Architectures for e-Textiles

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(ABSTRACT)

The huge advancement in the textiles industry and the accurate control on the mechanization process coupled with cost-effective manufacturing offer an innovative environment for new electronic systems, namely electronic textiles. The abundance of fabrics in our regular life offers immense possibilities for electronic integration both in wearable and large-scale applications. Augmenting this technology with a set of precepts and a simulation environment creates a new software/hardware architecture with widely useful implementations in wearable and large-area computational systems. The software environment acts as a functional modeling and testing platform, providing estimates of design metrics such as power consumption. The construction of an electronic textile (e-textile) hardware prototype, a large-scale acoustic beamformer, provides a basis for the simulator and offers experience in building these systems. The contributions of this research focus on defining the electronic textile architecture, creating a simulation environment, defining a networking scheme, and implementing hardware prototypes.

Dedication

To (Samir, Layla, Youssef, Wassim) Nakad

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Chapter 1

Introduction

The textile industry has reached a highly advanced stage with the different types and qualities of fabrics that can be manufactured. This industry provides a low-cost fully automated and minutely controlled (down to the crossing of each fabric thread) means of manufacturing textiles [1]. This automation and control offer a cost-effective means of manufacturing fabrics that can be used in conjunction with electronics to create computational fabrics called electronic textiles (e-textiles), creating novel processing systems with many practical applications.

Inexpensive, flexible, large-area systems that can be draped over a vehicle or a tent are examples of applications that are difficult to achieve with conventional technologies but possible through electronic textiles. The use of fabrics as a platform to deploy electronics has great possibilities in applications in the wearable computing area; components are integrated into the system and thus are less likely to hinder the user or become snagged by the user's surroundings. Another advantage of such a system is the ability of the fabric to dynamically conform to new requirements of the application; the components (sensors, actuators, processing elements, etc.) can be changed and their relative position altered [2], [3]. Several examples of such systems were introduced and discussed in [4], [5], [6]. Emerging fiber technologies will greatly improve such systems. Fiber or thin film components can be in-

corporated directly into the textile, adding to the concealment factor in hostile territories and the comfort factor in wearable systems. Examples of such components are battery and acoustic sensor elements [7], [8].

Future research and advances in the area of electronic textiles will enable a plethora of applications ranging from accomplishing the simplest of everyday chores to mapping a fire-fighter's location in a smoke-filled building. Embedded system [9] technologies alongside smart materials [10] can be integrated and interfaced to create new possibilities. Advanced e-textile systems will require simultaneous hardware and software design operations; similar situations have surfaced in the embedded systems area and given rise to hardware/software co-design [9]. The hardware and software are closely knit in e-textile systems; the level of complexity and intelligence of one modifies the requirements and operations of the other. Careful consideration should be made at the outset of the design process to determine which part of the system (hardware or software) controls each task. These decisions will affect the complexity, cost, and effectiveness of the whole system [9].

Developing an e-textile architecture to serve as a software/hardware architecture for a specific class of applications will require the establishment of a set of precepts. The precepts will help the user make decisions governing the application being created. These precepts will be based on past experience and developing concepts. A software backplane derived from these precepts and offered as a chassis to build upon would facilitate the work to be done in future research. The use of this backplane in developing a prototype will implement these precepts thus utilizing the offered experience. This backplane will be augmented by a general simulation environment that can govern emerging e-textile applications. The importance of creating this software/hardware architecture lies in providing an easier way of creating e-textile systems by:

1. offering our gained experience in a testing environment to be used before and throughout physical implementation,

2. creating the design precepts to minimize re-invention, and

3. detailing the techniques used in combining electronic components and fabrics.

This architecture will be offered as a tool to ease the creation and progress of future research projects. Current research within the Virginia Tech e-textiles group is using a preliminary version of this architecture in developing new prototypes for different e-textile applications.

The first step in this research was the construction of a hardware prototype to support the theories and test the implementation, in addition to gaining a better understanding of fabrics, the connections between electronics and fabrics, and the embedded conductive threads. The implemented system is a large scale acoustic beamformer that senses the presence of a large vehicle and reports the position and direction of motion of this vehicle. The system receives acoustic data from several microphones, processes this data, determines the direction with acoustic beamforming [11], and communicates the computed result to peer systems or the outside world. Long running times in potentially hostile territory require the implementation of a low-power, fault-tolerant scheme. This prototype is the first e-textile that includes both processing and communication in the fabric.

A simulation environment has been created for this architecture. This environment will cover the functioning of the processing nodes, their communications, and the power consumption in the system. Faults and operation under differing situations are also supported. The implemented communication protocols can be tested with faults and in more complex prototypes.

Work on this dissertation contributed:

- The definition of an Electronic Textile Architecture as a set of precepts. The creation of these precepts was based on experience attained from several e-textile projects in the Configurable Computing Lab and the Wearable Computing Lab at Virginia Tech.
- The creation of a modeling and simulation environment that provides a platform to test new concepts and improve extant prototypes. This environment encompasses the mentioned precepts.

- The development of a networking scheme that provides communication between the nodes in the system while routing around faults and sleeping nodes.

- The implementation of a hardware prototype, the Acoustic Beamforming Array, which helped in the creation, implementation, and testing of the previously mentioned contributions.

The dissertation is organized as follows: Chapter 2 discusses related research. Chapter 3 cites the advantages of e-textiles along with implementation issues and exploring procedures and Chapter 4 details the Electronic Textile Architecture. The simulation and testing environment are examined in Chapter 5. The networking scheme is detailed in Chapter 6. Chapter 7 will provide conclusions and comment on future advancements.

Chapter 2

Literature Review

Creating an e-textile system consisting of many communicating nodes requires in-depth knowledge of the underlying networking scheme, the location of the computational nodes and the sensors they use, the types of the sensors used, and a system simulation to assist in exploring aspects of the system.

This chapter will discuss a network architecture and algorithm derived from the multiaccess mesh networks [12], [13], [14], [15]. The Ptolemy simulation environment for this project will be described. Acoustic beamforming algorithms related to the demonstration prototype will be examined. E-Textile research done in both academia and industry will be reported.

2.1 E-Textile Component Communication

The communication between the different components of an e-textile depends on the level of complexity of these components. Different components can exist in such a system, for example, sensors, actuators, and processing nodes. The fabric implementation offers a set of novel issues that are different from regular systems. The relative distance between sensors and processing nodes is variable and this variation can render a sensor useless to a specific

node at a given time or extremely useful at another (line of sight detection, for example).

2.1.1 Processing Node - Sensor Communication

Node to sensor communication depends on the level of sophistication of the sensor. As an example a passive microphone sends its values at all times. A smarter sensor would provide its data when queried and go into a sleeping mode between requests. On the other hand, a component can be in range to sense or communicate, or far enough to be dormant. The distance between sensor and processor is also affected by the physical flexibility of the fabric, for example, a sensor that is 10 cm away from a processing node at a specific point in time is not guaranteed to be there if the textile changes shape.

2.1.2 Processing Node - Processing Node Communication, Token Grid Network

The communication network needed in an e-textile system should be easily implemented in a fabric backplane, communicate inner network information, provide scalability, and offer fault-tolerance. In an e-textile system, the number of the nodes to be connected would not be known a priori and that number is expected to change throughout the lifetime of the system. Several network schemes can be applied such as hypercube or tree-type architectures. The node degree, number of connections at the node, increases linearly with an increase in the dimension of a hypercube [16]. Given the fixed node degree in fabric, this renders architectures similar to the hypercube unsuitable for e-textiles. A tree-type architecture relies heavily on specific nodes for connections between different branches, which does not map well to the faulty environments of e-textile applications. The fixed degree, fault-tolerance, and reasonable scalability of the token grid are the primary attractive features. A token traversing the network can be used to keep information about the topology and the state of the nodes, another benefit of the token grid shown in 2.1. This network matches the inherent

X_Y layout of a fabric facilitating its implementation on a fabric backplane.

According to Terence Todd, communication networks used for LAN (Local Areal Networks) are usually based on linear technologies, buses or rings for example [12], [15]. These networks offer an easy and economical solution to the networking problem. The downside is the throughput limit imposed by the speed of communication in the physical media. The performance of these networks does not scale with the number of nodes [12], [15]. The token grid network introduced in [12] and [15] offers a solution to these problems including a fault-tolerant scheme for node failures [13]. In addition, the token can be used to transport information about each node in the ring. The bisection bandwidth of a unidirectional ring is BW (BW: bandwidth of the communication link). The bisection bandwidth of the token grid is N*BW (N is the number of rings across the bisection).

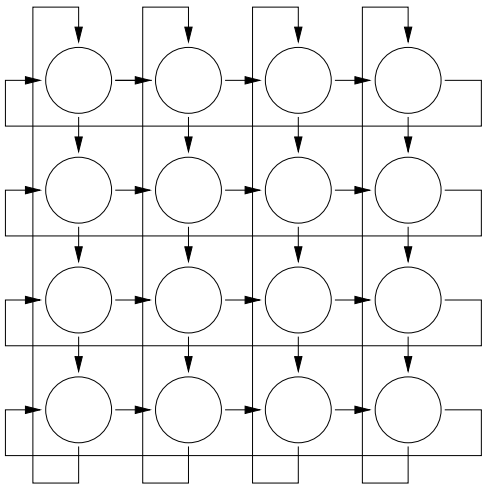


Figure 2.1: A Token Grid with four rows and four columns; a circle depicts a communicating node and an arrow a unidirectional communication link (based on information from [12]).

Each node in the token grid is connected to two token rings. Figure 2.1 shows a schematic of such a grid with four row rings and four column rings. This architecture offers a significant advantage in throughput as compared to common rings or bus networks. The throughput of this network architecture increases with the number of nodes. This increase in throughput is a significant benefit to systems for which the number of nodes on the grid is not known.

The physical aspect of this architecture maps well to the inherent X-Y nature of a fabric weave.

The network interface of each node on this network has two configurations as shown in Figure 2.2. In the DR (Double Ring) configuration (see Figure 2.2 (a)), the rings converging at this node are separate. The second configuration is the SR (Single Ring) configuration, shown in Figure 2.2 (b), in which the rings converging at this node are merged and operate as a single ring. Special tokens are released in such a situation; Figure 2.3 shows the same network with two rings merged at Node (1,2).

Full connectivity can be maintained in this network when faults occur. The condition to establish this connectivity is that the network interface of each node can be configured to remain in either the DR or SR state upon failure. The state to be mapped upon failure is determined based on a failure-backbone; a specific node is configured to the SR state upon failure if it belongs to the failure-backbone or to the DR state otherwise. If a node of the failure-backbone detects a failure on its row, it forces itself into an SR state. This scheme offers a slowly degrading performance upon failure while keeping full connectivity in the network [13], [14]. This strategy only deals with failures of the node, not the link. The other assumption is that the network interface of the failed node still forwards the packets in its permanent DR or SR state. The following example shown in Figure 2.4, derived from [13], will illustrate this feature:

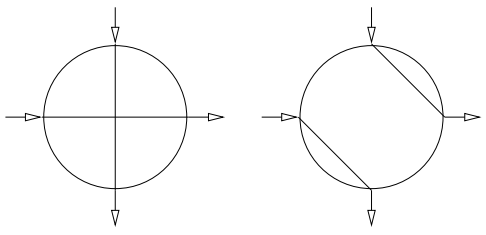


Figure 2.2: Communication through a node can be configured as a Double Ring or a Single Ring (based on information from [12]).

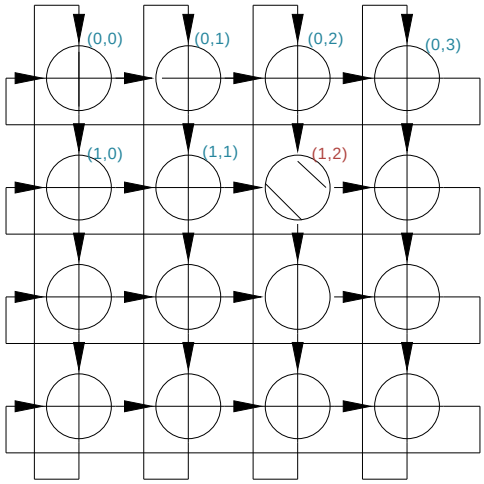


Figure 2.3: Row 1 and Column 2 of this Token Grid are merged at node (1,2) (based on information from [12]).

1. Column 0 is assumed to be the failure backbone.
2. Node 0,0 fails and is "fused" into the SR state.
3. Node 3,3 fails and is "fused" into the DR state.
4. The failure on node (3,3) forces node (3,0) into the SR state.
5. The result is a permanent ring spanning row 0, column 0, and row 3.

2.2 System Simulation

Building a separate prototype to conform to every decision point or aspect of the project is extremely time consuming, raising the need to simulate the system, test several options, and only implement the best result.

Creating a simulation environment is a complex and large undertaking, thus the decision to use already existing simulation environments. Opnet [17] and Ptolemy [18], [19] will serve as the simulation environments. The communication scheme between processing nodes on

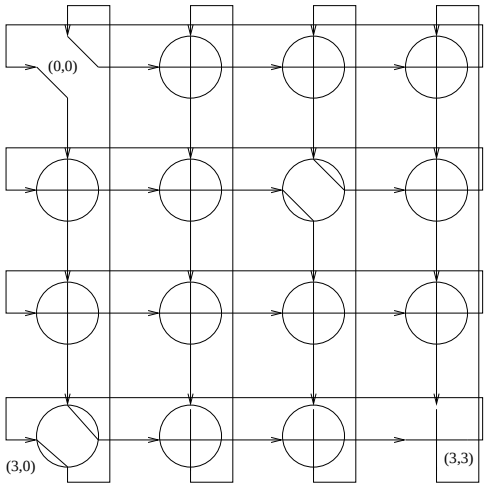


Figure 2.4: Column 0 is the "failure backbone," Nodes (0,0) and (3,3) have failed and are fused into the SR and DR configurations respectively. Node (3,0) forces itself into an SR state (based on information from [13]).

a computational fabric can be simulated in both environments. The entire operation of the system, from the sensor behavior to the processing done on the nodes, can be simulated with Ptolemy, thus covering all the significant aspects of the system.

2.2.1 Simulation Using Ptolemy

Ptolemy provides a heterogeneous simulation environment targeted to the simulation of embedded systems; Ptolemy can represent systems that mix different technologies and devices [19]. Ptolemy imposes some structure on the simulated systems. The components simulated have to be encapsulated in Ptolemy actors. The interactions of components are controlled by a "model of computation," with several models provided. The best suited for the system at hand has to be picked before the simulation is created. The different models deal differently with time and concurrency. A list of nine different models of computations are provided in [19] with a description of each model. These models are: Communication Sequential Processes (CSP), Continuous Time (CT), Discrete Events (DE), Distributed Discrete Events (DDE), Discrete Time (DT), Finite-State Machines (FSM), Process Networks

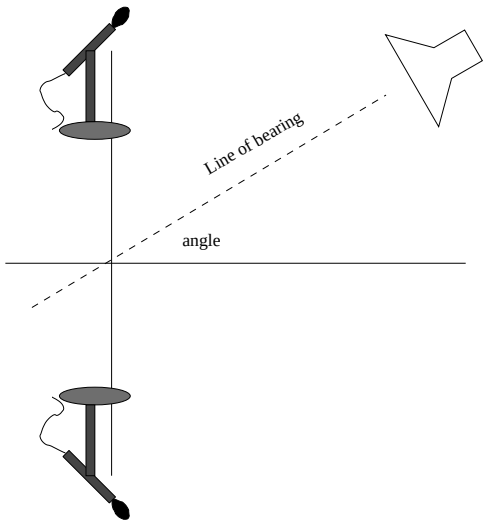


Figure 2.5: Acoustic beamforming is used to determine the Line of Bearing of a noise source.

(PN), Synchronous Dataflow(SDF), Synchronous/Reactive (SR).

An e-textile system is constituted from different interacting components ranging from complex processing nodes to simple acoustic sensors. The high-level simulation and the inclusion of multiple interacting systems in the Ptolemy simulation environment map directly to such a computational system. All of the components placed on the fabric can be simulated as actors and their interactions as one of the models of computation. Significant aspects of the physical world can be added to the simulation; for example, the sound of a passing large vehicle.

2.3 Acoustic Beamforming

The e-textile prototype reports the line of bearing of large vehicles. To accomplish this, acoustic beamforming is used to determine the direction of an incoming noise source as shown in Figure 2.5.

Acoustic beamforming has been used in [20] to locate the source of the speaker for hands-free telephony, and in [21] in a wearable computer system to determine if the speaker is the

user or a person in conversation, differentiating between commands and regular speech. The same principle was used in [22] for sound pickup in teleconference systems.

A low power beamforming algorithm compatible with integer mathematics has been reported in [11]. This algorithm allows changing several variables to vary the accuracy and the power consumption of the implementation. This variation permits different running options and enables testing the trade-off between power and accuracy. The variables are: the number of microphones used to collect the acoustic data, the number of acoustic samples collected, and the number of search angles tested to decide the L.O.B. (Line Of Bearing) of the noise source.

The process used in obtaining the L.O.B. is the following: the signals received at the microphones are time shifted to account for an assumed location of the sound source, these signals are then added and the values recorded; this process is repeated for a predefined number of search angles. The power of the summed signals will increase as the assumed search angle is closer to the L.O.B. and thus the search angle with the most resultant power will be reported as the L.O.B. [11].

The principle of acoustic beamforming can be used to determine the distance between two separate acoustic receivers. The maximum distance between the receivers allowed is the wavelength of the sensed signal. The amount needed to shift one of the signals to get both signals in phase is equivalent to the distance between them. This process is used to find the distance between separate components.

2.4 Computational Fabric Research

The increasing attention paid to computational fabrics is boosting the research done in this area. Emerging practical and useful implementations are helping in this advancement. Industrial and academic research will be discussed in the following subsection.

2.4.1 Pressure Sensing Fabric

ElekSen has developed a soft sensing fabric capable of interfacing to a multitude of devices. ElekTex, the technology released by ElekSen, is a "soft sensing and switching system" that provides digital signals to different devices based on impulses sensed by the fabric [23].

ElekTex thus acts as a smart and durable interface to already extant technology. Some of the off-the-shelf items utilizing this technology reported by ElekSen are the ElekTex keyboard and the Soft cell phone. The fabric in the phone acts as both the input interface and the case.

The fabric can be designed to interact with different components to form a system with a soft interface. The fabric is formed from regular and conductive fiber; the conductive fiber can be made to detect separate areas on the fabric, buttons for example, of "about any size [24]," other than sensing the X-Y position with a possible resolution of up to $1mm^2$. A Z dimension sensing can also be accomplished where the third dimension is the strength of the pressure exerted. Durability testing on the fabric simulated high pressures, folding, tumbling, and tugging, after which the fabric (keyboard in this case) emerged with no faults. The details of the test are available in [23].

2.4.2 Conductive Fiber

Electrical connections in any computational system are a must. With e-textiles, single strand wires can be woven into the fabric, but such wires are not as malleable as natural fiber or as discreet. Conductive fiber available in the market is mostly based on electro-static dissipation needs; the conductivity of this fiber is not great enough to replace regular wire. Conductrol [25] and Guilford Technical Textiles [26] are two examples of companies providing such fibers.

Some research projects have been successful with the use of conductive fibers in their systems. Metallic organza has been used in both the row and column fabric keyboard [4]

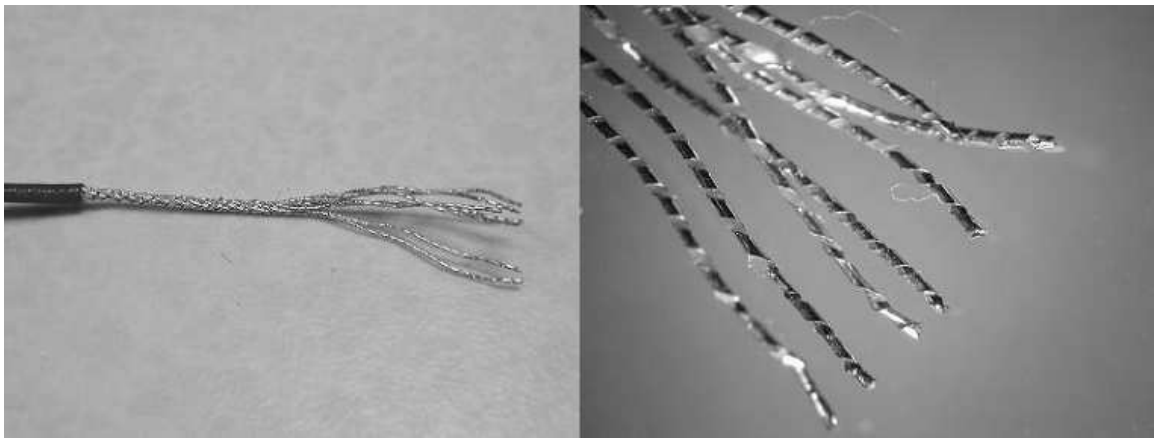


Figure 2.6: The multiple flexible strands in the tinsel wire provides the malleability needed to weave this wire into fabric.

and the musical jacket with embroidered keypad [4]. The keyboard uses direct electrical connections while the keypad on the jacket utilizes capacitance change as a sign of pressing a key [4]. Conductive fibers have also been used in the fabrics discussed in 2.4.1.

Bekintex, a member of the Bekaert group, offers a thread woven from extremely thin stainless steel wires [27]. The resistance of this wire, Bekinox VN, is approximately 10Ω/m. This thread is well-suited for computational fabric applications due its low resistance and malleability. Low resistance is needed to provide connections for power and communication channels. This wire is composed of stainless steel which renders it impossible to solder. This wire can only be used with mechanical connectors.

A middle ground between regular copper wire and the Bekintex wire is reached with tinsel wire. This wire is malleable enough to be weaved in a fabric and it can be soldered. The multiple strands in this wire are shown Figure 2.6; this wire is insulated with a detergent-resistant coating.

2.4.3 Wearable Computing and Computational Fabrics

Wearable computers promise to provide unobtrusive computing to the user, but to date most wearable computers are bulky and cumbersome. Most users would not appreciate the need to carry a backpack or components with significant bulk. Recent research has been addressing these needs [28], [29], [30], [31], [32].

In the following sections, the computer system is separated into the areas of, input, output, processing, power, and sensing devices, to allow for examination of e-textile progress in each area.

2.4.3.1 Direct Input Devices

Many research efforts have been directed at making the direct input from the user less obtrusive and more conformant to regular life activities. Some of the efforts focus on discarding the need for the input device to be held. Sensing the movement of the fingers is one promising research direction; examples of such research projects are:

- Lightglove: this system detects the motion of the fingers by sensing reflectance off the fingers of optical beams sent and received by photosensitive elements located in a wristband [28].

- The active dressware research utilizes conductive polymers made to sense the hand and finger movements when worn as a glove [29].

- Combining two mice (track-balls); each trackball controls a pie-shaped input and the combination of the inputs of both trackballs operates as an input device [30].

- A glove input device was created in the Configurable Computing Lab at Virginia Tech with the use of piezoelectric material. The study of the use of the piezoelectric sensors in combination with fabrics in this device is closely related to this dissertation's research [32].

These examples show the direction of research in making wearable computers less obtrusive. The use of computational fabrics in incorporating the sensors needed to sense such inputs and the wires needed to send the signals to the processing node can be of great help in increasing the wearability of the system and making it less obtrusive.

