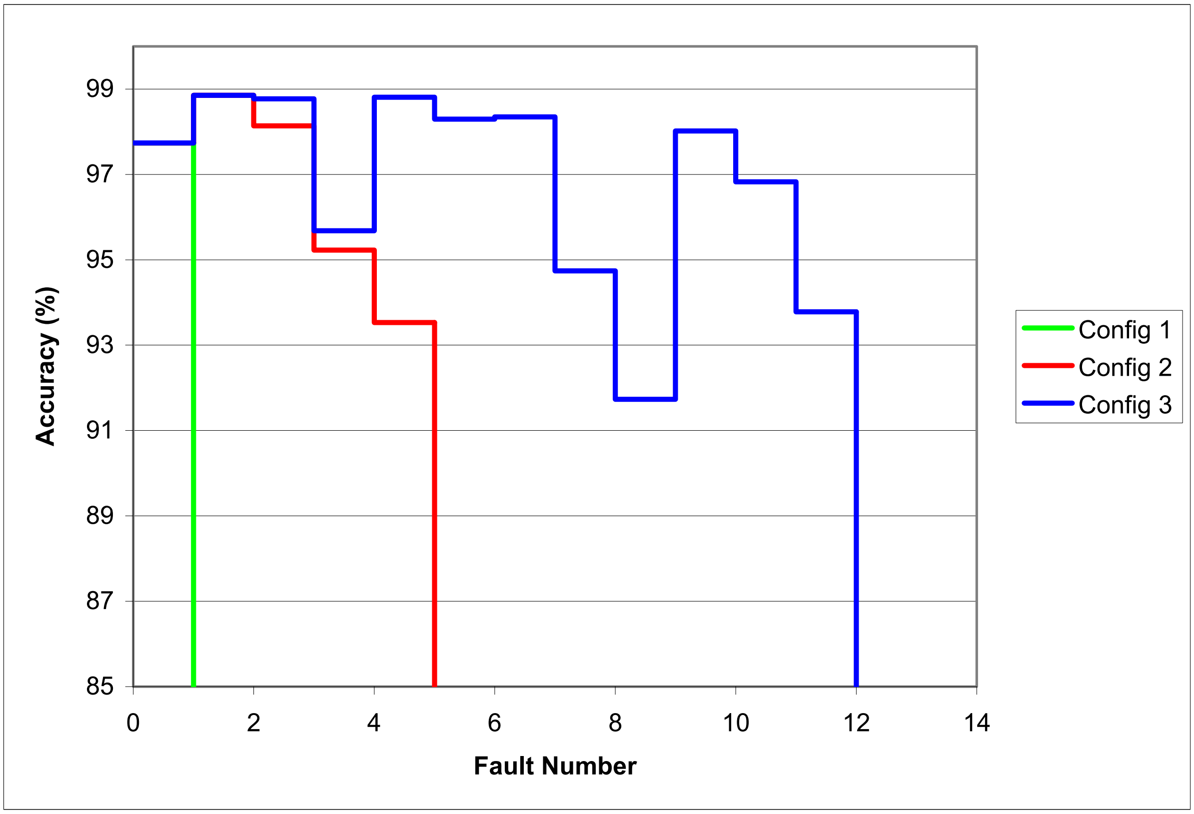

Figure 26: Variation of accuracy for one single set of faults

The sound source is moving over an angle of 90 degrees, in 13 seconds. Faults were introduced every second of the fabric, and the fabric was run for the different configurations. For each second of simulation, the beamforming has an accuracy that is independent of the accuracies of the previous and next seconds. From Figure 26, it can be seen that, the first fault renders configuration 1 useless for further computations. Configuration 2 and 3 can tolerate more faults before collapsing.

The configurations were tested for 15 different sets of faults created randomly. In the absence of suitable fault models for the fabrics, these sets serve as a suitable testbench.

	Accuracy without faults	Avg Time of First Fault	Accuracy after first fault	Avg Time of Second Fault	Accuracy after second fault	Avg Time of Third Fault	Accuracy after third fault	Avg Time of Fourth Fault	Accuracy after fourth fault
Config 1	97.73%	1 s	0%						
Config 2	98.51%	4 s	92.89%	5.9 s	0%				
Config 3	98.34%	2.9 s	96.40%	4.5 s	94.58%	6.8 s	94.88%	10.8 s	0%

Table 4: Effect of random faults sets

Table 4 gives the performance of the different configurations to the random sets of faults. On an average, configuration 3 will always lead in the time period of operation of the e-textile.