The keyboard approach as an input interface can also benefit from e-textiles. The ElekTex keyboard is an example along with the GesturePad [31]. These keyboards can be hidden inside the fabric with conductive thread sending the output to the processing node.

2.4.3.2 Interconnections Between the Separate Components

Computational fabrics can offer a communication medium using conductive fiber in the textile of the garment. This type of connection will be invisible to the outside world and more comfortable to the user. This will replace the use of regular wire as used in the MIThril [33].

The Georgia Tech Wearable Motherboard (GTWM) [34] is an example of a system in which the interconnections are inherent in the fabric. This system is to be used in a combat situation to assess the seriousness of a soldier's wound and communicate this data. The interconnections in this fabric will detect if a bullet hit the user and determine the location of the penetration. The system offers connections to other discreet components that can monitor vital signs including heart rate and blood pressure. This system is to be worn as an undergarment to offer minimal interference with the soldier's operation.

The GTWM can be used as a PAN (Personal Area Network) where the devices carried by the user can interact and share data [6]. The closeness of the devices to the user in such a system allows the use of sensors in the fabric to learn "habits" of the user and thus to react in different ways to different user situations, which is discussed in further detail in Section 2.4.3.5.

2.4.3.3 Processing Device

The use of computational fabrics with the processing elements is limited to providing connections to the other devices in the system. The creation of switching elements in the distant future in fiber format can provide the basis of creating fabric processing elements. The Macroelectronics Group at Princeton University is working on creating macroelectronics, integrated circuits made by thin film techniques. Macroelectronics are larger than semiconductor wafers but they will be flexible and rugged [35].

2.4.3.4 Power Device

Wearable computing can be considered a direct application of e-textiles. Bulky battery packs will not fit the e-textiles objectives in creating a ubiquitous system. The following section will provide an overview of some power cell products provided in a thin package. Ultralife [36] 1mm battery packs; Infinite Power Solutions provide a film form battery, the LiTE*STAR. The LiTE*STAR is an extremely thin battery with a great cycle life and an all solid-state construction [37].

The development of fiber-form batteries would be extremely helpful in decreasing the bulk in a wearable system. This fabric would be incorporated seamlessly in the e-textile. Textile batteries are being studied at NCSU [38]. The electrochemical synthesis of conductive polymers is reported in [8]. Currently off-the-shelf products are offered as thin batteries from Ultralife [36] for example or film solar cells from Iowa Thin Films [39].

2.4.3.5 Context Awareness

The operation and application of a wearable computer should vary based upon its surroundings. The response to certain actions of the user, gestures for example, should be different depending on the present location/setting of the user [40]. Context awareness depends greatly on the ability of the computer system to sense the surrounding environment. In

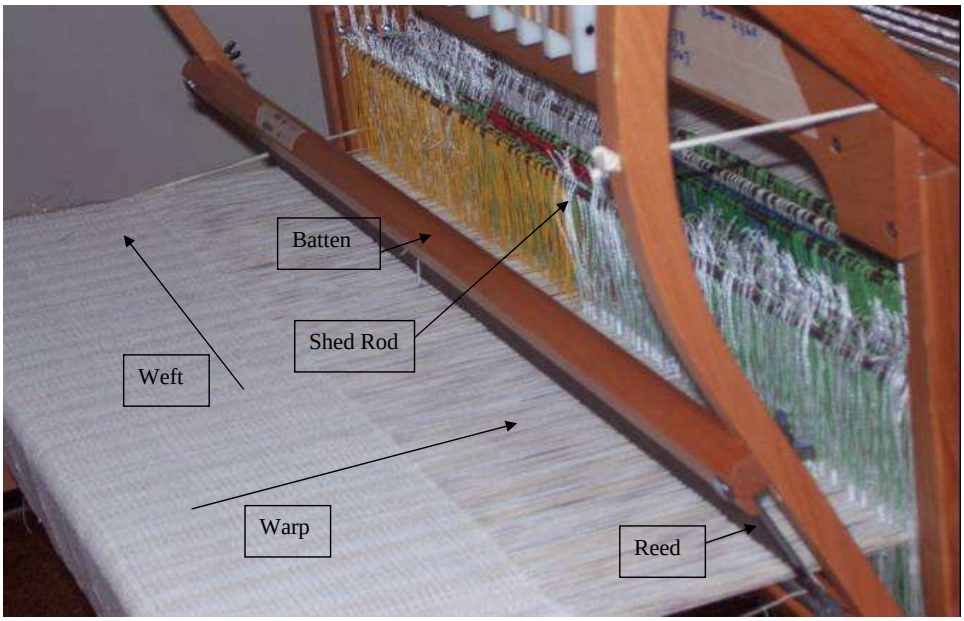


Figure 2.7: The basic loom used in creating the prototypes for this research.

an e-textile application, the sensors (acoustic, motion, video, etc.) will be attached to the fabric and the communication will be provided through the fabric to the processing node. The e-textile can offer the routing capabilities required; the relevant sensors will be queried when the processing node requires data from all the sensors "facing forward," for example.

Computational fabrics will enhance this research area in wearable computing by offering the ability to distribute sensors over the fabric. Different types of sensors can be incorporated at the same time. The system will be able to adapt to different situations with added fault-tolerance. A Sensor Jacket is reported in [41]; this jacket can detect the posture and movement of the wearer with the use of knitted stretch sensors. Machine-learning techniques were used to achieve 2% error in an in-door navigation application with the use of cheap wearable sensors [42].

2.5 Manufacturing Textiles

Hand looms for weaving textiles have existed for at least eight thousand years [43]. The study of the ancient hand looms offers an understanding of the weaving process of fabrics. The following description follows that of [43]. The first set of yarns used are stretched with the use of hanging weights, the weight of the weaver, or between the ends of a fixed frame. These yarns are called the *warp* yarns and after being stretched they are interlaced by the *weft* or *filling* yarns. The filling yarns are pushed over and under the warp yarns, the simplest scheme is going on top and below each stretched warp yarn. Figure 2.7 shows the basic parts of a loom.The filling yarns can be fed with the use of a *shuttle* carrying a bobbin that provides the yarn that needs to be interlaced. Some modern looms use shuttles but faster looms use other mechanisms that shoot the yarn through separated warp yarns [43]. To pack in the newly added *weft* yarn, a comb-like structure, the *reed*, is used to push the *filling* yarn in place. The reed is mounted on a frame, the *batten*, that helps in pushing the reed and keeping it steady; the *batten* is used in the automated looms. Moving the shuttle through a separated set of yarns is easier and faster than going over and under each individual warp thread. The *shed rod* or *heddles* are used to lift specific warp yarns from the level of their neighbors and ease the introduction of the filling yarn. This is a simplified description of the process of weaving which has advanced to increasingly complex looms and techniques but is sufficient for understanding the shape and creation of fabrics for our purpose. Visualizing the process of weaving can help in understanding some of the design decisions we took. The preceding was a short summary of the information provided in [43]. In the designing process, the wires in the warp, as the weaving starts, are permanent, while changes in the weft wires can be made during the weaving.

Chapter 3

Exploring the e-Textile Architecture

The advancement of the textile industry has resulted in a high level of automation along with relatively cheap process of manufacturing. Textiles offer a useful form factor for new electronic technology applications. The formation of a platform for deploying the sensing and processing elements required in a wearable computing system without the use of external wires is much needed. The fabrication of large textiles offers the environment needed for deploying the components for large scale systems. Research initiatives in using electronic textiles as a platform for pervasive computing is presented in [44].

This chapter explores the e-textiles domain. The issues faced will be described along with the temporary or permanent solutions used. Several projects under study will be introduced.

3.1 Motivations for e-Textiles?

The first question asked is, why e-textiles? The following section describes the benefits expected from the e-textile architecture.

3.1.1 Cheap and Large-Area Backplane

Fully automated and large-scale industrial looms make it affordable and easy to create large-area textiles [1]. The textiles are fabricated economically and with precise control. This technology acts as a basis for the e-textile architecture.

Applications requiring large-area systems will benefit greatly from the combination of electronic components and these textiles. This combination will create a backplane to be tailored to economically fit the requirements of each specific application. Other textile properties, flexibility for example, can add to the benefits of such a new architecture. Surrounding a solid object, vehicle, or building, with sensors is easily done by draping the object with a textile "sprinkled" with the required sensors.

3.1.2 Ease of Deployment

E-textile systems are easily deployable, especially for large scale applications. The system can be rolled up into bundles and spread out in the field. In military applications, an enemy-monitoring system can be deployed in a parachute; the fabric of the parachute would be the active element of the system, while the object attached can be just a decoy. User operation in confined areas, e.g., maintenance work on an airplane, can be made easier by the use of wearable e-textile systems to incorporate the equipment and plans needed.

3.1.3 Concealment and Comfort

Integrating the components and their connections into the fabric that constitutes the backplane of the system can be extremely beneficial. In wearable computing systems, unobtrusiveness is highly appreciated along with concealment from the outside world. Concealment is also needed in large area systems, particularly for military and ubiquitous computing applications. With more advanced fiber [23], [27], [38], [8] and packaging technologies [45],

e-textile systems can be made invisible to the outside world.

3.1.4 Fault-Tolerance

Any tear in the fabric can result in severing connection lines, thus the need for implementing alternative communication routes. The manufacturing process and operation in hostile territories can introduce tears in the fabric (communication and power disruption). Destruction of computational nodes and sensors are other faults that can occur during operation. The fabric does offer a less fragile environment than just spreading wires between different components, but is perhaps not as robust to physical faults as a wireless network.

The low cost and the form factor of e-textile systems make it easy to incorporate redundancy into the system. Attaching redundant components does not use up expensive real-estate and extra communication routes can be easily added by exchanging a regular thread with a conducting one.

3.1.5 Power Consumption

E-Textiles can act as an alternative to wireless personal area networks. In such applications, e-textiles offer a reduction in component cost and in power consumption. The savings are derived from a reduction in the number of communicating modules and in the inherently cheaper wired communication. A methodology for quantifying such savings was presented in [46], which showed at least a factor of 14 savings in energy consumption by using an e-textile implementation rather than a full wireless one.

3.2 Implementation Issues

E-Textiles are relatively new and thus lack the support of off-the-shelf products or reliable processes. The following section will discuss some of the issues encountered in implementing applications on e-textile architectures.

3.2.1 Embroidery or Weaving

E-Textiles offer inherent electrical connections for power and data in the fabric, but the issue of how to integrate conductive fibers must be addressed. The first idea explored was embroidery machines. The use of embroidery machines would follow directly from PCB (Printed Circuit Board) design; the circuit for the interconnections would be drawn and a direct mapping done to create the system. Embroidery machines from Bernina [47] and Brother [48] are controlled by computers, with the user providing a digital image of the embroidery. With the use of conducting thread or wire, this process becomes the direct translation of the PCB design in the e-textiles world.

The researchers in [4] were able to embroider successfully for their needs using silk-organza. The high resistance of silk-organza, however, makes data and power transmission difficult. The trials at the Virginia Tech Configurable Computing Lab on standard wires fouled the embroidery equipment. In addition, embroidery is considered to be a fairly expensive process in the textile business.

Another option for integrating the wires is weaving. The first advantage of weaving is the seamless integration of the process in large looms, by replacing some threads with conductive wires. Stainless steel wire from Bekintex [27] or tinsel wire can easily replace thread in the loom; both wires were integrated in e-textile prototypes in the lab. Unlike embroidery, the insertion of the wires is done at the time of weaving the textile and is not nearly as flexible in terms of thread positioning.

With the weaving option, two types of implementations have been explored. The first is a multiple layer textile that uses an insulating layer, allowing uninsulated conductive threads to be used in different layers with the connections between different layers done mechanically by crossing through the insulating layer. The other option is a one layer solution, where at least one of the directions of the wires, warp or weft, has to insulated. Electric connections are more difficult because the insulation at the connection point has to be removed. On the other hand, the one layer option is less bulky, less expensive to make, and avoids possible inadvertent shorts.

3.2.2 Connections and Attachments

The integration of components into the fabric is a driving force behind the e-textile architecture. The components to be integrated vary greatly depending on the application. The perfect situation for e-textiles would be to have all the components in fiber form: fiber microphones, batteries, etc. The fiber form components are integrated into the system in the same manner as the conductive threads. The electrical connection needed for these components can be made using solder. Other techniques, utilizing mechanical connectors for example, are under investigation.

Other components will be attached to the fabric in their discrete, off-the-shelf form. The number of pins to be attached is important and affects the decision on the type of attachment. Some components, e.g. microphones, require minimal connections. These components can be attached directly to the conductive threads with solder or a mechanical connector.

Higher-density components, primarily ICs, require a very tight connecting mesh of lines made possible by PCB boards. Connecting all of these pins directly to the fabric is impossible at the present time. Thus an interface-pin-reducer is needed; for example, a regular PCB board that takes care of connecting the needed ICs for a specific application. The ICs on this board will create a node with minimal connections to the fabric. The node in the acoustic beamformer is a perfect example and it was attached with mechanical means, 2-mm pin

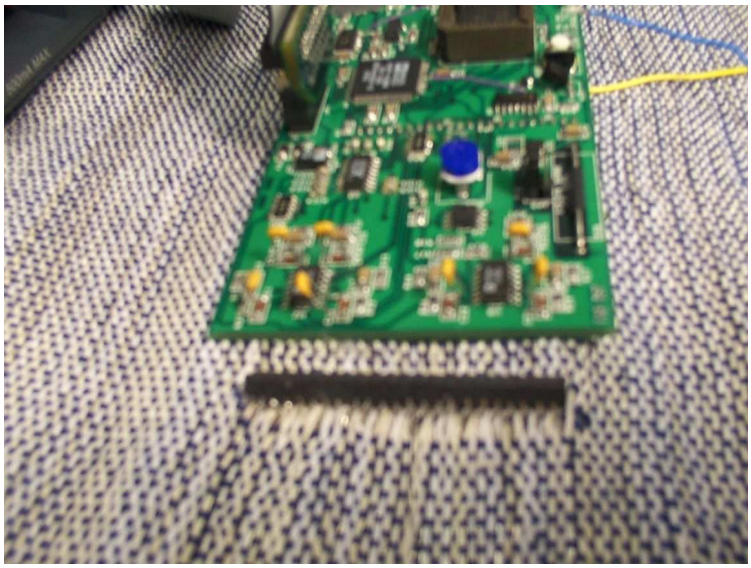


Figure 3.1: 2mm header pin used to connect the board to the prototype fabric

header connectors (Figure 3.1), and solder. Recent technology [45] allows for the packaging of this type of node into foldable layers, reducing their size significantly. This reduction in size helps in meeting the promise of unobtrusive e-textiles.

The use of solder in our prototype with the 2-mm pin headers proved to be time consuming and fragile. This type of connection does not render itself easy for mechanization, and thus the process will be hard to automate to reach a production phase with e-textiles. The proposed connecters will use mechanical means for connections, such as insulation displacement. These connectors are generally formed of two clamping pieces that are easily aligned and clamped in a mechanized fashion. The 3M^{TM} ScotchLok^{TM} Insulation Displacement Connectors (IDCs) are examples of such connectors.

3.3 How to Explore?

Fully exploring a new and undeveloped architecture requires experimentation. Novel applications have been created to serve as an input to further the development of the architecture

and help in creating a set of guidelines to serve as the basis for future research in the area. These guidelines and experiences helped in creating the simulation environment that serves as an enhancer for the current projects and a drawing-board for new ideas.

3.3.1 Prototypes Under Construction

The following section will give a brief description of several projects under development in collaboration between the CCL (Configurable Computing Lab) and the WCL (Wearable Computing Lab) at Virginia Tech.

- **Mapper Garment:** This vest maps the position of the user in relation to the room as well as determines the motion of the user. Ultrasonic sensors are used to find the distance between the user and the walls or objects in the room.

- **Acoustic Beamformer:** This is a large-area application; the fabric has multiple beamforming units along its length. Each unit is a cluster containing a processing node and several acoustic sensors. Each unit can be enhanced with other components for tasks such as communication and location finding. This beamformer is designed to find the location and direction of motion of a large passing vehicle and to report this information. This e-textile is easily deployable, possesses a long field life, and tolerates faults. This application will be studied in detail in Section 3.4.

- **Shape Sensing:** This e-textile can sense its own form. The strategically placed sensors on this fabric sense the "flex" of the shape of the fabric at that location, the combination of the results of all these sensors will result in an overall understanding of the shape of the fabric at a specific point in time. The properties for this type of fabric as described in [40] are of direct application in the wearable computing world, along with applications in physical therapy and even athletic training. A specific implementation of such a fabric in a pants configuration can determine with the use of neural networks if the user is running, standing, or falling. If the person is falling,

the pants could order the deployment of an airbag. Examples of the sensors used are accelerometers and piezo-electric sensors.

- **Vest Beamformer:** Certain wearable computers, operating on audio signals, require the need to distinguish between the user and a person in conversation with the user. This vest uses the same beamforming algorithms implemented in the Acoustic Beamformer, but uses a different configuration of the microphones. The microphones used are located in a straight line along the shoulders as shown by Figure 3.2. Figure 3.2 a) shows the first created prototype; the vest version depicted Figure 3.2 b) is under construction. The creation of this vest had to consider the different sizes of people and provide a way to provide the spacing needed between the microphones for the beamforming algorithm to operate correctly. The Shape Sensing and the Vest Beamformer projects are discussed in more detail in [50].

- **e-TAGS [51]:** This project focuses on the creation of detachable components for e-textile applications. The e-tags will also have their own communication scheme using I^2C [52] allowing for the integration of different e-tags and the ability to create new ones that can be added to an existing project. This work is also investigating the creation of custom connectors for e-textile applications similar to the IDC connectors concept.

3.3.2 Simulation Based on Experience in Prototyping

The work listed in the last subsection surveyed the prototypes that are under construction; the creation of the prototypes led to a better understanding of the architecture and textiles. The prototypes also provided enough data to create a simulation environment. The simulation environment was then used in the development phases of improved versions of these prototypes and it will implement the software aspects of the e-textiles architecture.

(a) (b)

Figure 3.2: The Vest Beamformer is able to locate and distinguish between different audio sources.

The simulation environment provides designers with the means to explore the e-textiles architecture space without resorting to the creation of physical prototypes. This environment also helps in fine-tuning current designs to, for example, reach a better configuration in terms of power consumption or accuracy of results [53], [54]. The design of the simulation environment will be discussed in further detail in Chapter 5.

The process of the development of the e-textiles architecture based on the cycle presented in Figure 3.3 can start at any node in the cycle. Staring with the creation of a concept, depending on the complexity or ease of implementation we can move to either simulation or physical testing and use the remaining step as verification. In the first developments, the concept of the beamformer was the starting point, the hardware was then created for lack of any other means, and last moved to creating the simulation environment. This environment was then used to fine-tune the hardware. A new project would be started by the creation of the concept, simulating the process, and finally physical implementation. In the same way, during simulation, a new concept can be conceived, designed, and implemented in hardware.

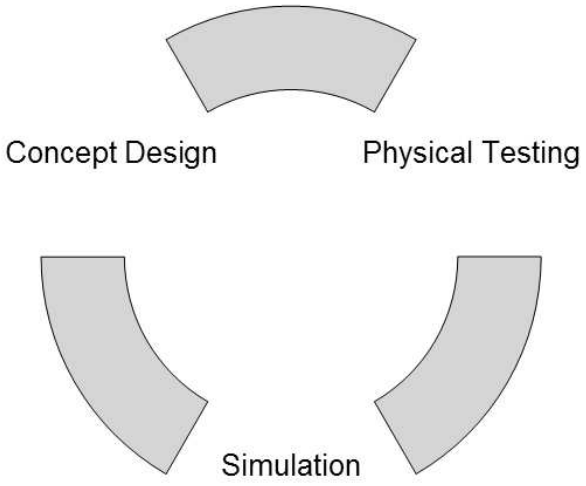


Figure 3.3: The relationship between the theoretical concept, simulation, and prototyping follows the cycle shown in both directions and at any starting point.

The same applies in a physical testing ⇒ concept design ⇒ simulation ⇒ physical testing cycle.

3.4 Acoustic Beamformer Prototype

The following section discusses the implementation of the beamforming array. The architectural nomenclature, node creation, component connection, and the prototype construction will be presented. The software running in the processing nodes will be introduced.

3.4.1 Acoustic Beamforming Array

The implemented system collects acoustic data from several microphones, converts the analog data to digital format, and runs a beamforming algorithm to determine the line of bearing of a large vehicle. The computed value is communicated to peer systems or the outside world. Operation in hostile territories requires the implementation of fault-tolerant schemes; for example, this system is augmented with seven sensors when only three sensors are absolutely

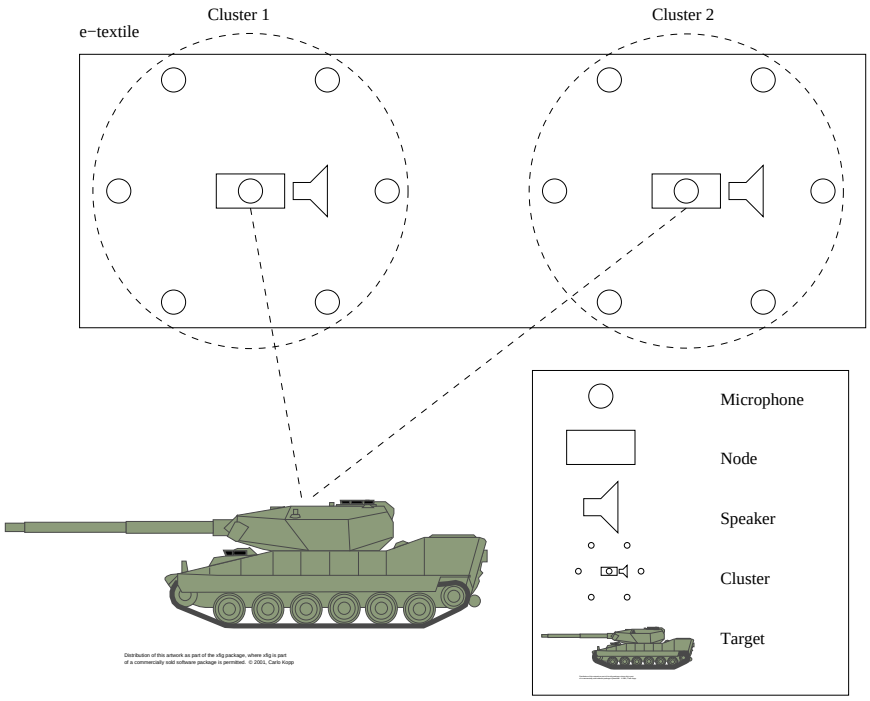


Figure 3.4: A conceptual rendering of a computational fabric with two acoustic array clusters.

needed to provide the information needed for the beamformer [3]. The following definitions will be used throughout the discussion. A *node* is the processing component, it is able to gather information from the acoustic sensors, convert it to digital format, compute the direction of the vehicle and communicate the result. A *cluster* includes the node and the sensors directly connected to it. A cluster can operate as a stand-alone system and provide useful information independently. An *acoustic beamformer* includes one or more clusters. Such a system will benefit from the redundancy in fault-tolerant schemes and in improving the computed result. The angle result computed at every cluster can be combined to provide position data via triangulation. Figure 3.4 shows an abstract view of the introduced terms.

The fabric is the platform where the components of the system are deployed as shown in Figure 3.5. The placement of the several components on the fabric initially deals with the textiles as a planar structure. Figure 3.6 shows the plan used to implement the conductive wires along with the positions of the components when the fabric is held in a plane. This

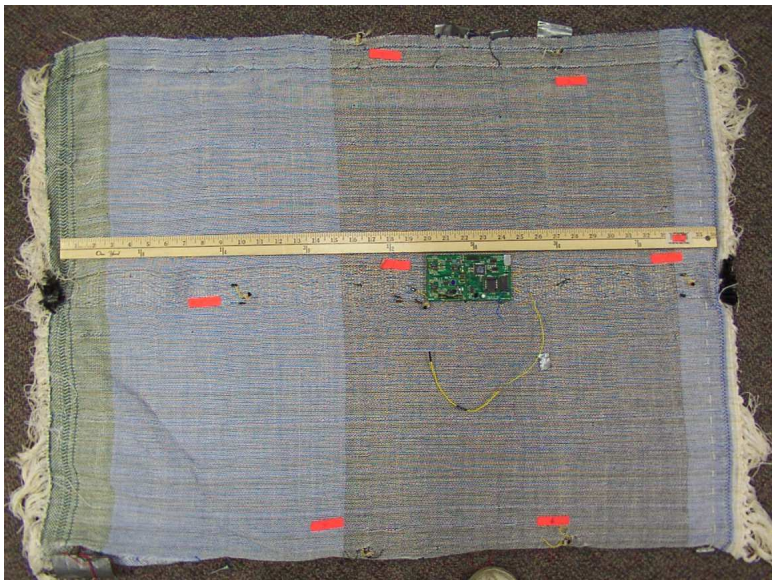


Figure 3.5: The implemented Acoustic Beamforming Array (one cluster) shown on a multi-layer fabric.

diagram was used to help the weaver in creating our fabric prototypes that resulted in the acoustic beamformer.

In any stand-alone system, power is a major issue. Battery replacement is an impossibility or a highly improbable luxury; thus, sensing operations on battlefields necessitates power efficiency. The tasks implemented and the hardware operation should be power-aware; using approximations and pushing the processors into dormant states. The software running on the nodes in the implemented 30-foot fabric can force the hardware to a dormant state, the node will wake up only when there is a significant acoustic signal. A node in this system can also be awakened by another node in the system by sending a data packet.

3.4.2 Hardware and Software of the Processing Node

The hardware processing node in the acoustic beamformer was designed for this specific project. The experience gained from its creation had a more general effect. The implemented interrupt-driven software guided the simulation effort as will be discussed in Chapter 5. The

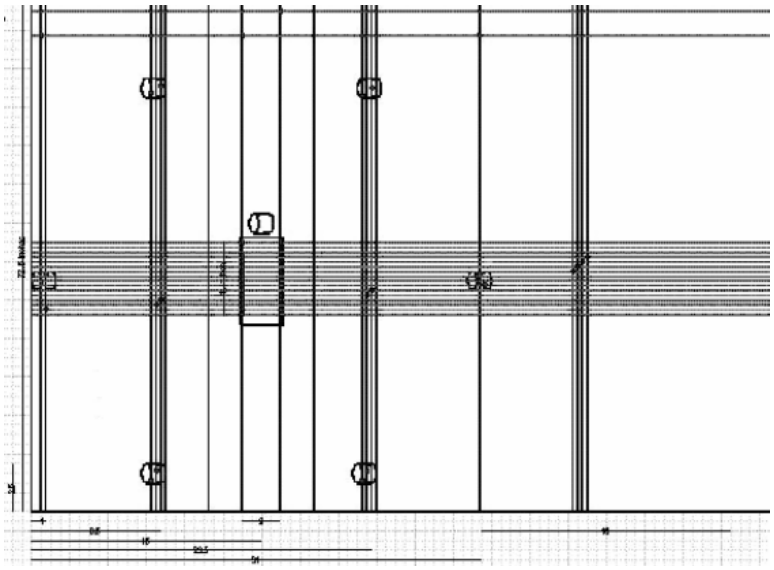


Figure 3.6: The textile schematic of the Acoustic Beamformer shown with one node and seven microphones along with the conductive threads in the fabric.

hardware design provided significant experience in printed circuit board design, and mixed-signal circuit design.

Figure 3.7 shows the block diagram of this node. The ADSP-2188 [55] is a low-power fixed-point processor with enough memory space and interrupt handling capability to deal with the acoustic data collection and the L.O.B formation. The board is also equipped with a hardware wake-up scheme that sums the acoustic data and sends a wake-up signal to the processor if a certain "loudness" threshold is crossed. The software running on the DSP (Digital Signal Processor) is downloaded with the use of the flash memory, and the output of the beamforming is communicated through a serial port.

The whole process on the board is controlled by a timer interrupt that acts as the lowest granularity of events that can occur. This timer interrupt signals the A/D to acquire data and this data is communicated to the DSP. Data transmission and reception from the A/D are controlled by interrupts as all the other aspects of this software. Data acquisition continues until a pre-determined buffer size is filled and the beamforming code is instantiated; the results are then computed and communicated.

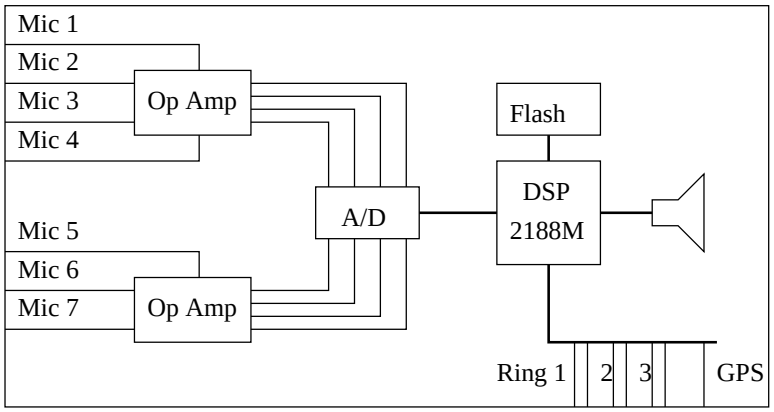


Figure 3.7: The block diagram of a node shows the interface with the fabric along with the inner connections

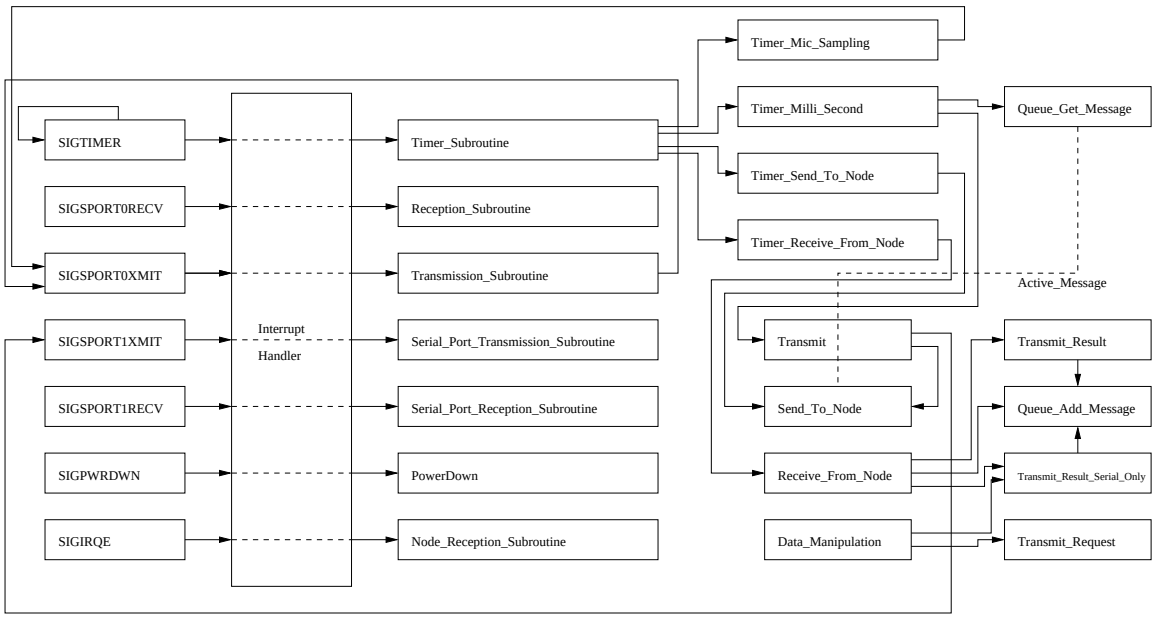


Figure 3.8: The software block diagram shows the interaction between the interrupts handling routines and the other functions in the node software.

The DSP has two generic serial ports, one is used to communicate with the A/D and the other with a host machine. Sending data between nodes is done with the help of flag pins; every character to be sent is encoded in a fashion similar to RS-232. The flags send out their values using the timer interrupt as a synchronization. The reception side is more complex. Each incoming data line is tied to an interrupt and a data pin (RAM data pin). At the reception of the first bit (forced to be a 1), the interrupt signals the reception of data and is disabled until the end of the reception, and the DSP reads the data as if reading from its memory. The memory reads are also synchronized with the timer interrupt. All nodes have to run the timer interrupt at the same frequency. A more advanced node would use a DSP with more communication ports to enable the use of I^2C for example. Data packets are controlled with the use of a general message queue. This queue stores all the packets that need to be communicated and controls transmission in a FIFO (first-in first-out) fashion. Figure 3.8 depicts all the interacting parts of the software including the interrupt handlers. A specific path in this diagram will be scrutinized in detail in Chapter 5 to show the operation of the simulator alongside the operation of the hardware.

Chapter 4

Electronic Textile Architecture

The work described in Chapter 3 provided the input to create the basis of the *Electronic Textile Architecture*. This architecture will derive its precepts from the previous experiences and show possibilities for future directions. These directions will later be either positively proved as precepts or negatively dismissed as were previous attempts. This section will provide an overview of the created precepts and the discarded attempts in relation to tasks in the creation and implementation of an electronic textile system.

4.1 Embedding of Conductive Channels

An electronic textile is defined as a set of sensors, processors, and actuators embedded in a fabric backplane interacting to serve a specific goal, with all communication and power lines integrated in the fabric. The integration of the communication and power lines is integral to the architecture. This section will discuss the discarded attempts, precepts, and open issues of the architecture.

4.1.1 Embroidery vs. Weaving

Using weaving as the method for incorporating conductive channels in an electronic textile was discussed in detail in Section 3.2.1. The conclusions from our experience are:

- **Precept:** Weaving will be used to incorporate conductive channels. The locations of these channels will be determined at the outset of the weaving process. Weaving dictates an X-Y structure in the network.

- **Attempt:** Embroidery did not prove successful for the type of conductive elements we are using in this architecture. The embroidery machines were jammed by the used conductive channels.

4.1.2 Uninsulated vs Insulated Conductors

The choice between insulated and uninsulated wire or conductive channel (will be referred to as wires until the end of the section) has a great impact on the direction and the design decisions to be taken. Uninsulated wires provide ease of connection but at a cost. In our implementation of a beamforming cluster using uninsulated wires we implemented the fabric in multiple layers; two layers carrying wires either along the length or width of the fabric and an insulation layer between them. The connection between wires on separate layers goes through the insulation layer and is fixed mechanically. This type of connection proved to be unstable. The uninsulated wires provided short circuit risks if the fabric is subjected to crumpling. Another problem with uninsulated stranded wire is the "fraying" of the strands as these wires undergo the weaving process in a loom, creating the potential for short circuits.

The use of insulated wires provides the ability to use single layer fabrics, much simpler to manufacture, but there is the issue of removing the insulation when a connection is needed. The method of connecting to these wires will be discussed in Section 4.2.1.

- **Precept:** Use insulated wires to simplify the manufacturing of the fabric while devising

better wire connection techniques.

- **Attempt:** Use of uninsulated wires was not successful for the above mentioned reasons.

4.1.3 Conductive Material

The different types of wires in an electronic textile has been discussed in detail in Section 3.2.1. The conclusions are as follows:

- **Precept:** The properties of the tinsel wire combines flexibility, conductivity, and solderability. The insulation on these wires is detergent resistant and thus can withstand cleaning the fabric.

- **Attempt:** Single strand wire did not provide the needed flexibility and at high gauges it was susceptible to breakages. The Bekintex wire has a tendency to "fray" which can introduce short circuits.

- **Open Issues:** More research and experimentation is required on the use of conductive polymers to determine their utility in carrying power, analog data, and digital data.

4.1.4 Analog vs Digital Signals

The question of sending analog or digital signals on the wires is application dependent, but there are aspects that can be generalized. Analog transmission is more prone to noise and interference, but we were successful with the acoustic beamformer due to the low sampling rates and the low communication speeds on other lines in the fabric. Interference will have a higher impact in a motion sensing vest, for example, that incorporates cameras and/or antennas.

Using digital communication for all the signals on an electronic textile will provide a more stable system, along with pushing analog processing of the data closer to the sensors. The

processing nodes will only receive digital signals in this setup. Using I^2C, for example, for all signal communications eases the general design of the system. When a specific standard is tested and then used for all consequent applications, the number of variables in a system is reduced. For example I^2C forces the use of four wires for any communication channel, thus any channel in the fabric should consist of four wires throughout. Digital transmission, on the other hand, adds the cost of analog/digital conversion and communication hardware to each sensor.

- **Precept:** Digital transmission should be used for all of the signals on such a system.
- **Attempt:** Analog transmission can also be used, but is not recommended.

4.1.5 Communication Busses

Following the previous discussion, digital signals will be used throughout an electronic textile system. The use of I^2C busses throughout helps in standardizing the layout of the fabric as can be seen in Figure 4.1 which represents a unit of the fabric used in creating the textile component of the Shape Sensing project [50]. The wires are implemented in sets of four to carry all the signals of the busses, and these busses are repeated to generalize the fabric created and to provide support for future endevours using the same fabric. The fabric used in the Acoustic Beamformer was specifically designed for that project and cannot be configured for other implementations.

- **Precept:** Use a standard bus communication method for all signals in the fabric to help in generalizing the fabric design.
- **Attempt:** Design the fabric for the specific application results in a loss of re-usability.

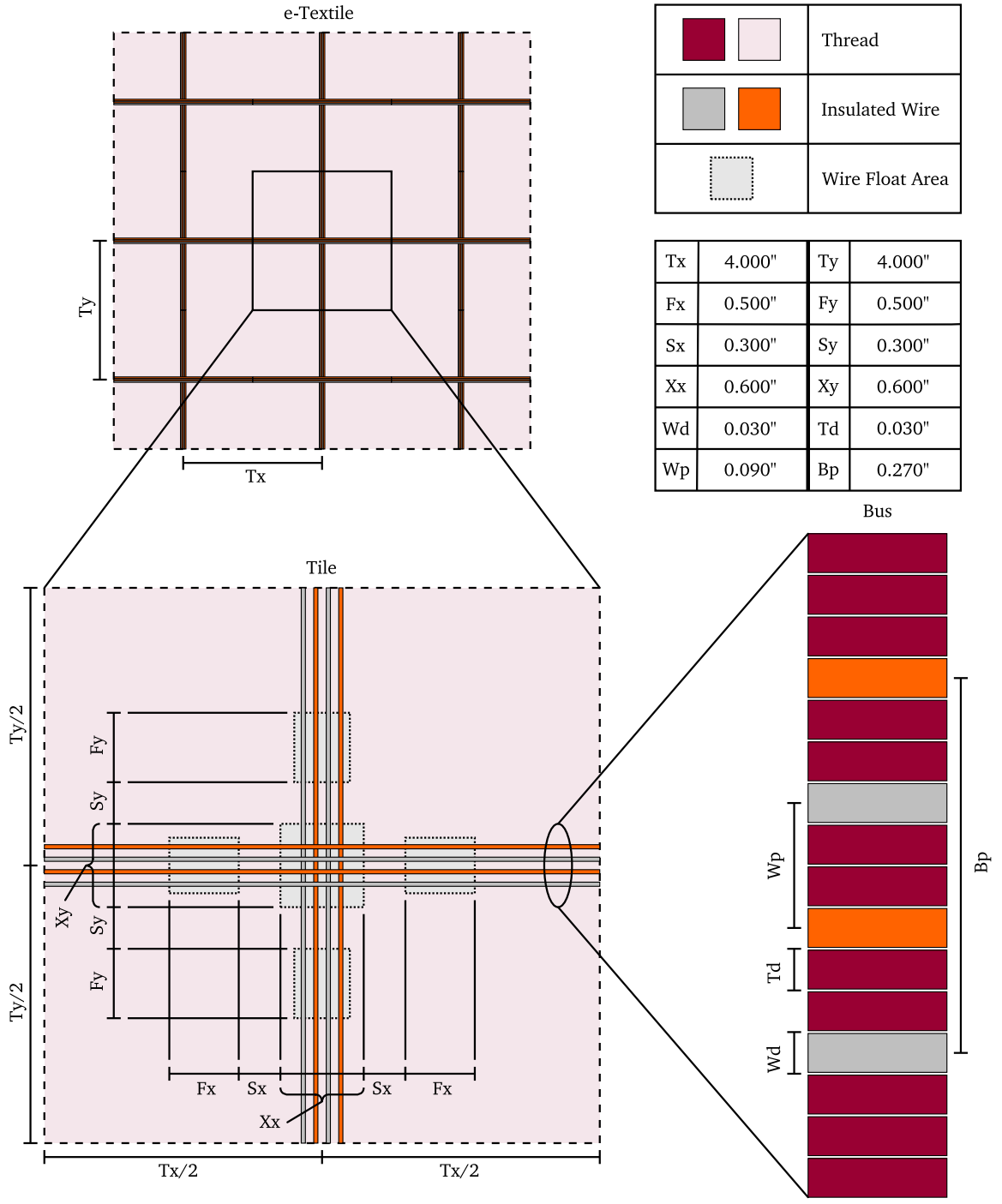


Figure 4.1: Schematic of a unit of fabric of the textile used in creating the shape sensing pants [56].

4.2 Manufacturability

The following section will discuss parts of the architecture that will help in creating a manufacturable electronic textile. The issues discussed address component/fabric connectors and a more general node design.

4.2.1 Fabric/Component Connectors

The connection between the components of the electronic textile and the fabric is harder than the straight-forward problem it seems to be. The following subsections will discuss the approaches used in the Acoustic Beamformer and the Shape Sensing projects and will provide insight into the creation of the needed connectors.

Soldering vs. Mechanical Connection

The first approach used with insulated wire was the use of standard 2mm header pins, stripping the insulation off regular wires and soldering. The solder is not flexible and when used on the fabric it was prone to breaking and open circuits. Solder also cannot be used with the stainless steel wire. Another approach was the use of conductive epoxy which provided the needed flexibility but it proved cumbersome and did not provide the needed strength for the physical connection. Mechanical means of connections with the use of knives to remove the insulation seem to be the best solution. These connectors can work with many types of wires, provide the needed physical support, and are easily mechanized.

- **Precept:** Use mechanical means for connections similar to insulation displacement connectors (mechanized connectors still need to be designed).
- **Attempt:** The use of solder or conductive epoxy was not totally successful nor totally merchandisable.

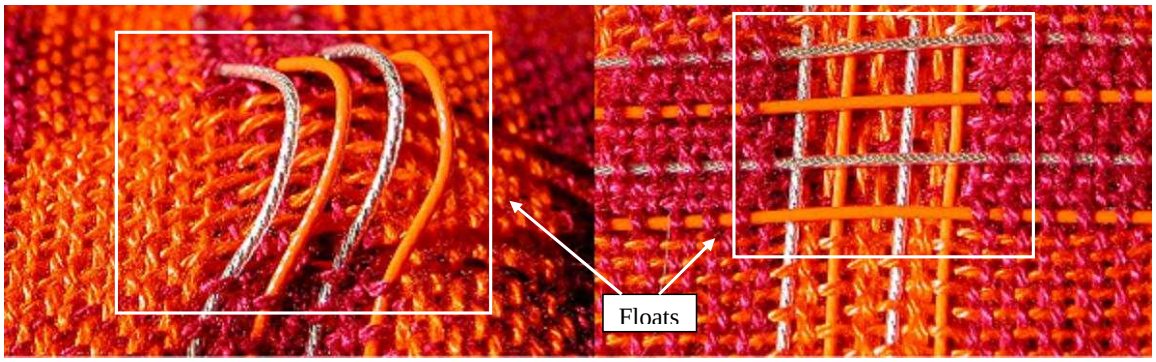


Figure 4.2: The wires will float at multiple intervals to provide for easier placement of the connectors.

Introduction of floats

Following the use of mechanical means for connections, and the need to generalize the fabric manufacturing process by designing repeatable swatches, floats are introduced. Floats are areas where the wire floats above the thread yarns; they provide access for sliding a mechanical connector underneath the wire it has to crimp as shown in Figure 4.2.

- **Precept:** Introduce floats at regular intervals to ease the introduction of connectors.

4.2.2 Repeatable Fabric Swatches

Designing a fabric for manufacturing has to follow the trend towards generality in the design. Creating the schematics for very large fabrics along the whole dimension of the fabric is a time-consuming task. The creation of a repeatable pattern of threads and wires is more adaptable to a manufacturing scheme. An example of such a design is shown in Figure 4.1.

- **Precept:** Design e-textiles based on a repeatable fabric swatch.
- **Attempt:** Designing a unique schematic for the whole fabric is a time-consuming task and does not map well to manufacturing techniques.

4.2.3 Smaller More General Nodes (Beamformer vs e-TAGS)

The design direction of sending all signals on digital busses spread in a regular pattern over the textile pushes the design space into the creation of more general processing nodes. There will be a need for sensor data processors that will convert the analog data and provide the communication interface. The generalization of these nodes will lead to the manufacturing of "sensor nodes" that can be tuned to the specific sensor. This path diverts from the first approach of designing a specific node for a specific job as was done with the Acoustic Beamformer. The same concept can be applied to the processing nodes. The creation of the more general nodes will decrease the price of manufacturing and designing by using a mass production approach, and will map better to the approach of standardizing all signal transmissions on these systems. This approach is under research in the e-TAGS project [51].

- **Precept:** Move to generalizing the nodes in the electronic textile.
- **Attempt:** The creation of specific nodes for specific jobs is too expensive.

4.2.4 Classes of Nodes

With the development of the electronic textile architecture and technology, two classes of nodes will arise. Sensor nodes that use simple microcontrollers will become smaller and will ultimately be integrated in the fabric. Communication hubs and processing nodes will get more powerful with technology advances.

- **Precept:** The architecture can be used to develop applications that will map to predicted technology advances and to the different classes of nodes.

4.3 Software

This section will provide the aspects of the software part of the the architecture. These aspects are provided in the simulation environment. The implementation in the software environment forces the simulated processes to follow these precepts by using the provided services.

4.3.1 Interrupt Driven Processing

An electronic textile system will most probably deal with sensing certain physical phenomena and react according to pre-determined procedures. Interrupt driven processing maps directly to such a situation; a processor will not process unless it receives data (interrupt event), sensor nodes will not report unless there is a significant action (interrupt event) and so forth. The simulator provides a core simulator of a processor that is able to process interrupts and respond accordingly. The simulated operation of the system can easily be moved to a hardware installation with an interrupt driven processor. This applies to the ADSP-2188 used in the Acoustic Beamformer and the microcontrollers used in the e-TAGS.