Referring to Figure 17,

Rate of Discharge per module = 16.30 µAh/second = 16.3 * 3600 = 58.68 mA

	Configuration 1	**Configuration 2**	**Configuration 3**
Operating Nodes	0, 3	0, 3	(a) 0, 3 (b) 1, 2
Operating Time	5.112 hours	5.112 hours	(a) 2.556 hours (b) 2.556 hours
Mean Error	3.7	3.7	(a) 3.7 (b) 10.6
Mean Accuracy	97.94%	97.94%	(a) 97.94% (a) 94.11%

Table 5: Accuracy in the absence of faults and for entire period of operation

Table 5 gives the accuracy over the lifetime of operation in each of the different configurations, in the absence of faults. In configurations 1 and 2, nodes 0, 3 will operate throughout the possible lifetime of 5.112 hours. The accuracy will be maintained for this time period. However with configuration 3, each battery will have a lifetime of only 2.556 hours. Hence there will be a change in the nodes which are operating during that time. Hence there will be a change in the accuracy throughout the lifetime of operation of the e-textile. To counteract this change in accuracy the e-textile will have to be configured for operation, first with nodes 0, 2 and then with nodes 1, 3. A constant accuracy will be attained, though it will be a lower than the accuracy obtained by using nodes 0, 3.

Chapter 6

6 Conclusion and Future Work

The battery and power tracker module was created. Its working was modeled on the power state diagram observed for the current module under test. A linear discharge model of the battery was assumed for the design. Table 2 is the simulation run for this module, which verifies its operation. This battery and power tracker module can be used to evaluate a power management scheme, wherein the power can be scheduled across different components.

All the analysis presented here is modeled on the beamforming fabric under development. The physical model, however, can be extended for simulating other shapes and applications of e-textiles. The accuracy of an application developed due to introduction of faults on the e-textile can be used as a metric to determine whether an e-textile or a part of it is worth using. Furthermore the arrangement of batteries on the e-textile can be decided depending upon areas most prone to damage. The battery lifetimes can be estimated from the discharge curves obtained. Similarly battery capacity can be decided depending upon their usage. In the case of an e-textile with different computational model designs (and hence different power consumption levels), the battery capacities may not be the same throughout. This could pose a logistic problem to stock batteries of different capacities, and to use them specifically for their designated module.

6.1 Future Work

Presently a power tracker has been created with a standard interface to the computational elements. This power tracker can be used in the future to analyze different power management schemes and to develop a power manager that can schedule power across different elements of the e-textile.

The physical modeling was accomplished for a rectangular beamforming array. One way to model other different garments, such as pants, is shown in Figure 27:

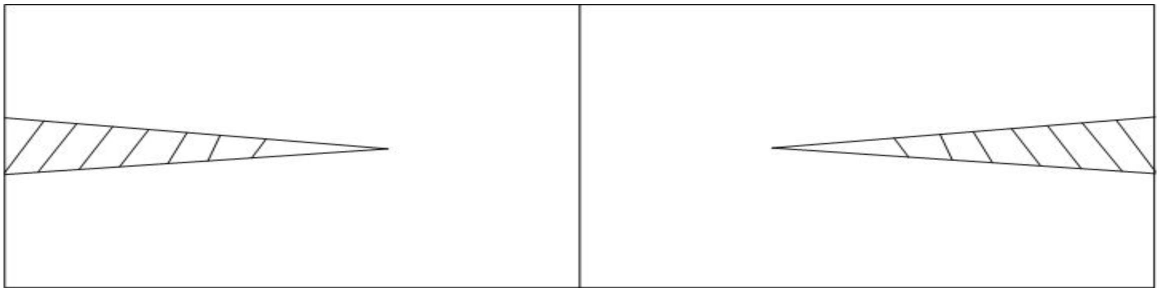

Figure 27: Layout of pants on the rectangular fabric

Although Figure 27 is a possible arrangement, it is not a complete solution. There are still many shapes such as circles, ellipses etc that will require modifications to the present rectangular arrangement. Also the routing of power and ground lines along different axes on the same fabric should be designed in the future .

The present work is, however, a physical model to start, in the absence of suitable fault models for e-textile applications. As research progresses, and e-textiles are deployed, better data will be available and more robust models would be created.

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Vita

Tanwir Sheikh completed his education in Calcutta (West Bengal), and Pune (Maharashtra). He joined Maharashtra Institute of Technology, Pune in July 1997 to pursue a Bachelors Degree in Electronics and Telecommunication Engineering. After graduating in 2001 with honors and winning the Motorola Gold Medal for his undergraduate work, he joined Virginia Tech in Fall 2001. In his second year in the Master of Science program, he began work with Dr. Tom Martin. Tanwir has interests in quizzing, hiking, trekking, traveling and sports. His research interests include Analog and Digital VLSI design, and Testing of Electronic Systems.