- **Precept:** Interrupt driven processing maps to the hardware process and the sensed phenomena and thus will be the processing model used in the architecture.

4.3.2 Fault-Tolerant Communication Scheme

The use of electronic textile systems in harsh environments will introduce faults in the system. Such a stand-alone system should be able to withstand such faults and continue operation perhaps with decreased functionality. The electronic textile architecture will provide a fault-tolerant communication scheme that will route around faults. The network will be discussed in great detail in Chapter 6. The provided network will also map to the X-Y topology of a weave and provide the support for “sleeping” nodes.

- **Precept:** Provide a communication scheme that maps to the geometry of the weave and provides a fault-tolerant scheme.

4.3.3 Human Motion Databases for Prototyping

The electronic textile architecture provides the ability to simulate a textile. For wearable systems, this architecture will provide the ability to test the design on a large number of people through the use of human motion databases available from [57], for example. An operational testing phase follows the creation of a prototype. The results of these tests are more credible because of the large number of test subjects. This architecture provides means for testing an e-textile prototype by using these human motion databases and thus providing access to a large number of test subjects to verify the operation of the prototype or its concept.

- **Precept:** Use a larger number of subjects to better test the prototype during both the conception and development stages.
- **Attempt:** The lack of ability to test a system before it is created in hardware can prove to be expensive, and testing on a small population can present misleading or biased results.

4.3.4 Component Distance Finding

The shape of an electronic textile system can change during its operation, thus causing the distances between the components in the system to vary. The importance of this variation is application dependent. The hardware implementation of the distance finding process was achieved. The full integration into the architecture will be accomplished at a later stage for the specific applications.

- **Precept:** Integration of distance finding capabilities into the electronic textile architecture will be done for applications where it is crucially required. The current prototypes have not required these capabilities.

The electronic textile architecture provides a structure and a path to be followed by new prototype endeavors. This architecture also provides a simulation environment to test concepts and improve extant hardware applications. A direction towards generality in the design to reach a more manufacturable technology is also conveyed; the weave design should allow for the creation of multiple sizes and types for different applications. Using a standard communication scheme, for example, will help in simplifying the hardware nodes and the communication portion of the design.

Chapter 5

Simulation

Our goal is to create an e-textile architecture that is accessible to future researchers. At the outset of a project, implementing every aspect of an e-textile system in hardware can be expensive and time consuming. Creating a software environment that simulates the operation of e-textile systems can be extremely beneficial by allowing the design space to be explored without having to build a prototype. Such a simulation environment can be used to enhance the performance of extant systems as well.

Writing a simulation package from scratch is a major task and thus we decided to use an available one. Ptolemy [19] was chosen because it is designed to simulate heterogeneous and embedded systems. The created environment will be discussed by showing its operation in regards to the system described in Section 3.4. This chapter will describe the different aspects of the simulator and will demonstrate its general usability, Section 5.1. With Ptolemy we are able to simulate the interaction with the outside world and the response created from the e-textile system. This chapter will discuss the simulation of the acoustic signals created by a large vehicle at a specific location with respect to each microphone, Section 5.2. The discussion will also cover the simulation of computing the result of the beamformer code, Section 5.3 along with the operation of this code while communicating with other nodes in the system Section 5.5. Power consumption is another aspect that the environment

reports to help in evaluating e-textile stand-alone systems, Section 5.4. The disucssion of the communicatgion simulation is provided in Section 5.5. The integration of the fault simulation and the communication scheme is discussed in Section 5.6 The creation of a hybrid mode of simulation will also be discussed, Section 5.7; this mode allows the simulation environment to interact with the actual hardware of the simulated system in a full or partial manner. This mode helps in grounding the results obtained. Finally, Section 5.8 discusses fine-tuning the Acoustic Beamformer using the simulator.

5.1 Simulator Architecture

The simulation environment simulates different aspects of an e-textile system and the physical world it interacts with. The following is a listing of the simulator parts that deal with these aspects:

- **Physical World:** This represents the simulation of the physical world that is sensed or interacted with by the simulated e-textile prototype. Simulations of the physical world are usually done in the CT domain (Continuous Time). This simulator interacts with the interrupt handling core to mimic the operation of a hardware system. Simulation of the physical world also includes simulating the faults that occur on the fabric and provide the disruptions in power or communication caused by these faults. The faults simulation is controlled by the DE domain (Discrete Event).

- **Interrupt Handling Core:** According to the developed precepts on software, the core of an e-textile prototype operates using interrupt driven processing. This model of operation is provided in the simulator along with interacting with the physical world simulator. This simulator is managed by the DE domain (Discrete Event) and provides its operational states to the power simulator to create power consumption values.

- **Power Simulation:** The power simulator collects the power state information from the core simulator. By tracking the states of operation the power simulator provides power consumption values in the whole system. This simulator is controlled by the DE domain (Discrete Event).

5.2 Physical World

The discussion of the physical world simulator will follow the simulation process of the Acoustic Beamforming Array. Every node on the array processes acoustic data received by its microphones. The first step in the simulation is creating these acoustic signals according to the simulated position of the vehicle. The acoustic signals are attenuated and phase shifted according to the location of the microphones on the fabric. The details of creating these simulated signals are provided in [53]. The Continuous Time (CT) domain was used to simulate the position of the vehicle and the created acoustic response at each microphone. This data is passed to the interrupt handling core at the request of the simulated node. The operation of the node is controlled by the Discrete Event (DE) domain as discussed in Section 5.3. Ptolemy provides the ability to combine simulators running in different domains; a list of these domains was provided in Section 2.2.1. The simulation of the physical world includes information about faults (fabric tears) that can be induced in the fabric; that aspect of the simulation will be discussed in Section 5.6.

5.3 Interrupt Handling Core

The interrupt handling core was used to simulate the operation of the DSP part of the Acoustic Beamforming Array. The current hardware acoustic beamformer includes four independent *cluster*s that can provide a line of bearing for a moving vehicle. Each cluster depends on the processing *node* for the computation of the line of sight. The implementation

of this prototype was discussed in detail in Section 3.4.

The simulator for this beamformer duplicates the operation of the *node*, which include: acoustic data collection, computation of the line of bearing, communication with the other nodes in the system, and triangulation of the obtained lines of bearing (from separate nodes) to determine position data. The simulator for the node reports a power state so that the power simulator can calculate the power consumed; the implementation of the power simulator will be discussed in more detail in Section 5.4.

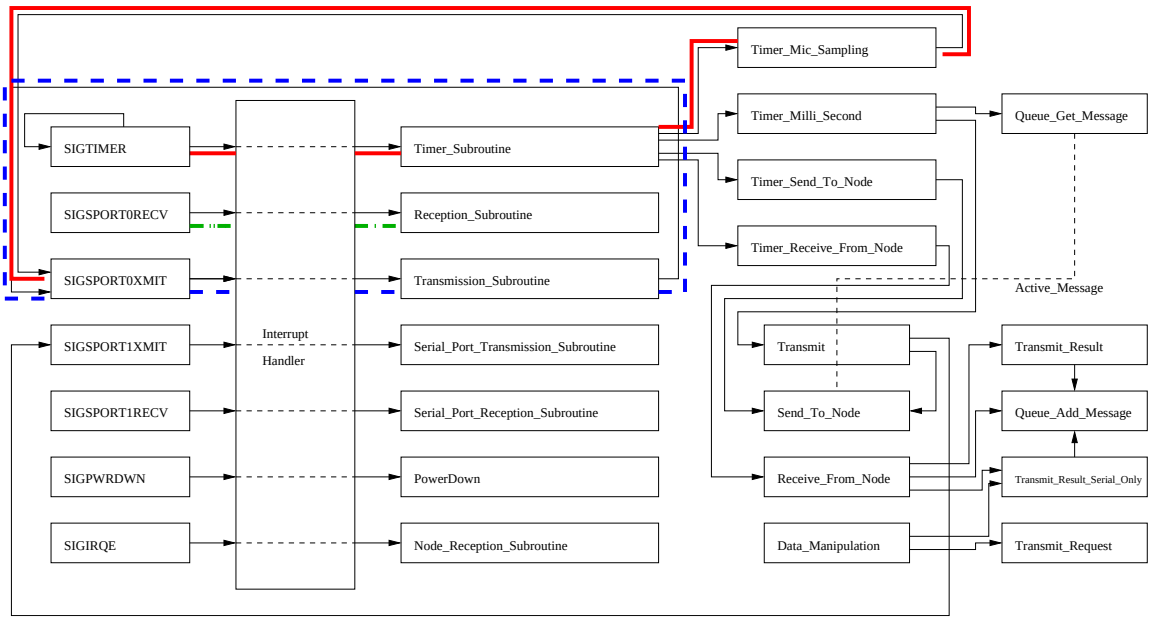


Figure 5.1: The abstract implementation of the simulator includes C code from the hardware implementation, JAVA code from the Ptolemy environment, and the JNI (Java Native Interface) [58] in between (Interrupt Handler). The thick lines highlight the advancement through the code following the description in Table 5.1

Ptolemy provides a heterogeneous simulation environment targeted at the simulation of embedded systems. Ptolemy can represent systems that mix different technologies and devices [19]. This environment imposes some structure on the simulated systems; the components have to be encapsulated in Ptolemy actors and the interactions of these components are controlled by a "model of computation," with several models provided. The acoustic beamformer simulator (interrupt handling core) utilizes the DE (Discrete Events) model.

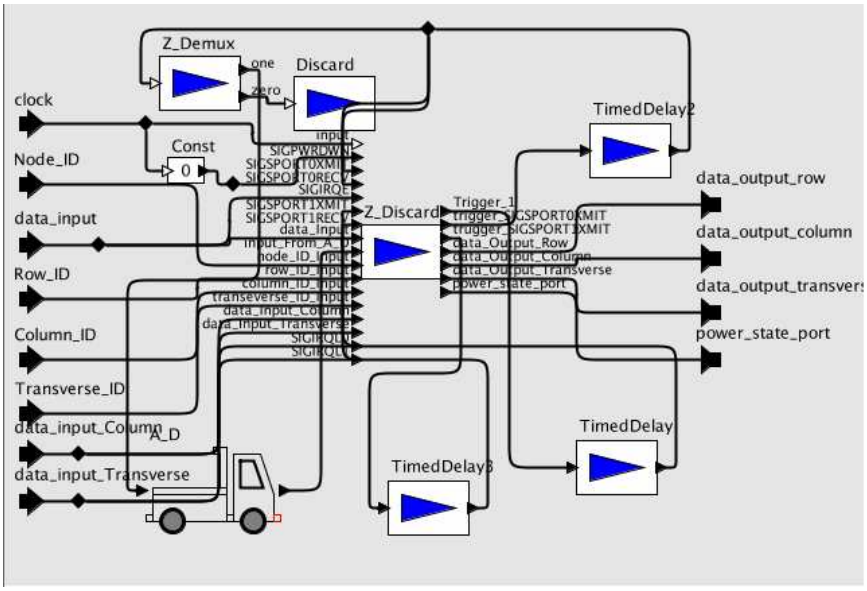


Figure 5.2: The node simulator in Ptolemy, this node connects using ports to other nodes in the network and interacts with the acoustic data simulator (truck).

The DE domain matches the interrupt-driven operation of the DSP in the *node*. This model governs the timing of events occurring in the simulation environment. These events include: timer interrupts, acoustic data collection, and line of bearing communication.

The Ptolemy environment is written in JAVA and so are the actors to be created by the users. The generation of the line of sight and interrupt handling at the DSP are implemented in C; the JNI is used as a link between them and the actor simulating the DSP operation in Ptolemy. Figure 5.1 (repetition of Figure 3.8) is a block diagram depicting the code implemented on the *node*. Each block is either implemented in C (native code from the DSP implementation) or Java (code simulating the operation of the DSP code in the hardware implementation and the interface between the Ptolemy environment and the other simulation elements). The number of interrupts implemented and their names are specific to the DSP used, the Analog Devices ADSP-2188, but this environment, the interrupt handling core, can be used as a general interrupt-driven processing element simulation. The whole simulation is driven by a periodic signal (Timer interrupt in this case); it checks for interrupts received and services these interrupts according to a pre-specified priority scheme. This simulation

aims at proving functionality and providing a power consumption estimate for the prototype. The *node* simultor in Ptolemy is shown in Figure 5.2.

The operation of the simulation will be explained by focusing on a small but representative part of the code and discussing it in detail. The acoustic data collection shown in Table 5.1 will be used as this representative part because it uses most of the aspects of the simulator implementation.

5.4 Power Simulation

Rate of power consumption is a crucial measure in stand-alone applications. Simulating power consumption provides a useful means of varying the operation of an application to reach a more efficient performance in terms of consumed power. Each processing node can be operating in one of a set of operation phases. The interrupt handling core reports these states to the power simulator.

In the Acoustic Beamforming Array, the processing node can be collecting data from the microphones, performing the beamforming operation, communicating with other nodes in the fabric, or waiting in the idle state. Physical measurements were performed to collect the power consumed in these phases. Using these basic values, the parameters of the system can be changed such as number of microphones and the power consumption values simulated. Each node in the simulation provides information about its processing states, a power tracker tracks these changes and based on the measured values computes the power consumption of the system. Multiple tables in [54] document this simulated data. These tables provide information about the operation of the prototypes under varying circumstances. The Acoustic Beamforming Array was the prototype in [54].

This simulation environment was used in [46] to provide energy consumption values while varying system parameters.The large increase in power consumption values when using wireless communication, reported in [46], shows the advantage of using e-textiles in large-area

Table 5.1: Acoustic Data Collection

Block	**Implementation**	**Function**
SIGTIMER	Ptolemy	The timer interrupt is created in the DSP by a dedicated counter. A clock is used in the simulation environment. This timer controls all the processes in the simulation (and hardware); specifically triggering the request for acoustic data.
Interrupt Handler	JAVA	This block simulates the interrupt handling in the DSP, it keeps a record of the received interrupts until served and branches to the required subroutine. The acoustic data request (transmit and receive) interrupts are handled here.
Timer Subroutine	C	The Interrupt Handler branches the operation to Timer Subroutine when the SIGTIMER interrupt is to be handled. This subroutine triggers all scheduled events including the request for the acoustic data.
Timer Mic Sampling	C	The branch inside the Timer Subroutine that deals with sampling the acoustic data.
SIGSPORT0XMIT	Ptolemy	The interrupt received at the transmission of the acoustic data request.
Transmission Subroutine	C	Sends the request for data from the mic that will be sampled next.
SIGSPORT0RECV	Ptolemy	The interrupt received at the reception of an acoustic data word.
Reception Subroutine	C-JAVA	Receive the data from the queried mics and keep track of filling the buffers of the acoustic data

sensing applications. A study of prolonging the operation of the Acoustic Beamforming Array by changing the number of power sources and dealing with faults in the power lines and the processing nodes was presented in [54] using this power simulator. The simulator descibed in Section 5.3 was used in conjuction an actor providing the fault information (Physical Model) and another actor tracking the power consumption (Power Tracker) to provide needed simulation [54].

5.5 Communication Simulation

Testing the implemented communication scheme through prototyping will require building enough hardware prototypes to significantly explore its operation. Simulation of multiple communicating nodes is more feasible and is viable with the use of the developed simulator. Figure 5.3 depicts a basic setup of two grids of 16 nodes each connected with a set of transverse links (these links are discussed in detail in Chapter 6). Creating all the connections by hand for each of the present ports is labor intensive. The representation of the connections in Ptolemy is done with XML (Extensible Markup Language) [60]. With the use of XML, large networks and the links between them can be created automatically. Automatic code generation provides a useful medium for testing different applications and computing performance metrics, as will be done in Section 6.5.

5.6 Integrating the Fault Simulation and the Communication Scheme

The communication scheme used in the system will be described in Chapter 6. This scheme can route around faults and sleeping nodes. The physical world simulator provides support to test this implementation by attaching a Fabric actor to the actor simulating a node in the Acoustic Beamforming Array. The Fabric actor shown in Figure 5.4 creates the error

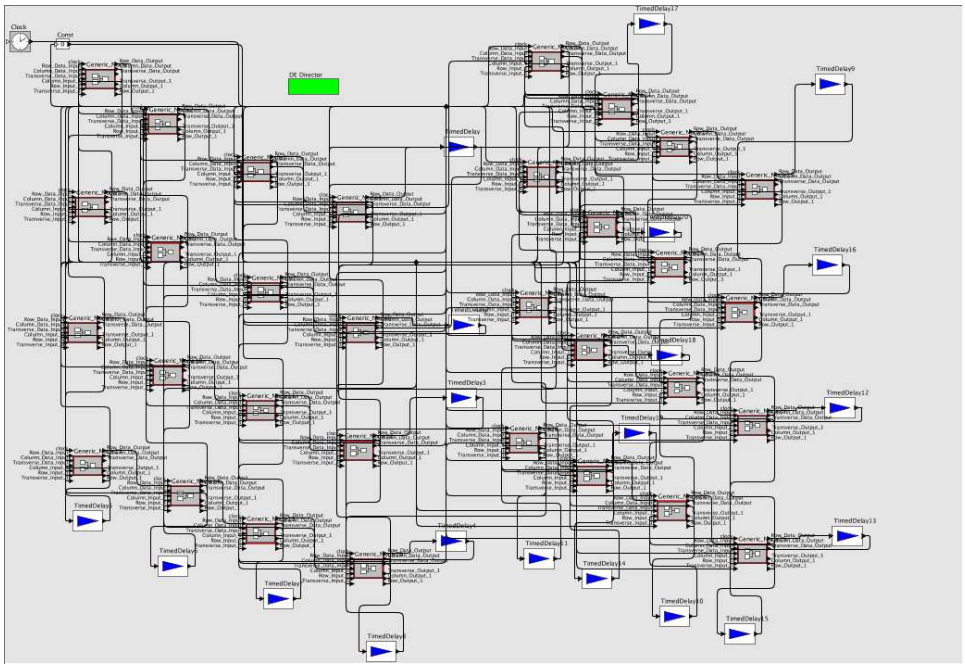


Figure 5.3: Simulation of 32 nodes on two separate grids joined with transverse links.

information that blocks data from crossing the communication channels that exist on the fabric. This is done by controlling multiplexors through the control signal provided. The Fabric actor also recognizes that an error in the communication channel can be to the "left" or the "right" of a node, or on the channel providing the link between the nodes at the ends of the ring. These channels are depicted in a block diagram in Figure 5.5. When a channel is disconnected a node detects this error and the fault tolerant process in the networking scheme deals with the error as discussed in Chapter 6. Figure 5.6 presents the simulator for the Acoustic Beamforming Array while using these nodes. More communication links are used in this case to account for the links traversing the ring between the edges. The physical world simulator was also used in [54] to test for power line disruptions caused by the introduced faults.

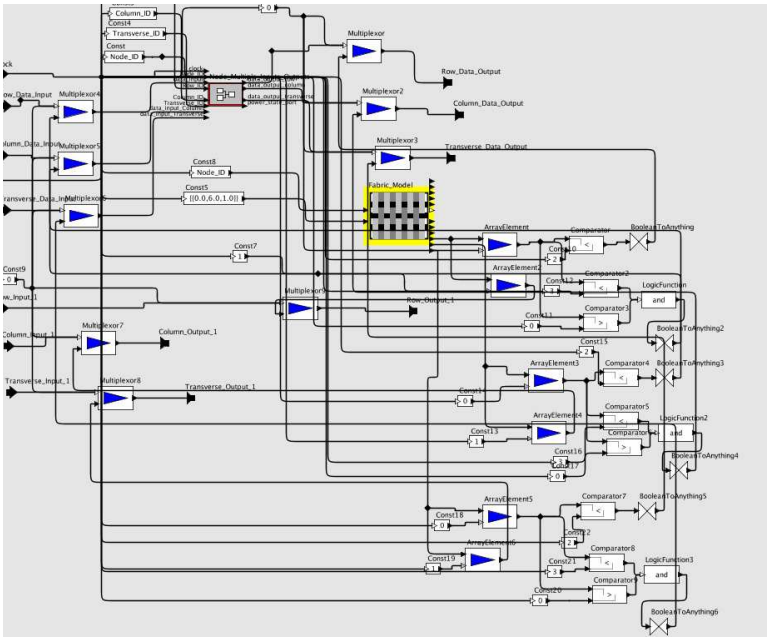


Figure 5.4: The processing node and the Fabric Model simulate the presence of faults on the fabric.

5.7 Hybrid Mode

A crucial task in the creation of a simulation environment is the ability to "ground" the results of the simulation. This can be done by comparing the results of the simulation to the results of prototypes in experimental setups. The introduced Hybrid mode allows the direct interaction of a running simulation and a hardware prototype. It also provides the ability to extend the testing of the hardware prototype by providing a direct connection between the simulation and the actual hardware.

The *node* in the acoustic beamformer sends its results through a serial port using RS-232 to a host computer, where this data is read and displayed. The serial port can be used to receive data as well. The specific node tested was set up to transmit its beamforming data on the reception of data on its serial port. This requires that each hardware node included in the simulation to be connected to a host computer with a serial port. The simulation environment was made to control several hardware nodes using the hybrid mode; the *actor*

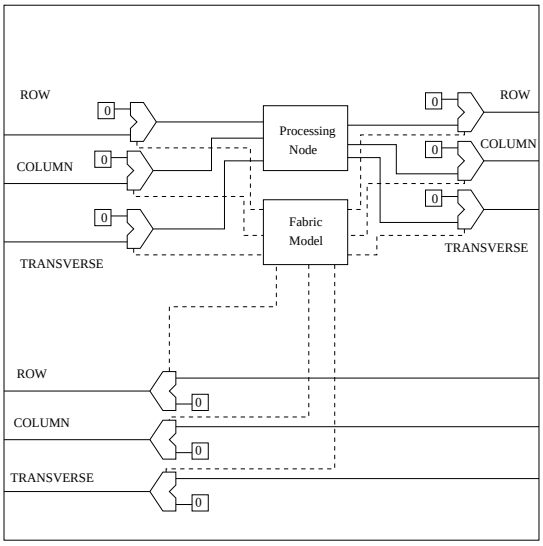


Figure 5.5: Multiplexors controlled by signals from the Fabric Model create the errors in the communication links.

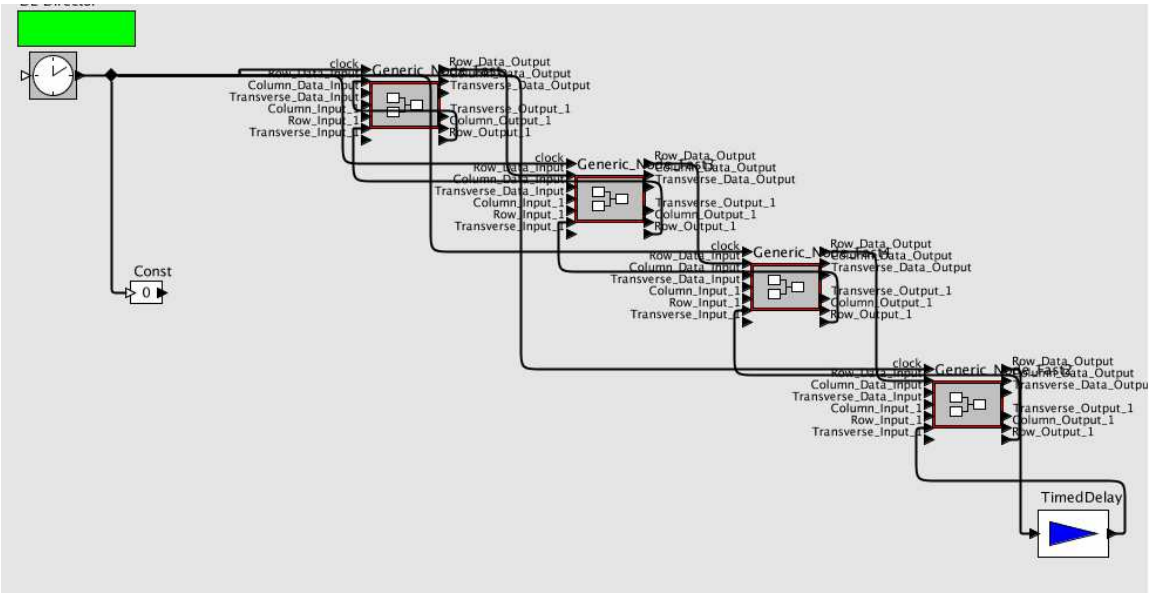


Figure 5.6: Extra connections to the new node, Figure 5.4, are required to represent the connections.

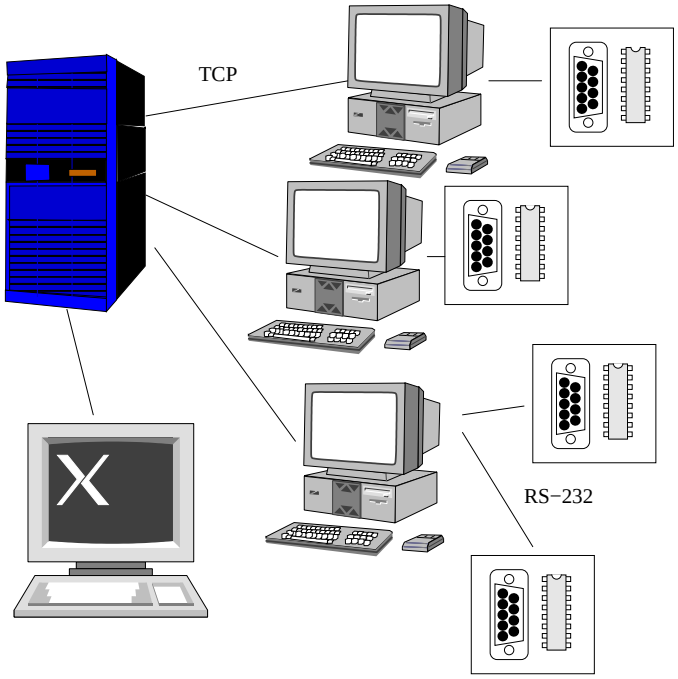


Figure 5.7: Using an X terminal, the simulation can be run on a server that connects through TCP to host computers controlling hardware nodes to be used in a "Hybrid Mode" simulation.

representing the hardware node creates a TCP connection to the host computer controlling the hardware node; the set up is shown in Figure 5.7, allowing the connection of several hardware nodes, limited by the number of host machines and nodes.

The hardware testing of a communication protocol on a large network is more feasible using this mode than using a large network of hardware nodes, thus compensating for a low number of hardware prototypes.

5.8 Fine-Tuning the Beamformer

The simulation environment provides a virtual space for designing and testing e-textile prototypes. This simulation environment was used extensively to test the results of the Acoustic Beamformer in [53]. The results of each node were tested with varying specific parameters; an example result shows the maximum error in the angle estimation with varying the number

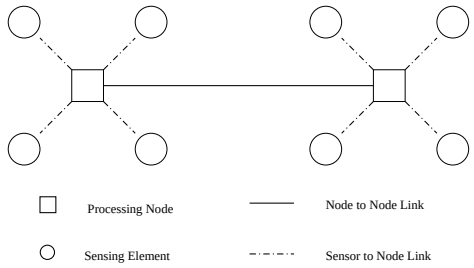


Figure 5.8: A general concept of an e-textile including the nodes, sensors, and communication channels.

of microphones used and the sampling rate (radius of cluster was fixed to 3 feet, and the SNR (Signal to Noise Ratio) to 5dB). The simulator was also used to test the operation of the Acoustic Beamforming Array in providing the location of the vehicle while using different numbers of clusters at specific distances.

The simulator helped us in fine-tuning the acoustic beamformer, by changing specific variables and recording the changes in accuracies and power consumption, before deciding on a major change in the implementation. A general concept of e-textile systems based on the acoustic array is shown in Fig. 5.8. This concept will help us in specifying the variables that would be changed in a simulation environment. The significant variables that affect the operation and power consumption of such a system are the number of clusters in the system, the number of sensors associated with each node, the format of the data transmitted between sensor and node (analog or digital), sampling rate, communication bandwidth and size of data chunks (sensor-node and node-node communication), to name a few [59].

Chapter 6

Networking

A networking scheme designed for e-textile applications will be discussed in this chapter. The scheme is based on the Token Grid described in Section 2.1.2. The modifications to this network are based upon the precepts stated in the electronic textile architecture detailed in Chapter 4.

The number of hops a token has to traverse is directly related to the number of nodes on the ring. In the case of large area e-textiles, a large number of nodes in a ring can slow the communication on the ring. Fabric swatches will be connected to form large or wearable fabrics (precept of the electronic textile architecture); the networks on these different fabrics must be connected. The addition of a third dimension to the networking scheme to address both of these issues will be discussed in Section 6.1.

Fault tolerance was integrated in the design of the networking scheme in accordance with the fault-tolerant communication scheme precept. The new fault-tolerance scheme differs from the Token Grid scheme for two main reasons. First, the Token Grid scheme assumes no faults on the communication links. Second, the Token Grid scheme assumes that the processing nodes will have the ability to forward data in the case of a failure. Both of these assumptions do not apply to e-textiles and thus a new scheme, presented in Section 6.2,

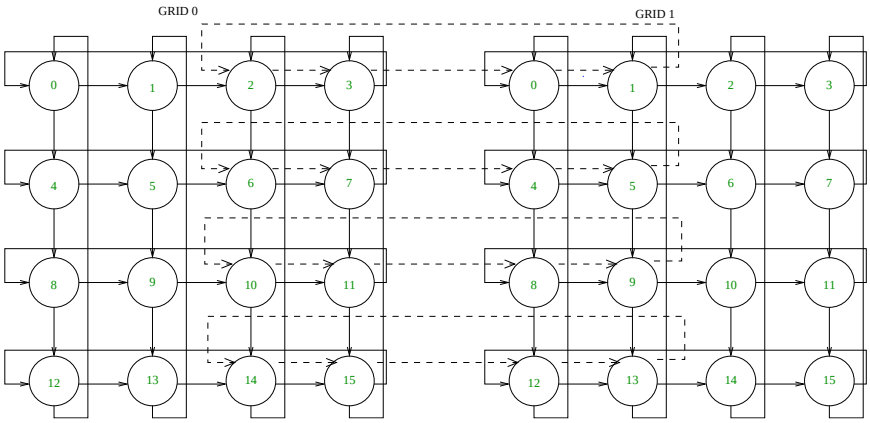


Figure 6.1: The new grid architecture has an added "transverse" ring.

was designed. Low-power operation of electronic textile systems dictates the support for "sleeping" nodes; the networking scheme avoids waking these nodes up unless necessary, this support is discussed in Section 6.3. Section 6.4 will provide a framework to be used in reporting the performance of the networking scheme under different conditions in Section 6.5.

6.1 Transverse Dimension

The use of weaving (precept of the electronic textile architecture) inherently forces an X-Y formation on the fabric; this formation fits the Token Grid network. A new dimension was added to the grid because the number of nodes in one ring cannot be increased indefinitely. Figure 6.1 shows the new grid architecture, where each grid of nodes will be connected to a similar grid. This increase adds to the ability of the system to support large numbers of nodes. Some nodes get duplicated direct connections and more indirect routes are available to increase fault tolerance. The potential number of network interfaces of each node in the new grid, the Textile Token Grid, must be increased. In the original token grid each node required two outputs and two inputs; this new system requires up to three outputs and three inputs.

In applying the new grid architecture to physical fabrics, the transverse dimension can

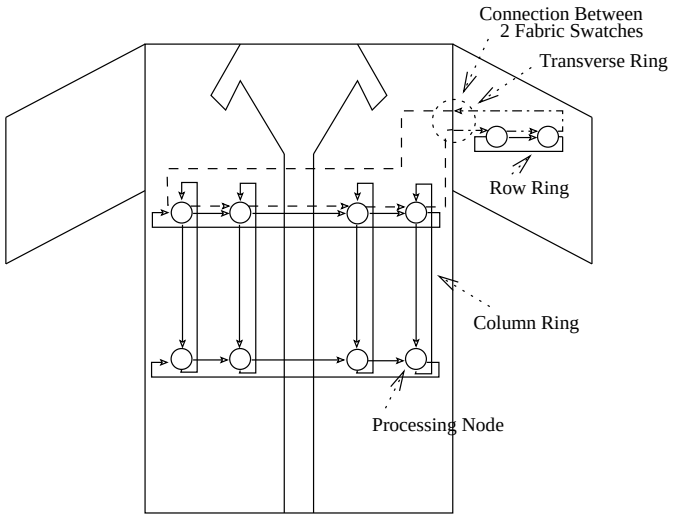


Figure 6.2: The transverse dimension can be used to join processing nodes on different fabric swatches.

have a very useful application in joining different networks on separate fabric swatches. The sleeve of a shirt is a perfect example. The network existing on the sleeve can connect to the network on the body of the shirt through the use of the transverse dimensions on both networks, as depicted in Figure 6.2.

The cost of communication between two nodes in this networking scheme is different depending on the location of the communicating nodes. In a network comprised of row and column rings (no transverse dimension), the fastest connection is between nodes on the same ring, while connecting using a merge is more expensive. The transverse dimension will thus only be used to communicate between what can be regarded as separate autonomous grids. In an effort to keep the networking algorithm simple, the transverse links will only be used to move packets from one grid to another with no regard to the Row ID and Column ID of the receiver. This concept is shown in Figure 6.3. Node 0 of Grid 1 creates a data packet to be sent to Node 3 of Grid 0. The grid ID of the destination is different from the local grid, so the transverse ring takes care of forwarding this data. When the data packet reaches Node 2 of Grid 0, that node recognizes that this data packet has just arrived from a different grid and thus will need more processing to be routed. Node 2 will add this data packet to its data queue as if it has created it. The routing now is performed on the row-column grid

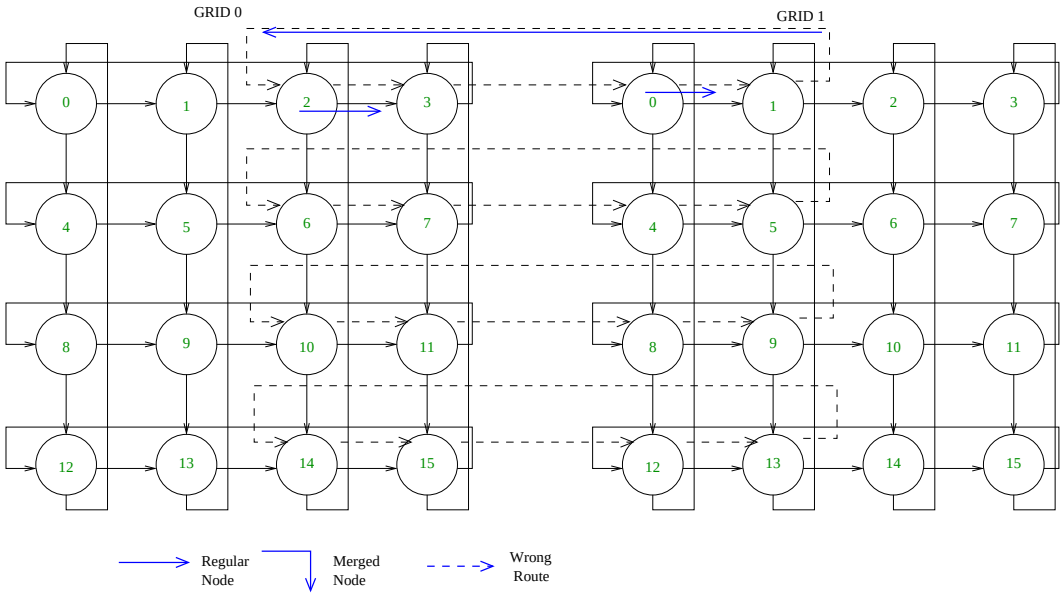


Figure 6.3: The transverse and the row links are used to send packets between Node 0 (Grid 1) and Node 3 (Grid 0).

with no reference to the transverse dimension. This data is then routed to Node 3 of Grid 0 on the row ring. Figure 6.4 displays another case where the data packet is destined for another grid. Node 2 of Grid 0 had to request a merge from Node 6, and the data was routed through that merge to Node 7 of Grid 0.

In both cases, Node 2 of Grid 0 added the data packet to its data queue when it did not have enough information or capability to route that packet without grabbing a token. This technique, of adding to the data queue, will be used in the fault tolerant scheme described in Section 6.2.

Each transverse ring traverses two different grids, the transverse token will keep a record of these grid IDs. In the case that the destination is on a grid other than the source, there exist two options. The first is to send the data packet on the transverse ring if it can reach the needed grid. The second is to use the row ring to reach a node connected to the other transverse ring. This decision will be taken with the help of a routing table. The construction of this routing table will be dependent on the application and will not be discussed in this

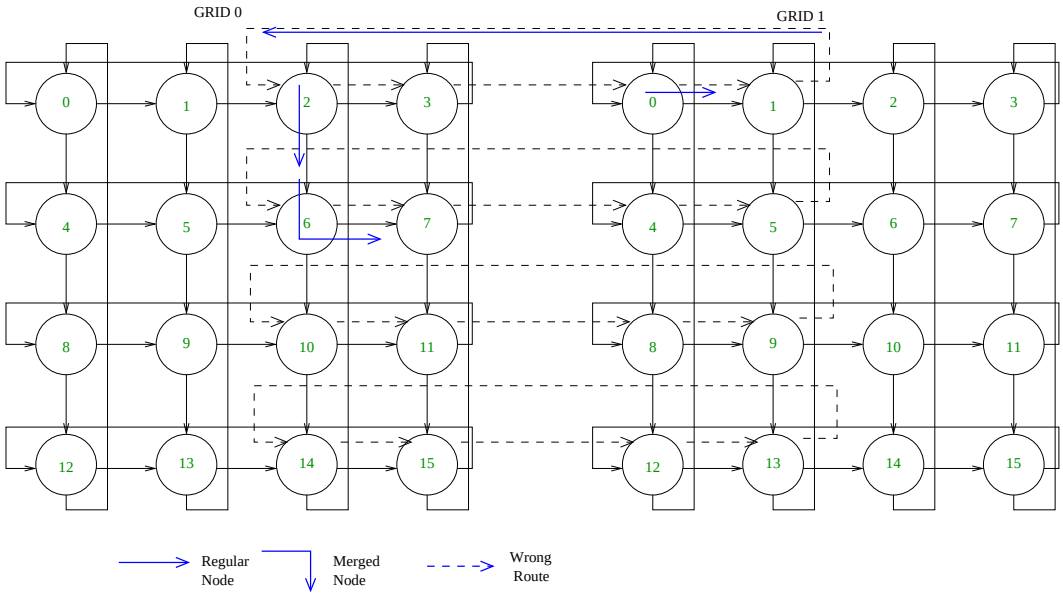


Figure 6.4: The data packet is treated as a new packet inside the receiving grid. Node 0 Grid 1 uses the transverse ring to reach Node 2 Grid 0, at Node 2 the packet is re-processed for routing and it is sent through a merge to Node 7 Grid 0.

dissertation. Figure 6.5 depicts a case where the row ring is needed before the data packet can reach the destination grid.

6.1.1 Size of the Grid

The size of the grid dictates the number of nodes in the rings. This is a decision metric that can affect the operation of the network. The values in Table 6.2 and Table 6.3, Section 6.4, show that communication inside the same ring is the fastest. The number of nodes in a ring directly affects TW_{token} (time to wait for a token) and thus controls the total waiting time and the number of hops each communication has to experience. The number of nodes in each ring also dictates the number of grids. Communication on transverse links (between grids) is more expensive and thus should be minimized. The boundaries between grids should be chosen considering the communication needs of the application.

In the presence of faults, a tear across the width of a fabric will totally sever the connection

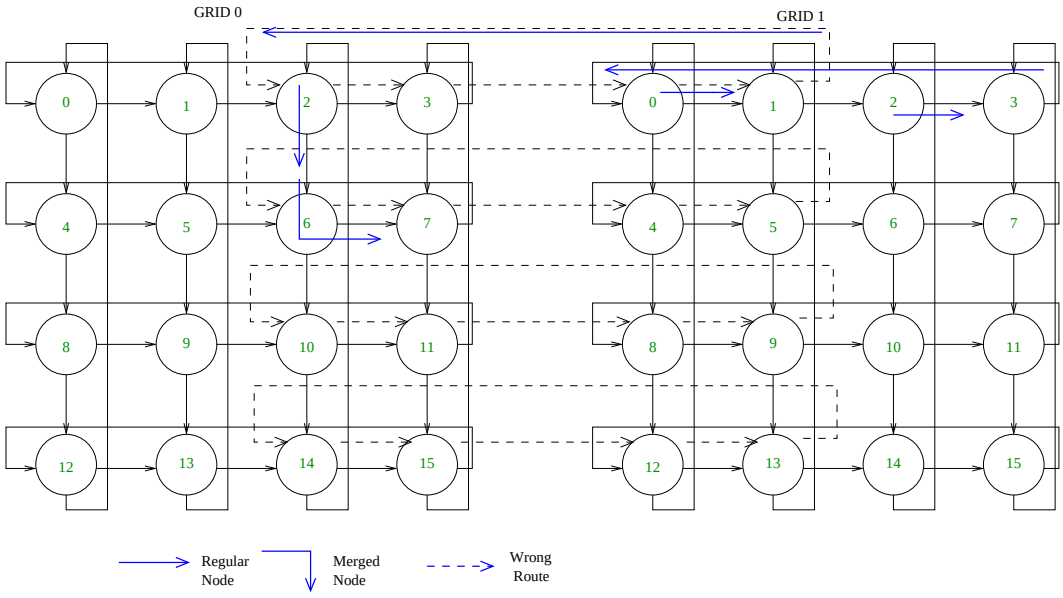


Figure 6.5: Node 2 of Grid 1 uses its row ring to forward the data packet to another transverse ring to reach Grid 0.

between the two parts, thus creating an almost useless grid. The larger the number of nodes in this grid the more significant the loss of nodes in the overall prototype. As a qualitative view, the number of nodes in a ring should be small enough to keep the communication speed-up and reduce the losses when a large tear occurs. The increase in communication cost across transverse links requires the use of enough nodes inside rings to span enough area to minimize the need for transverse connections. These views provide guidelines into deciding the sizes of separate grids. In wearable systems, the flexibility of choosing the grid size is constrained by the fabric swatches determined by the design of the garment.

6.2 Fault Tolerant Implementation

The implementation of a fault tolerant communication scheme is a must for electronic textiles systems. The following section discusses the fault tolerant scheme used in this architecture. Detection of errors and propagating information about the faults are the first aspects pre-

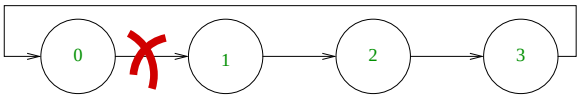


Figure 6.6: Node 1 has an error at the link directly to its "left."

sented. Utilization of this information in routing data is then discussed.

6.2.1 Creation of Error packets

The implemented fault tolerant scheme, discussed in detail in Section 6.2.2, requires that the nodes in the system update error information about the network. The detection of errors and the transmission of this information will be detailed in this section.

Error detection

Each node is connected to three different rings (row, column, and transverse). There are three possibilities for link errors. In the case that there are no data packets to be sent on any link, the nodes will forward the tokens. Each node will keep three separate Timeout Counters pertaining to each link it is connected to. These counters are reset to zero at the reception of any data (tokens, data packets, and error packets). If any of these counters reaches a pre-specified value an error is declared. This value will be dependent on the application and the specific topology; in this research it is set empirically. When an error is detected in this manner it means that there is an error to the "left" of the node. Figure 6.6 shows a specific example, Node 1 does not receive anything from its ring and after the timeout period it creates an error packet and sends it down the ring. Node 1 will also update a flag that states that the row it belongs to is in error. When a node receives an error packet it forwards that packet down the same ring and updates the flag stating that the ring is in error.

A situation may arise where Node 2 will reach its timeout value before it receives the error packet from Node 1. To determine which node is actually on the broken link, a temporary

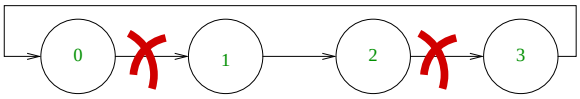


Figure 6.7: Node 1 and Node 3 have errors at the links directly to their "left."

error flag is used. When a node first reaches its timeout counter it sends the error packet and sets the temporary error flag. The error flag is not set unless the timeout period is reached while the temporary error flag is asserted. Following Figure 6.6, Node 2 will receive an error packet from Node 1 after it sends its own. This reception will reset the temporary error flag and thus Node 2 knows that there is an error on the ring and that error is on the link directly to the left of Node 1, the source of the error packet. Figure 6.7 depicts a case where there are two different errors on the same ring. The nodes on the ring will all have the information that there is an error on the ring. Following the scheme mentioned above Node 0 will have the information that Node 3 has an immediate error and Node 2 will have the same information about Node 1.

Error information propagation

Using the process discussed above, each node on a ring with an error has a flag that reflects that information. This information is to be propagated to other nodes in the network. If the error is on the row ring, then the column token that passes through each of these nodes will be updated to reflect that the specific row ring has an error. This has no propagation costs because the token is already traversing the whole column ring. Each node will have to keep another variable that pertains to errors. This variable will carry the information of errors on other rings in the network; three variables will be needed reflecting the information about the other rows, columns, and transverses in the network.

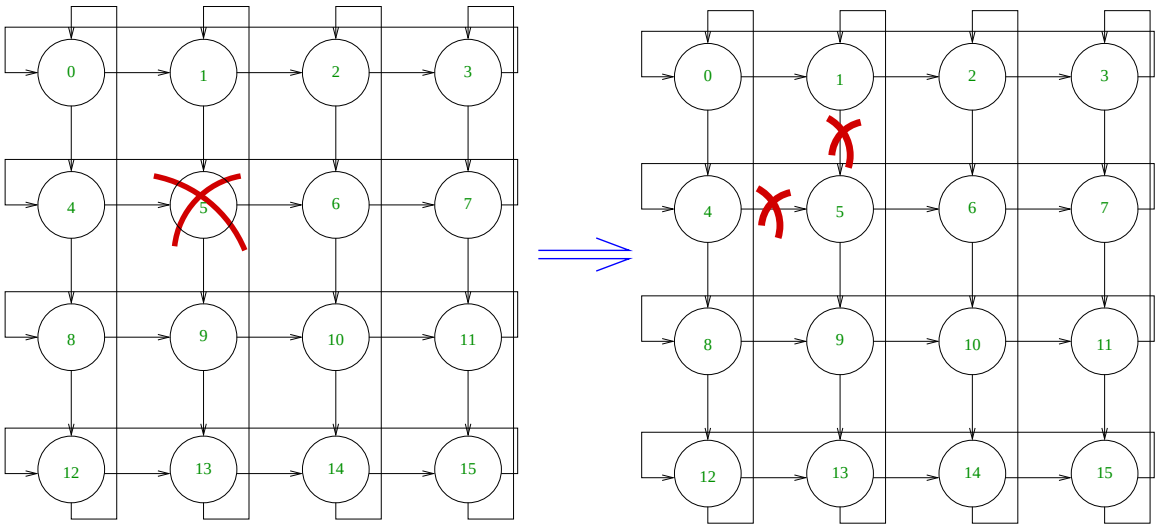


Figure 6.8: The Node 5 error is equivalent to two link errors, Row 1 and Column 1.

Node errors

Node errors will also be supported in the fault tolerant scheme. To simplify the implementation, these errors will be treated and detected as two separate link errors as shown in Figure 6.8.

6.2.2 The Fault Tolerant Scheme

This subsection will use several examples to demonstrate the operation of the fault tolerant scheme. Communication between nodes on the same row or column are dealt with directly by the token traversing the significant ring. When the destination lies on a different row and a different column then a merging process will be needed as described in Section 2.1.2. Figure 6.9 depicts a 16 node network. The nodes will be referenced with their node IDs, the numbers depicted in Figure 6.9, to ease the discussion. The addressing scheme is still based on the row and column ring IDs (the transverse IDs also in more complex networks). If Node 0 is to send a data packet to Node 5, it will ask either Node 1 or Node 4 to go to a merged state. In the merged state, either of these nodes will be able to forward the specific

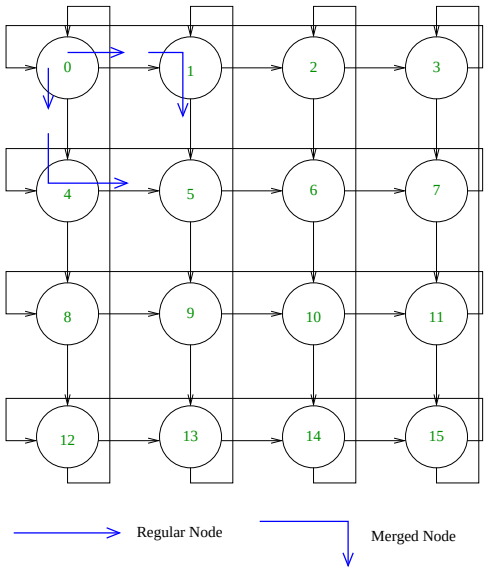


Figure 6.9: A 16 node network displaying the node IDs to ease the discussion of the networking algorithm.

packet to the Node 5. The operation of the algorithm is provided as a pseudo code (see Figure 6.10) that displays the functions performed at the reception of each kind of token and the reception of a data packet.

The operation of the scheme in the presence of faults will be described starting with simple cases and building in complexity (number of faults). The first case to consider is a link fault on the destination row as shown in Figure 6.11 (a). This discussion assumes that all of the significant error information has been transmitted and received as discussed in Section 6.2.1. From the error information, Node 0 will only request Node 1 to go to a merged state. Node 1 will receive the request for the merge through the row token. At the reception of the row/column Token, Node 0 will release the data packet that will be forwarded by Node 1 to Node 5. The second case considered has an error on Row 0 as shown in Figure 6.11 (b). The merge request is sent to Node 4 in this case, and the data is forwarded when the column/row token reaches Node 0, the data is then forward to Node 5 through Node 4.

A more complex case occurs when there is an error on both Row 0 and Row 1, as depicted in Figure 6.12 (a), with the same transmission from Node 0 to Node 5. In this case, both

- **Row Token Arrival:**
  - **if(Data Packet ready for sending):**
    - **If(Destination on same Grid):**
      - **If(Destination on same row):** Send data directly on Row ring.
      - **else:**
        - **If(Destination on same Column):** Column Token will take care of it, no action.
        - **else:** Need a Merger, request one from node on the same row as this, and same column as destination. This information is added to the token that is later released.
    - **else:** Transverse Token will take care of it, no action.
  - **else:** No Action
  - **If(Waiting_For_Row_Token == 1):**
    - //Column Token has been captured
    - Create a Row_Column Token
    - Merged_Status = 1;
    - Waiting_For_Row_Token = 0;
    - Send Token on Row ring.
  - **If(Merged_Status == 0):**
    - **If this node was asked to go to a merged state:**
      - Grab the token
      - Waiting_For_Column_Token = 1;
  - **else:** Release the Row Token on the Row ring.

(a)

- **Column Token Arrival:**
  - **if(Data Packet ready for sending):**
    - **If(Destination on same Grid):**
      - **If(Destination on same column:)** Send data directly on Column ring.
      - **else:**
        - **If(Destination on same Row):** Row Token will take care of it, no action.
        - **else:** Need a Merger, request one from node on the same column as this, and same row as destination. This information is added to the token that is later released.
    - **else:** Transverse Token will take care of it, no action.
  - **else:** No Action
  - **If(Waiting_For_Column_Token == 1):**
    - //Row Token has been captured
    - Create a Row_Column Token
    - Merged_Status = 1;
    - Waiting_For_Column_Token = 0;
    - Send Token on Row ring.
  - **If(Merged_Status == 0):**
    - **If this node was asked to go to a merged state:**
      - Grab the token
      - Waiting_For_Row_Token = 1;
  - **else:** Release the Column Token on the Column ring.

(b)

- **Row Column Token Arrival:**
  - **if(Data Packet ready for sending):**
    - **If(Destination on same Grid):**
      - **if(Destination Column == Column of Master of Token) && (This node on a different Row than Destination)**
        - **if this is the master node**: Send data on Column ring.
        - **else:** Send data on Row ring.
    - **else:** Transverse Token will take care of it, no action.
  - **else:** No Action
  - **if(This is the node that created the Row Column Token)**
    - Create Column_Row Token
    - Send Token on Column ring.
  - **else:** Release the Row Column on Row ring.

(c)

- **Column Row Token Arrival:**
  - **if(Data Packet ready for sending):**
    If(Destination on same Grid):
    - **if(Destination Row == Row of Master of Token) && (This node on a different Column than Destination)**
      - **if this is the master node**: Send data on Row ring.
      - **else:** Send data on Column ring.

    else: Transverse Token will take care of it, no action.
  - **else:** No Action
  - **if(This is the node that created the Column Row Token)**
    - //The Merged tokens have finished traversing the merged ring.
    - Create Row Token and send it on Row ring.
    - Create Column Token and send it on Column ring.
  - **else:** Release the Column Row on Column ring.

(d)

- **Data Packet Arrival:**
  - **if(Data Packet is meant for this node):** DONE
  - **else:**
    - **if(Destination on same Grid):**
      - **switch(Channel data recieved on)**
        - **case(Row):** if(Merged_Status == 0): Forward on Row. Else: Forward on Column.
        - **case(Column):** if(Merged_Status == 0): Forward Column. Else: Forward Row.
        - **case(Transverse):** Data just arrived from another grid, add it to then Data Queue to be processed later for forwarding.
    - **else:**
      - **if Data received on Transverse ring:** Forward Data on Transverse
      - **else:** Let the Transverse Token deal with forwarding this packet.

(e)

Figure 6.10: The operation of the algorithm is controlled by these separate processes.

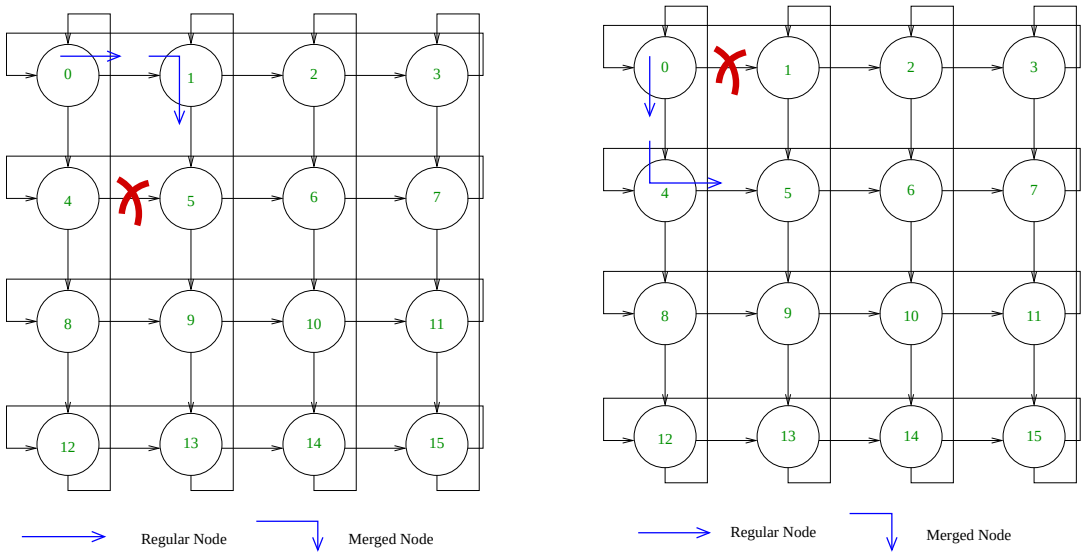
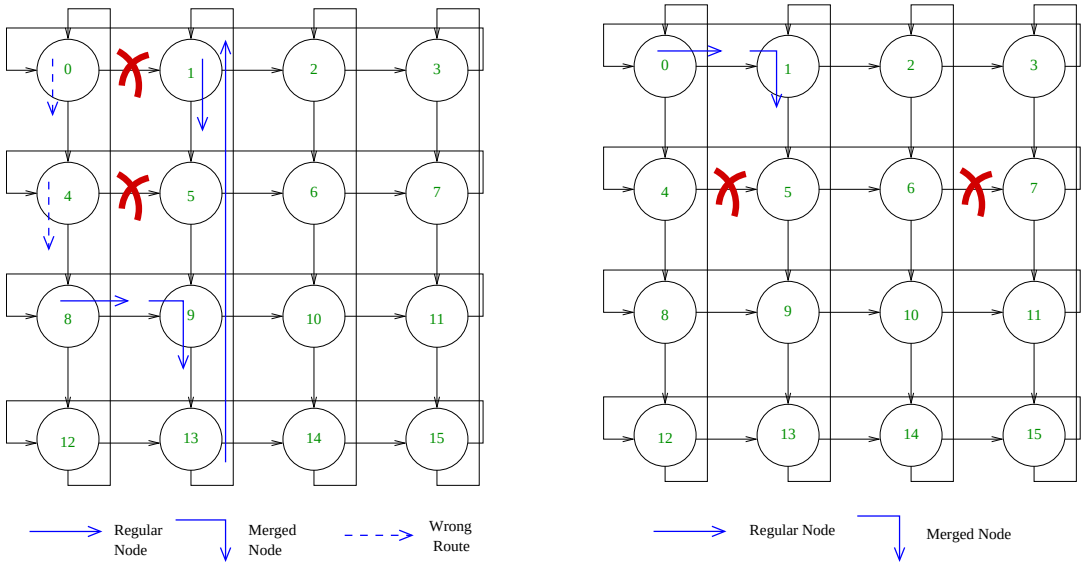


Figure 6.11: A link error on the destination row or on the same row in the transmission from Node 0 to Node 5 limits the merge options in each transmission.

nodes in position to offer a useful merge have errors on their significant rings. In this case the data packet will be forwarded on a "Wrong Route," the column in this case. The node that receives this data packet should be able to recognize that it should not forward it in the regular fashion, but will save it in its data queue for processing at the reception of a token. In the presented case, the data packet will first reach Node 4. At that node, the destination (Node 5) is not reachable because of the link error and the data packet is forwarded on the "Wrong Route" again, down the column. Node 8 will then request Node 9 for a merge; this final merge will enable the data packet to reach Node 5 through the column ring. In the case that two errors occur on the same row, as depicted in Figure 6.12 (b), the second error has no impact on the operation because in both cases the entire row is declared to be in error; the operation in this case will follow that described for the case of Figure 6.11 (a).

Figure 6.13 depicts a case where a node is trying to send to another node on its row with an error on the row. Node 6 creates the packet, the error on the row forces this node to send



(a) (b)

Figure 6.12: Link errors on Row 0 and Row 1 prevent a regular merging scheme and force a "Wrong Route." Two link errors on Row 1 affect the operation in the same manner as a single error.

the packet on a "Wrong Route" down the column to Node 10. Node 10 requests Node 9 to merge. When the merging process is finished the data packet will be routed from Node 10 through Row 2 to Node 9 that routes the packet through Column 1 to Node 5.

Figure 6.14 presents the pseudo code that responds to a data packet reception. The pseudo code is presented in two forms: the first assumes no faults in the network, the second utilizes the received error information to correctly route the data packet or push it on its data queue for later processing at the reception of a token. The operation of the fault tolerant pseudo code follows closely the simpler version, but it detects the case of a "Wrong Route" and uses the same method of re-processing this data as when a data packet is received from another grid. The fault tolerant pseudo codes for the other events are more complex and are provided in Appendix A.

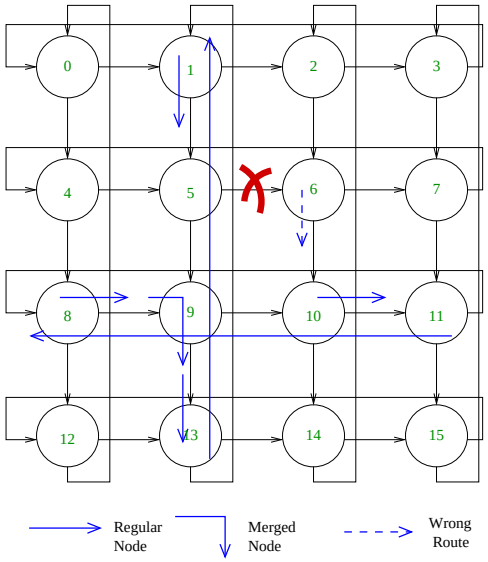


Figure 6.13: The path of a data packet from Node 6 to Node 5 with an error on Row 1.

6.2.3 The Fault Tolerant Scheme on the Transverse Link

The transverse links in the network carry packets destined to a grid different from their source. The forwarding of these packets on the transverse links is done in a manner unrelated to their specific destination. Any node that receives a packet on its transverse link whose destination is on the same grid adds this packet to its data queue and processes it later for forwarding on the grid. This simplistic approach to grid-to-grid forwarding supports a simple fault-tolerant scheme on the transverse links. When a node needs to forward a packet on its transverse link and there is an error on that link, a "Wrong Route" is forced down the column. This also applies when the data is destined for another grid but is forwarded on the row ring to reach the appropriate transverse ring. These two cases are depicted in Figure 6.15 and Figure 6.16. In Figure 6.15 Node 0 uses the "Wrong Route" to reach Node 3, and Node 3 then uses its transverse ring to forward the packet to Grid 0. In Figure 6.16, Node 2 must forward the packet on its row ring to reach the correct transverse ring. The row error forced Node 2 to use the "Wrong Route" to reach Node 6. Node 6 uses its row ring to forward the packet to the correct transverse ring and from there to Grid 0.

- **Data Packet Arrival:**
  - **if(Data Packet is meant for this node):** DONE
  - **else:**
    - **if(Destination on same Grid):**
      - **switch(Channel data recieved on)**
        - **case(Row):** if(Merged_Status == 0): Forward on Row. Else: Forward on Column.
        - **case(Column):** if(Merged_Status == 0): Forward Column. Else: Forward Row.
        - **case(Transverse):** Data just arrived from another grid, add it to then Data Queue to be processed later for forwarding.
    - **else:**
      - **if Data received on Transverse ring:** Forward Data on Transverse
      - **else:** Let the Transverse Token deal with forwarding this packet.

(a)

- **Data Packet Arrival:**
  - **if(This is the source of the Data Packet):** DISCARD
  - **if(Data Packet is meant for this node):** DONE
  - **else:**
    - **if(Destination on same Grid):**
      - **switch(Channel data recieved on)**
        - **case(Row):**
          - **if((Destination_Row != Row_ID)&&(Destination_Column != Column_ID)):** can be a "Wrong Route" or Merged_Ring
          - **if(there is a column error on column before): re-process the packet.**
          - **else:**
          - **if(Merged_Status == 0):** Forward on Row ring.
          - **else:** Forward on Column ring.
        - **case(Column):**
          - **if((Destination_Row != Row_ID)&&(Destination_Column != Column_ID)):** can be a "Wrong Route" or Merged_Ring
          - **if(there is a row error on row before): re-process the packet.**
          - **else:**
          - **if(Merged_Status == 0):** Forward on Column ring.
          - **else:** Forward on Row ring.
        - **case(Transverse):**
          - Data just arrived from another grid, add it to the Data Queue to be processed later for forwarding.
    - **else:**
      - **if Data received on Transverse ring:** Forward Data on Transverse
      - **else:** Let the Transverse Token deal with forwarding this packet.

(b)

Figure 6.14: The Data Packet Arrival pseudo codes with and without fault tolerance implemented.

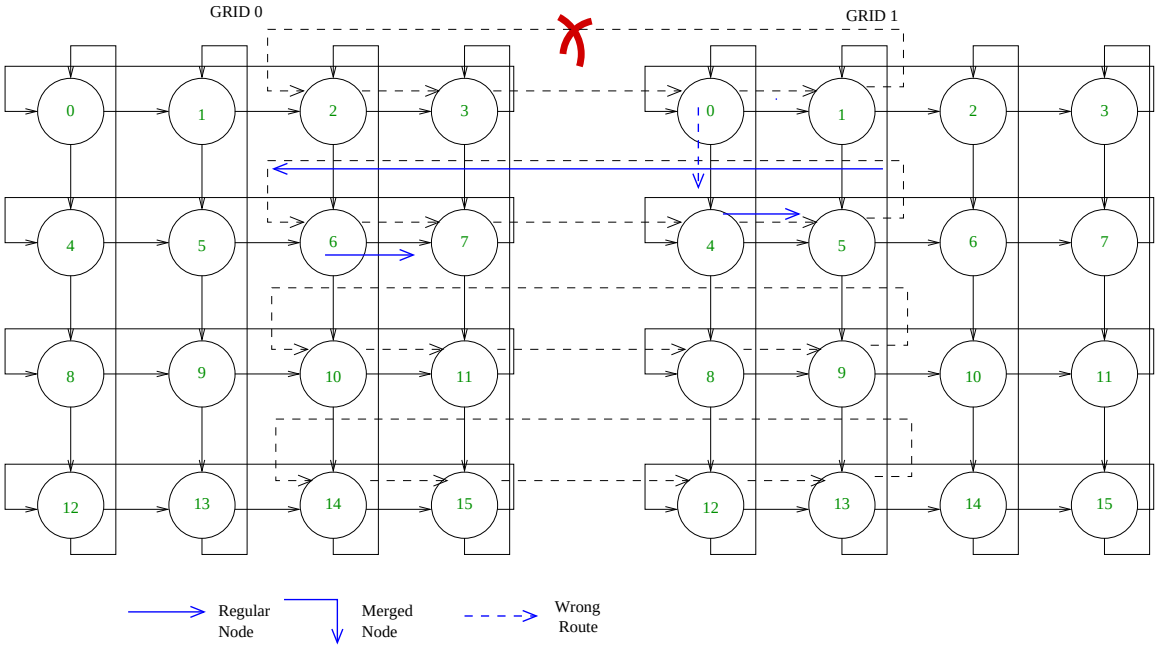


Figure 6.15: The data packet path from Node 0 Grid 1 to Node 7 Grid 0 with an error on Transverse 0.

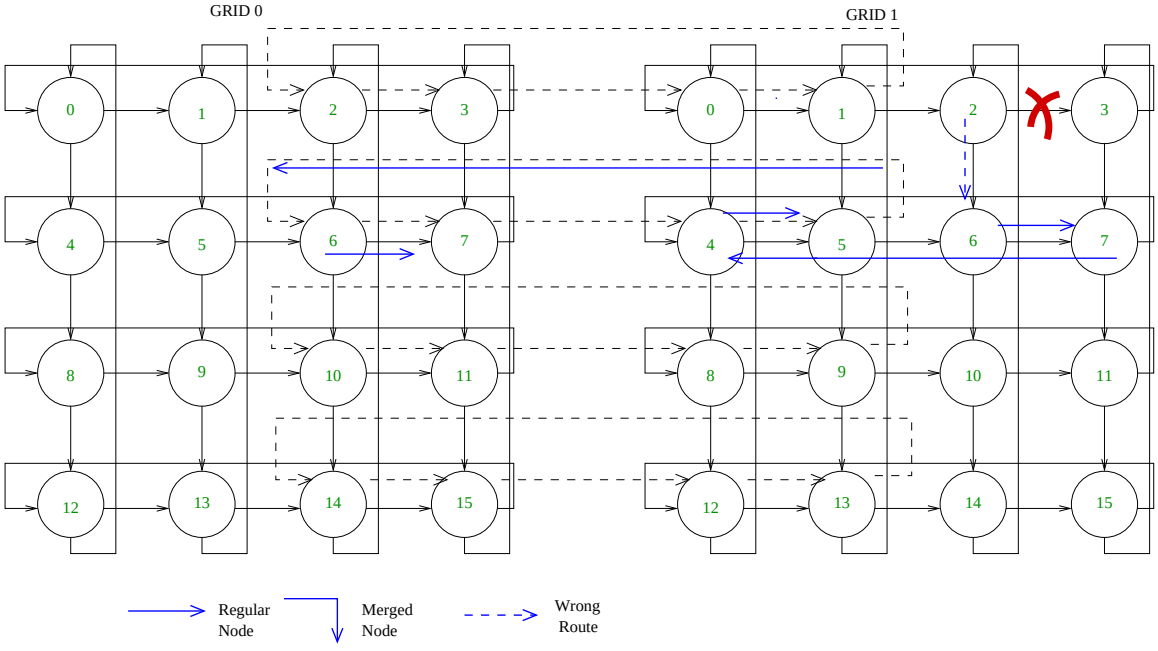


Figure 6.16: The Data Packet path from Node 2 Grid 1 to Node 7 Grid 0 with an error on Row 0.

6.3 Sleeping Nodes

The network has to operate in the presence of faults and sleeping nodes. When a node enters a sleeping mode it creates the same effect a node failure has on the network as shown in Figure 6.8. The network has to support sleeping nodes in the same manner a failure is dealt with; the only difference is that a sleeping node can be re-activated. The network also avoids waking sleeping nodes unless necessary.

Before a node enters a sleep mode, it sends a sleep packet on its rings in the same manner an error packet was sent. The information is propagated through the network in the same manner as the error information. There are two ways a node can be re-activated: the first is through its own hardware, and the second is through reception from another node in the network.

In the Acoustic Beamforming Array when a node receives a strong audio signal it is re-activated. When a node is re-activated it declares itself master of the rings it is connected to. These rings are not functional since the tokens are not circulating. The nodes that receive the new tokens update their information pertaining to the sleeping node and this same information is propagated through the network.

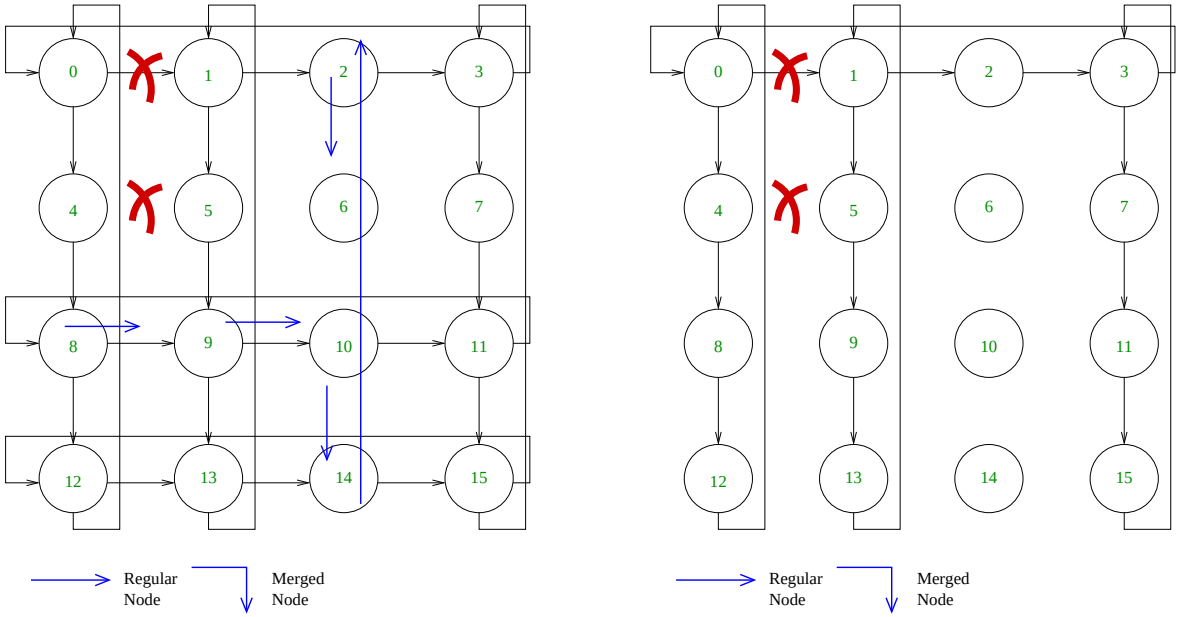
A sleeping node can be awakened by another node in the network. If a node needs to communicate with a sleeping node (the row and column of the destination node are asleep) it creates a special data packet and sends it on its row and column. In regular operation of forwarding data packets, a packet is discarded if its destination row and column are in error. In this case that packet will be forwarded based on the following scheme. If this packet is received on the row and the node belongs to the row of the source, then it forwards the wake-up packet on the row and column. If the data is received on the row and the node belongs to the source column, then discard the packet. If the node does not belong to any source rings, then forward on the row. The same process is repeated when receiving from the column. If the source receives a wake-up packet, it is discarded. The following is a pseudo

code for this process:

```
if(Receiving_Node == Source_of_Wake_Up)
     Discard packet;
else
     if(Channel_Received_On == Row)
          if(Row_ID == Source_Row)
               Forward packet on row and column
          else
               if(Column_ID == Source_Column)
                    Discard the packet
               else
                    Forward on Row
     if(Channel_Received_On == Column)
          if(Column_ID == Source_Column)
               Forward packet on column and row
          else
               if(Row_ID == Source_Row)
                    Discard the packet
               else
                    Forward on Column
```

This scheme is made clearer in the following example shown in Figure 6.17 (a). Node 6 is asleep and Node 0 needs to wake it. Row 0 has a fault, and Row 1 has a fault that occurred after Node 6 entered a sleeping stage, thus there is no report of that fault.

Node 0 sends the wake-up signal, the row error prevents the signal from traversing the row. Node 4 faces the same problem with the undetected error on its row. Node 8 forwards the wake-up on the row and the column and so does Node 12. Node 0 discards the wake-up packet it receives on its column, Nodes 9 and 13 forward the packet on the row. Nodes 10 and 14 forward the packets on the column because they belong to the destination column. Node 6 receives two wake-up packets that it discards and then enters an active state. An interesting case, Figure 6.17 (b), can occur where Nodes 6, 10, and 14 are asleep. If the packets are not forwarded on sleeping rings, there might be a case where the required node is not awakened, and if the packet is forwarded more nodes than necessary might be awakened. Two classes



(a) (b)

Figure 6.17: Forwarding the wake-up packet depends on the type of the wake-up required. The lack of links denotes the rings affected by the sleeping nodes.

of wake-up signals are created to solve this problem. If a node is not awake after the first trial, another class of wake-up signal is used.

6.4 Enumeration of Transmission Costs

An enumeration of the cost to send a packet from a source to a destination is needed to provide any study on the performance of the network under varying fault schemes. Given the networking scheme used, the location of the destination has a direct effect on the amount of processing and forwarding required from the network and the nodes in question. The following section will study the different costs attributed to sending a data packet from a fixed node to a set of different destinations. Two costs will be presented, the first represents the cost of transmission for the source node, the second represents the number of hops in

the network to reach the destination.

The simplest case is sending to a node on the same ring (a ring can be a row, column, or transverse). The first step is to wait for the token TW_{token}. After the token is captured, the node can send the data packet. The time needed to send this packet is TS_{data}. After that the node can release the token. The operation of the network requires that a token is always rotated around the ring; thus, the extra cost of sending the data packet is the parameter, TS_{data}. Table 6.1 presents a set of variables that will be used throughout this in reporting measures of network performance.

To clarify the presented values in Table 6.1, a more in-depth discussion of some terms is presented. TW_{token} is the waiting time experienced by a node that needs to send a data packet. The first assumption is that the token is not held in the current node and that it has been released to the ring earlier. This assumption simplifies the discussion by not considering cases where the node is actively releasing the token to the ring, thus the time needed to finish sending the remaining part of the token will have to be considered in TW_{token}. Another simplifying assumption is that the processing time inside a node and the link latencies are negligible. Using these two assumptions, TW_{token} becomes the number of hops the token needs to reach the sending node multiplied by the time needed to send the token (TS_{token}). If node 0 in Figure 6.18 is the sending node, then TW_{token} has a minimum value of TS_{token} when the token is in Node 3 and a maximum value of (N - 1)TS_{token} = 3(TS_{token}) when the token is in Node 1. There are three different cases for this ring with wait values of 1, 2, or 3 multiples of TS_{token}; the average is then 2(TS_{token}) = (N/2)(TS_{token}).

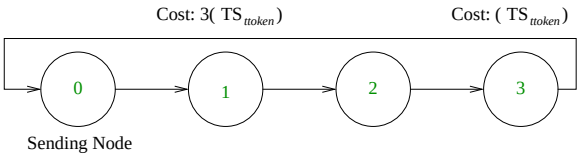


Figure 6.18: The time to wait for the token depends on the location of the token in the ring. The average case is (N/2)(TS_{token}).

The operation of the networking scheme is that it sends a row/column token when a node

Table 6.1: Nomenclatures and Variables used in the discussion.

Variable Name	**Value**	**Explanation**
Grid	-	A set of connected Rows and Columns
Ring	-	Row, Column, or Transverse
N	-	Number of nodes in a ring.
N^2	-	Number of nodes in a Grid ($N_{Row} = N_{Column}$).
BW	-	Bandwidth of the communication links.
TS_{token}	$Size_{token}$/BW	Time required to transmit a token.
TW_{token} min[1]	TS_{token}	Time required to wait for reception of token
max[2]	(N - 1)TS_{token}	(min) Preceding node is sending the token
average	(N/2)TS_{token}	(max) Following node is sending the token
TS_{data}	$Size_{data}$/BW	Time required to transmit a data packet
$TW_{rc-token}$ min[3]	TS_{token}	Time required to wait for reception of token
max	(N - 1)TS_{token}	(min) Preceding node is sending the token
average	(N/2)TS_{token}	(max) Farthest node is sending the token
$TW_{cr-token}$	$TW_{rc-token}$	
$TW_{merged-token}$	TW_{token}+	Token carrying request to reach merging node
(sending with	TW_{token}+	Time required to capture the other token
row_column)	$TW_{rc-token}$+	Time required to wait for row_column token.
$TW_{merged-token}$	TW_{token}+	Token carrying request to reach merging node
(sending with	TW_{token}+	Time required to capture the other token
column_row)	$TW_{rc-token}$+	Time required to wait for row_column token.
	$TW_{cr-token}$	Time required to wait for column_row token.
$TW_{merged-token}$	2(TW_{token}) +	Assuming equal distribution between
(average)	1.5(TW_{token})	rc and cr merged tokens

[1]The Node processing times and the link latencies are considered negligible to simplify the discussion.
[2]Considering there are no other data packet transmissions (light load).
[3]rc-token : row column token, cr-token: column row token.

Table 6.2: Enumerated Communication Timing Costs (to the sending node)

Type	**Dest.**	**Total Time**	**Extra Cost**	**Explanation**
Ring Token[1]	–	TW_{token} + TS_{token}	–	Time waiting for token Time to send that token
Data Packet	Same Ring	TW_{token} + TS_{data} + TS_{token}	TS_{data}	Time waiting for token Time sending the data Time sending the token
Data Packet	Different Row & Column	TW_{token} + $TW_{merged-token}$ + TS_{data} + $TS_{merged-token}$	$TW_{merged-token}$ + TS_{data}	Waiting (to request merge) Time waiting for merged Time sending the data Time sending the merged
Data Packet	Different Grid[2]	TW_{token} + TS_{data} + TS_{token}	TS_{data}	Waiting for Transverse or Row Token[3]. Send data. Send token.

[1]The value of TW_{token} assumes no data transmissions from other nodes on the ring.
[2]The cost to the node here is less than the cost to send the packet. The packet will have to be re-routed once it reaches the other Grid (adding that cost to the receiving node).
[3]If the node is on the wrong Transverse ring, then forward on the Row ring until it reaches the correct link. The cost to this node is the same.

first merges. This token traverses the row ring allowing nodes sending to the merged column to send. When the merged node receives this token, it releases a column/row token on the column ring to allow nodes on the column to send on the row ring. This provides a smaller waiting time for a node sending from the row to the column and that is reflected in Table 6.1.

Table 6.2 provides the costs of communication as perceived by the sending node. When the destination node is on the same ring, the specific location on the ring is not related to the cost of sending to the source. The source node waits to capture the ring token, sends the data packet, and then releases the token. This operation is the same if the destination is the next node in the ring or the farthest. The increase of cost in sending to a farther node is manifest in the number of hops traversed, this cost is reported in Table 6.3.

In the case of sending to a node on a different grid, the sending node decides to send

on either the transverse ring or the row ring. This decision is based on the grids that a certain transverse ring traverses. If this ring reaches the grid in question, then the data is forwarded on it, or the data is forwarded on the row ring to reach the other transverse ring. The assumption here is that the other Transverse Ring will be able to reach the requested grid. The cost in both cases is the same to the transmitting node, waiting for the needed token and then sending the data and the token.

This case is totally different when the significant cost is the number of hops in the network. Assume the node is on the transverse ring that reaches the destination grid. The node has to capture the transverse token first, and the data is then released on that ring. To reach the destination grid, the packet has to be forwarded by a node whose transverse link reaches the other grid. That node is Node 1 on Grid 1 as shown in Figure 6.19, when the communication is from Grid 1 to Grid 0. If Node 1 is the source of the data, the packet needs to jump one hop before reaching the other grid, which is the minimum case. If Node 0 is the source, the first step is 2 jumps or (N/2) jumps. When the packed reaches the new grid, the data is re-processed for forwarding. The number of hops will then depend on the location of the final destination.

A last point to investigate is the operation of this networking scheme in a large network, or the deterioration of the networking performance with an increasing number of nodes in the network. As mentioned earlier the connection cost includes two costs, the cost to the sending node and the cost in number of hops to reach the destination. The cost to the sending node as shown in Table 6.2 depends on TW_{token} or $\mathrm{TW}_{merged-token}$. According to Table 6.1 $\mathrm{TW}_{merged-token}$ is a function of TW_{token} which is dependent on N (the number of nodes in a ring). The cost to the sending node increases with increasing the number of nodes in the ring and not the number of nodes in the network. In a square network, this increase is dependant on $\sqrt{N^2} = N$ where N^2 is the number of nodes in the network. The cost on the sending node is not affected in the presence of a transverse connection because in both cases the node waits for TW_{token} before sending.

Table 6.3: Enumerated Number of Hops (cost to the network)

Type	**Destination**	**Total Cost**	**Explanation**
Ring Token	–	1	One hop source to destination
Data Packet	Same Ring	1 (min) N - 1 (max) N/2 (average)	Destination is next node Destination is previous node
Data Packet	Different Row & Column	2 (min) N (average) 2(N-1) (max)	One Row and one Column off. (N-1)Rows and (N-1)Columns off.
Data Packet	Different Grid (correct Tran.)	1(min),(N/2)(max) + Cost of Data Packet	To reach the other grid Routed as a regular Packet
Data Packet	Different Grid (wrong Tran.)	1(min),(N/2)(max)+ 1(min),(N/2)(max)+ Cost Data Packet	To reach the other Tran To reach the other grid Regular Data Packet

The cost in terms of hop count is different. If there are no transverse connections, the connection cost is an average of N/2 for same ring connections and N for a different row and column connections. The communication cost also grows in order of N, the number of nodes in the ring. In the case of transverse connections, the connection to another grid is a constant factor increase over a regular connection inside the grid and thus is dependant on N. For a network with multiple grids, the maximum communication cost will be that of traversing all of the transverse connections. Let M be the number of nodes in the network and N the number of nodes on a ring. Assume all of the grids are square and of the same size. The number of grids in the network is $\frac{M}{N^2}$, therefore the maximum connection cost is $O(\frac{M}{N^2} * N)$ (N represents the order of increase for a tranverse connection).

There are two cases where the network scales, one in which the physical size stays fixed and the density increases, and one in which the physical size increases. In the case of a wearable fabric, the number of grids cannot be increased indefinitely as the number of nodes

is increased. In this case the factor $\frac{M}{N^2}$ is O(1) and the overall communication cost is O(N). In a large-scale application the number of grids in the network increases with the number of nodes and thus the communication cost is O($\frac{M}{N^2} * N$) = O(M/N).

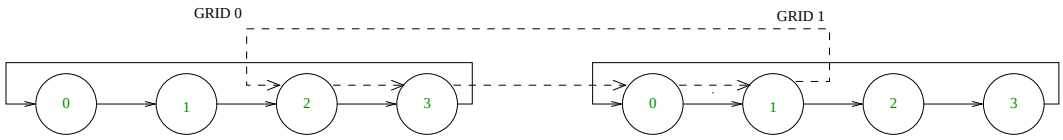


Figure 6.19: Communication costs (number of hops) varies greatly when the data packet transverses two grids.

6.4.1 Transmission Costs in the Presence of Errors

There is almost always an increase in the cost of transmission in the presence of faults. This increase in cost is more dramatic in the number of hops measure. The two measures introduced in the previous section will be used to measure the cost of communication between Node 0 and Node 5 in the scenarios provided in Figures 6.9-6.12. Table 6.4 reports these numbers.

The cost of communication varies with the location of the fault and the specific communication path under study. A more quantitative study will be provided in Section 6.5. Specific communication sequences will be provided with the effects of the faults. The next section will provide two approaches to studying the network behavior, an analytical method to predict the general response of the network and a simulation approach to describe the complex behaviors.

6.5 Results

The following section presents the results collected from simulating the networking scheme under varying fault occurrences, loads, and sleeping nodes. The networking scheme was

Table 6.4: Node 0 - Node 5, Cost of Communication w/ and w/o faults

Figure	**Delay**	**Number of Hops**	**Explanation**
6.9	TW_{token} + $TW_{merged-token}$ + TS_{data} + $TS_{merged-token}$	2	Regular merge process
6.11 (a) & (b)	TW_{token} + $TW_{merged-token}$ + TS_{data} + $TS_{merged-token}$	2	Regular merge process[1]
6.12 (a)	TW_{token} + TS_{data} +	6	The cost to the network also includes the cost at Nodes 4 & 5
6.12 (b)	–	–	Same as 6.11 (a) & (b)

[1]Node 0 might wait more than TW_{token} in the beginning because it can be the second token that gets the merged status, but that delay can be considered inside TW_{token}.

tested by using a model of communication based on either a general communication setup or an e-textile application setup. Depending on the application, the Transverse dimension is either included or not. The simulation results obtained will be compared with our predicted analytical results to prove that the networking scheme operates as expected. The results will also depict the degradation in performance with additional faults and loads.

6.5.1 General Communication Setup

This section will provide a study of a simple 16 node (4 Rows, 4 Columns) setup with no Transverse dimension. Node 0 is used to send a data packet to each node in the network (Node 0 - Node 15). This scheme was chosen because it forces communication with every node on the network. At the reception of a data packet the receiving node sends a reply back to Node 0. Node 0 waits for these replies before sending a new request. The whole process is finished when Node 0 receives the response from Node 15. The time consumed to finish

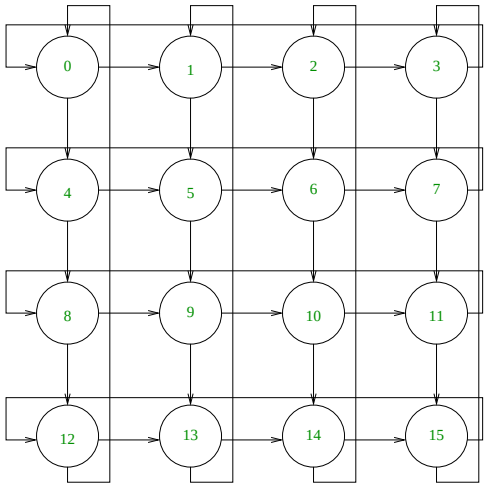


Figure 6.20: The Basic 16 Node network used to report the communication metrics.

this sequence of communication is then reported. The time is reported as an increment of a timed counter representing the smallest granularity of operation in the node. Each node decides on transmission of data at an increment of this counter. This reported value covers both significant metrics described in Tables 6.2 and 6.3. The network used in the first test is shown in Figure 6.20. The communication scheme required 211 increments of the counter to finish with no link errors in the network. The delay from every node is included in the final result reported (211 in this case).

Using the obtained values and the enumerations provided in Section 6.4 an analytical explanation is now provided. A few assumptions are made to simplify the analysis. The first is considering the cost of physically sending a packet to be negligible (TS_{token} or TS_{data}) and adding this cost to the hop count. The second is considering the hop cost to be equivalent to the duration of one increment of the timed counter. The physical implementation used in recording this data was attempted to be close to this assumption to ease the discussion. The cases used to carry this study are shown in Figure 6.21.

Each data communication on the network can be to a destination on the same ring, a different row and column ring, or a "Wrong Route". The cost of each of these connections will first be used to ease the study of the overall operation of the network. Sending on the

same ring requires a TW_{token} according to Table 6.2 and an average of N/2 hops according to Table 6.3, where N is the number of nodes in the ring. The cost in overall time to send a data packet on the ring is then (TW_{token} + (N/2)) counter iterations. Using the stated assumption that TW_{token} = (N/2), considering the cost to send the token and the hop itself equivalent to a counter iteration, the cost of sending on the ring (X) in this case is:

$$X = \frac{N}{2} + \frac{N}{2} = N = 4 \tag{6.1}$$

Sending a data packet to a destination on a different row and column requires the use of a merge. The sending Node has to wait for $TW_{merged-token}$ and the connection will require N hops on average. The cost of sending with a merge (Y) is:

$$Y = TW_{merged-token} + N = 3.5(TW_{token}) + N = 3.5 * (\frac{N}{2}) + N = 11 \tag{6.2}$$

The last communication type to consider is the "Wrong Route," which occurs in some of the cases with faults in the network. In the cases considered for the study, shown in Figure 6.21 (b) and (c) the "Wrong Route" forces the packets on rings that require a merge to reach the final destination. The "Wrong Route" forces an additional TW_{token} to wait for the token in the forced direction, then one hop to the corresponding ring, another TW_{token} awaiting the processing at the data queue and finally a merged communication. The total cost of the connection (W) is (where Y1 is the merge cost, which will be explained in the next paragraph):

$$W = 2(TW_{token}) + 1(hop) + Y1 = 2(\frac{N}{2}) + 1 + Y1 = 5 + Y1 \tag{6.3}$$

Equations 6.1, 6.2, and 6.3 will be used to analyze the communication in the networks shown in Figure 6.21. In case (a), Node 0 sends requests to all the nodes on the network, and these requests will be sent to seven nodes that belong directly to the rings that Node 0 belongs to: Nodes 0, 1, 2, 3, 4, 8, and 12. The other nine nodes in the network require merge communications. The same case exists for the responses to these requests. The total communication cost for this scheme is:

$$a) : 7(X) + 9(Y) + 7(X) + 9(Y) = 14(X) + 18(Y) = 254 \tag{6.4}$$

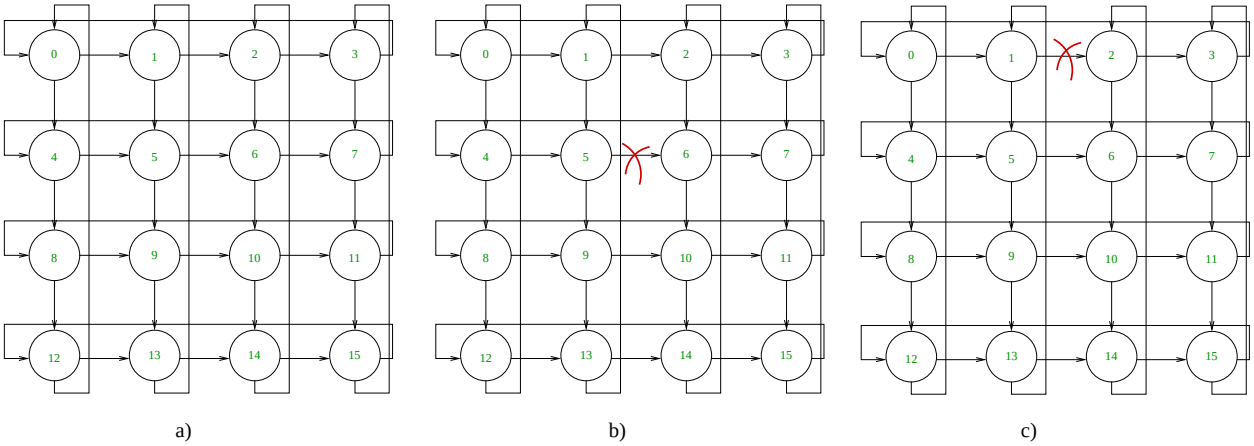


Figure 6.21: The general cases for communication with one link errors are shown in b) and c). The link error in c) belongs to the same ring as Node 0.

6.5.1 Fault Introduction

The following section introduces faults and reports the delay value. The operation of the whole network with faults is thus scrutinized. The fault tolerant scheme declares a node unreachable when both its row and column ring are in error. This is a simplistic approach that only utilizes local error information. This information reports what rings are in error and not the specific links. The graceful degradation in the performance of the network with increasing the number of faults will be represented in both the predicted and the simulated results. This same scheme was tested with one link failure chosen at random for several different trials. The communication scheme responds differently based on the location of the faulty link. This difference is attributed to the operation of the networking scheme. Figure 6.22 shows five trials and the simulated counter value. The two cases presented in Figure 6.21 (b) and (c) will be used to predict the performance of the networking scheme.

The incremental delays between the one fault cases and the no faults case are the following: Trial 1: 106, Trial 2: 27, Trial 3: 16, Trial 4: 28, Trial 5: 130. Trial 1 and 5 have a significantly more severe impact on the operation of the network. Both of these cases have the link error on a ring that Node 0 (the source of all requests and the destination of all replies in the

communication scheme) belongs to. There are two effects to that situation. Node 0 is creating all the requests and thus all requests destined to a node on the ring with the error will require a "Wrong Route," which is usually an expensive operation. When Node 0 is the destination of all the responses, because this node is on a ring with a link error, every response has to be dealt with using the fault tolerant scheme (almost always more expensive than regular operation or at the same cost). When the error is on a ring that Node 0 does not belong to, such as Trials 2, 3, and 4, the fault tolerant scheme is used in a substantially smaller portion of the communication and thus the cost is less.

For case (b) in Figure 6.21, Node 0 sends to the same seven nodes directly on the rings. The six nodes 9, 10, 11, 13, 14, and 15 are again reached using a merged connection. Nodes 5, 6, 7 are also reached through merged connections, but Node 0 has to wait for its row token to send the merging request; in the other cases it can send either using the row token or the column token. This increases the initial waiting period. In a regular case the sending node waits for the token and creates the request; in this case there is probability of 0.5 that it gets the wrong token first and thus has to wait for another TW_{token}. Thus Nodes 5, 6, 7 will have an increment of $0.5(\mathrm{TW}_{token})$, the merge cost Y will be represented by Y1 in this case where $\mathrm{Y1} = \mathrm{Y} + 0.5(\mathrm{TW}_{token})$. The seven nodes on the direct rings send back on those rings. Nodes 9, 10, 11, 13, 14, 15 communicate using regular merging, while Nodes 5, 6, 7 require a "Wrong Route" to reach Row 2 and then a merge to reach Node 0. The

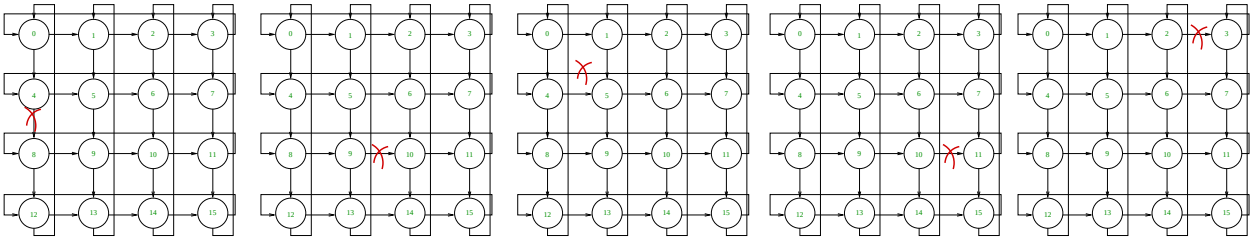


Figure 6.22: Five trials of one link failures and their respective cost of communication.

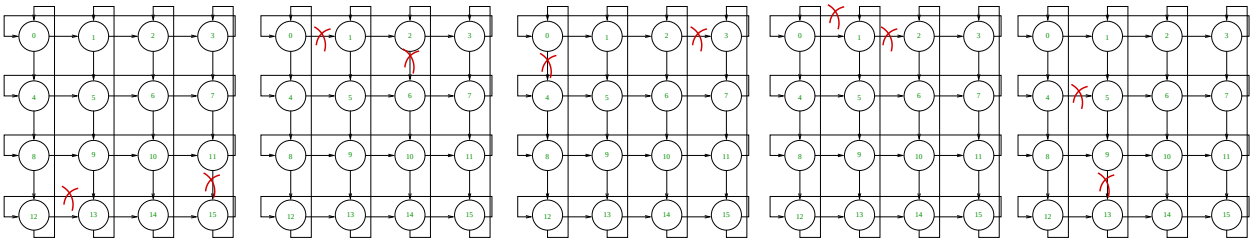


Figure 6.23: Five trials of two link failures and their respective cost of communication.

communication cost for this case is:

$$b) : 14(X)+12(Y)+3(Y1)+3(W) = 14(X)+15(Y)+3(\frac{TW_{token}}{2})+3(5+Y+1) = 275 \quad (6.5)$$

For case c), Node 0 sends to Nodes 0, 4, 8, 12 directly on the ring, and to the nine merging nodes using regular merges with the addition of the extra waiting period because there is only one merge that is possible. For Nodes 1, 2, and 3, a "Wrong Route" is used; this route reaches Node 4 and merges are instantiated from there. The responses in this case follow the same communication routes as the requests and thus the total cost for this case is:

$$c) : 2(4(X) + 9(Y1) + 3(W)) = 2(4(X) + 12(Y1) + 15) = 350 \quad (6.6)$$

The values calculated using 6.4, 6.5, and 6.6 are representative of the values collected from the simulator and reported in Figure 6.22. These calculations offer a way to estimate the cost of communications and to understand the differences in the simulated data. The discrepancies in the values are attributed to the assumptions taken and probabilities inherent in creating these enumerations. From the calculated and recorded results, it can be seen that schemes requiring "Wrong Routes" can increase the cost of communication significantly.

The same general communication scheme was tested with two link errors in the network. Figure 6.23 presents a portion of the trials tested and the cost values for each case. The implemented fault tolerant scheme assumes that if a node has an error on its row and column then that node is unreachable, which is why there is no result for case 3 in Figure 6.23. The same discussion that applied to the location of the errors in the one fault case applies here.

When the fault is on one of the rings of Node 0, the cost increases by a large amount, as shown by Trials 2 and 4. Since both faults in Trial 4 belong to one ring, then the effect is the same as that of one link error on that ring. Another point to be added in this discussion is that the sender will discard any request for a node with an error on its row and column, Node 4 in Trial 5, for example. This saves on the overall time needed because that request is never sent. In the case that one error is on a ring connected to Node 0, for example, Row 0 in Trial 2, Node 0 will not learn of the column error on Column 2, and thus will try to send to Node 2 without discarding the data packet. Node 0 in this case sends to Node 4 using a "Wrong Route"; Node 4 discards the data packet, but Node 0 waits for a timeout period before it realizes that the connection does not exist. In our case that timeout was set to 50 counter cycles. Following this analytically, Node 0 requests 0, 4, 8, 12 through ring connections with cost 4(X), 5, 6, 7, 9, 10, 11, 13, 14, 15 through merges with cost 9(Y1), and 1, 3 through "Wrong Routes" with cost 2(W), Node 2 costs 50 from the timeout. On the response a cost of 4(X) from 0, 4, 8, 12; 7(W) from 6, 10, 14, 1, 3 and 6(Y1) from the remaining nodes. The total cost is (which compares favorably to the cost of 372 obtained by simulation):

$$8(X) + 15(Y1) + 7(W) + 50 = 381 \tag{6.7}$$

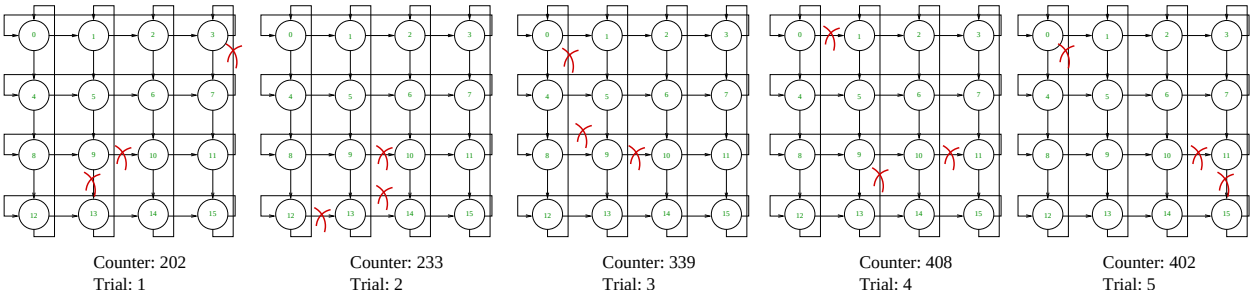


Figure 6.24: Five trials of three link failures and their respective cost of communication.

Three fault links in the network have the same effect as previously stated. The effect of the errors are much larger when on the same ring as Node 0, and there is a larger probability for timeout cases, for example, Trial 4 and Trial 5 had 2 timeouts each, as shown in Figure 6.24. The result of Trial 1 is the lowest recorded even though the network has three link errors.

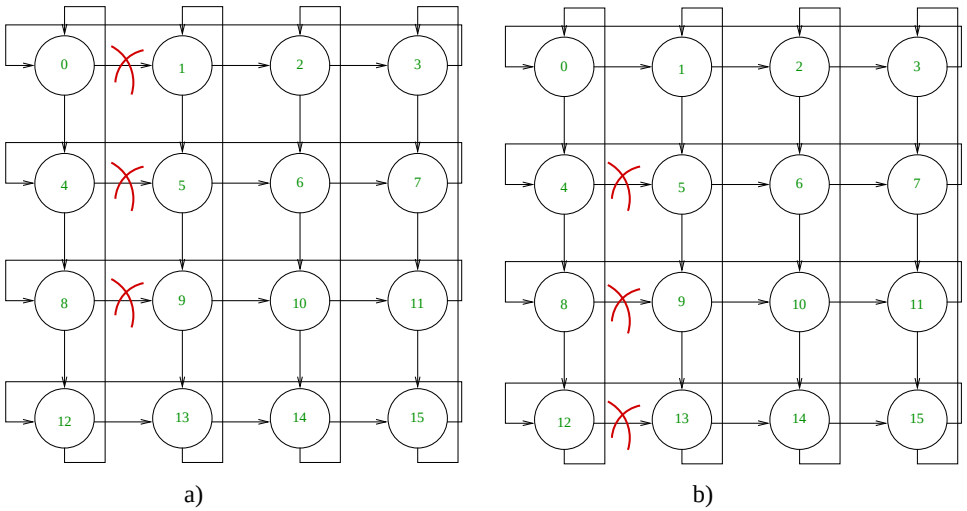


Figure 6.25: The two cases with a fabric tear with one surviving link in the tear path.

This is attributed to discarding two request/result pairs at Node 0 (for Nodes 9 and 11). Table 6.5 provides a summary of the simulation values collected for different fault numbers. The trials were repeated until clear confidence intervals were reached for the different cases. For each fault number tested, there are two cases one with a fault occurring on Row 0 or Column 0 and the other where these rings do not have faults. A few assumptions were used in representing this data, if more than one fault occur on the same ring, the effect on the operation of the networking scheme is the same and thus this is considered as one fault and reported as thus. If Node 0 recognizes that a node has a row and column error and thus does not send to it, the value 50 (timeout value) was added to the cumulative cost to represent this loss in connectivity. The reported 95% confidence interval was calculated using [61]:

$$Mean \pm \frac{(Standard\ \ Deviation)(2.776)}{\sqrt{Number\ \ of\ \ Samples}} \tag{6.8}$$

The reported values manifest the graceful degradation of the networking performance with the addition of faults.

Tears across the fabric are expected during the operation of an e-textile. The largest tolerable tear error is one that leaves at least one link in operation as shown in Figure 6.25. As observed earlier, when the error is on the same ring as Node 0 the communication cost

Table 6.5: Summary of Simulation Values (in Counter Increments)

			95% Confidence Interval	
Case	**Mean**	**Standard Deviation**	**Lower Bound**	**Upper Bound**
1 fault not on ring[1]	228.40	5.941	221.04	235.77
1 fault on ring	321.80	14.37	303.95	339.64
2 faults not on ring	267	5.29	258.51	275.48
2 faults on ring	392.5	26.85	355.23	429.76
3 faults not on ring	302	1	300.39	303.60
3 faults on ring	459	8.36	447.38	470.61

[1]Ring denotes a ring directly attached to Node 0 in this example (Row 0 or Column 0).

is much larger. In this case this increase is more significant because all the communications outside Column 0 have to use a "Wrong Route", as shown in Figure 6.25, and this route has to be pushed down the column three times before it is forwarded, adding a TW_{token} at nodes 4, 8, 12, along with the hop cost.

The costs for the networks shown in Figure 6.26 are 489 for (a) and 225 for (b). This significant increase is due to Node 0 having to use "Wrong Routes" to reach all the nodes that are not on Column 0. For case a) Node 0 uses ring connections to send requests to 0, 4, 8, 12. To connect to 13, 14, 15 a "Wrong Route" is used three times to reach Node 12 and then a ring connection. Each "Wrong Route" uses 2 TW_{token} and one hop. The cost for each these connections is 3*2(N/2) + 3 + X. For all other nodes the ring connection from 12 is replaced with a merge of cost Y1. The total cost for requesting is: 4(X) + 3(15 + X) + 9(15 + Y1). On the reply side, 1, 4, 8, 12 use a ring connection, thus having a cost of 4(X). 13, 14, 15 use a merge connection 3(Y1). 9, 10, 11 use a "Wrong Route" with one

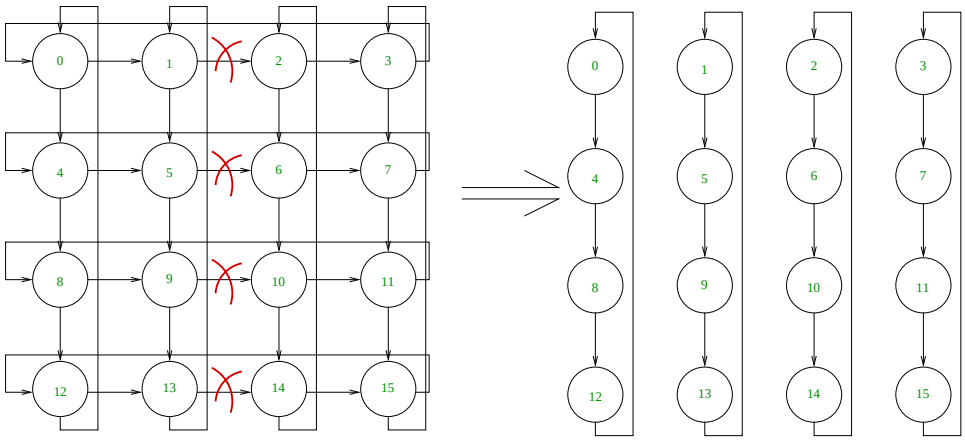


Figure 6.26: The two cases with a fabric tear with one surviving link in the tear path.

hop and then a merge (Y1), thus having a cost of 3(5 + Y1). 5, 6, 7 use a two hop "Wrong Route" with a cost of 3(10 + Y1). 1, 2, 3 use the three hop one at a cost of 3(15 + Y1). The analytical total cost of the network is:

$$11(X) + 21(Y1) + 15(15) + 15 + 30 = 566. \tag{6.9}$$

6.5.2 Increasing the Load

Increasing the load in the network is another important metric. To deal with heavy loads the work in [15] forced all the nodes to go to merged states when the respective tokens are captured, and to send on the row-column and column-row rings only. This implementation of the network deals with light loads, and thus merges will only be asked for when they are necessary. The topology of this network allows for simultaneous transmissions to take place at different rings with no effect to the total cost if there is no need for merges. Thus increasing the load will have no effect on the communication cost of certain communication schemes (if the communication is restricted inside the rings). The scheme used to test for communication costs will use the same protocol presented earlier, using a single node to send requests and wait for replies from all the nodes in the network in a round-robin fashion. To show the increase in the cost, the method uses multiple nodes to send the same requests

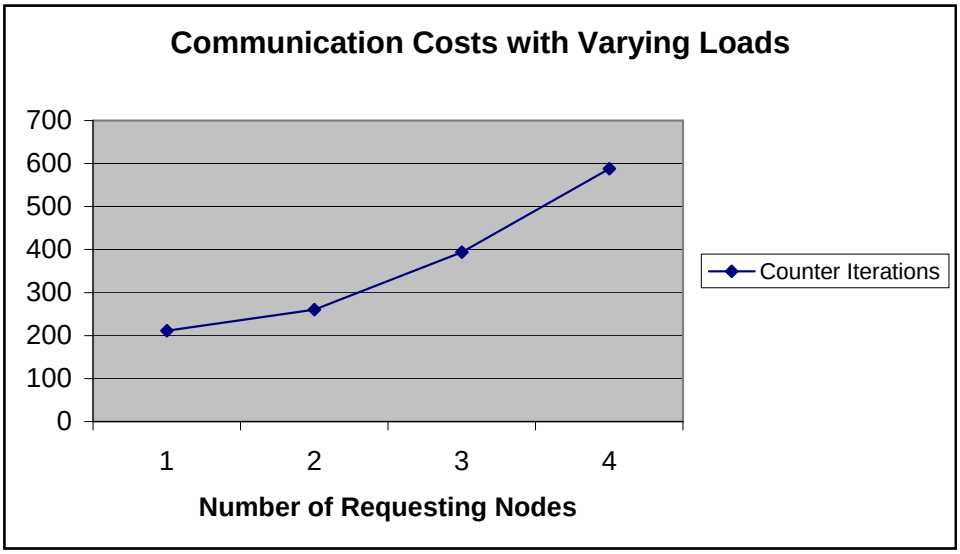


Figure 6.27: The communication cost of the general communication scheme increases significantly while increasing the number of requesting nodes.

in the same fashion starting with Node 0 and ending in Node 15. For the one sender case, the value is already reported at 211, where Node 0 was the sender. Three more cases are presented: two sending nodes (Node 0 and Node 15), three sending nodes (Node 0, Node 15, and Node 12), and four sending nodes (Node 0, Node 15, Node 12, and Node 3). The reported cost was as follows: one requesting Node: 211, two requesting Nodes: 260, three requesting Nodes: 394, four requesting Nodes: 588. These values are plotted in Figure 6.27. This specific method of increasing the requesting nodes and using these nodes to communicate with the same destinations was chosen to increase contention and show the degradation in the response of the networking scheme.

This increase in the cost can be attributed to multiple factors. The first is that when a node has more than one data packet in its data queue, it only sends one out and thus the waiting period for the second packet is doubled. Another situation arises when a node (a) needs to send a data packet on the row, but a merge is already in place and the master of that merge is circling the row-column token. If node (a) misses sending with this token, the waiting period is extended (waiting for the column-row to finish circulating and then waiting

for the row token), thus increasing the wait to double the time on the data packet to be sent. Combining such factors can delay specific packets considerably, and since the protocol does not work until all packets are received or timed-out, this increases the communication cost of the studied protocol. A third factor is the need to wait for a merge state on a specific ring to end before another node can start with another merge. The occurrence of these factors increases with increasing the load as shown by the collected results. To take advantage of the topology of the network, the application protocol should create "communities of interest" [15] and localize the communication under heavy loads. In the best case, all communications are restricted to the rings and there will be no effects on the communication cost by increasing the load.

6.5.3 Shirt Network

This section will provide data pertaining to the effects of the transverse dimension on the communication cost. The expected increase in communication cost using these links, Section 6.1.1, is verified analytically and by simulation. The application is based on a shirt e-textile with two 16-Node networks, one on the front of the shirt and one on the back. These networks are connected by the transverse dimension across the front and back textiles. The application protocol is as follows: Node 0 on Grid 0 (front) sends requests and waits for replies from three nodes on the front and one node on the back. The cost of this application protocol is provided under varying fault schemes. The base network is shown in Figure 6.28, and the transverse links are used to connect the two fabrics together across the shoulders of the vest. Three nodes were picked at random from the front grid (Nodes 8, 14, 15) and a fourth on the back grid (Node 15). This case provides the cost of sending over the transverse link, Case 1. Two more cases are presented to study the effect of link failures on the transverse links. The first, Case 2 in Figure 6.29, provides an error on the link used by the reply to reach Grid 0. The second, Case 3 in Figure 6.29, provides errors on the both of the links used by the request and the reply and thus forces a "Wrong Route" in both cases.

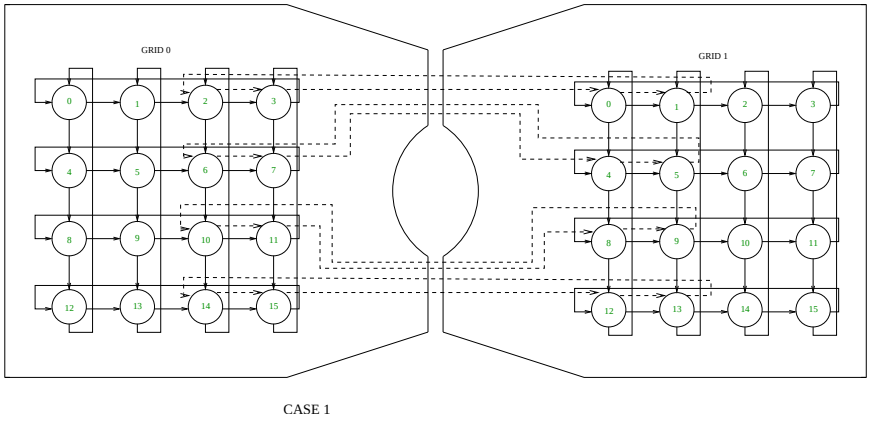


Figure 6.28: The Transverse Links are used to connect both networks on the front and the back of the vest.

For Case 1, the request from Node 0 to Node 8 is on the ring so the cost is (X). The requests to both 14 and 15 require a merge and thus each costs (Y). To send a request to Node 15 on the back Grid, Node 0 first forces its data on the row because it is not connected to the correct transverse link. This has a cost of (X) to reach Node 2. Node 2 realizes that this data packet is destined to another grid and thus sends it over the transverse link, which is another cost of (X) to reach Node 0 (Back). The cost at Node 16 is the same as a "Wrong Route" and a merge to get to Node 15 (Back), thus costing (5 + Y). The replies have the same cost, but the path from Node 15 (Back) to Node 0 utilizes the transverse link between Node 13 (Back) and Node 14. The total cost is:

$$2(X + 2(Y) + 2(X) + 5 + Y) = 2(3(X) + 3(Y) + 5) = 100 \tag{6.10}$$

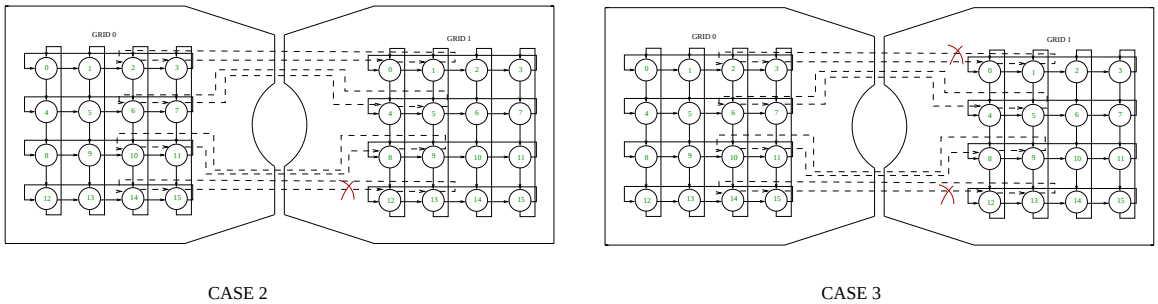


Figure 6.29: The two cases provide means to study the effect of an error on the used Transverse links.

In Case 2, Node 12 (Back) realizes that it cannot use its transverse link and thus forces a "Wrong Route" on the column, then Node 0 (Back) will route the data to Node 2, at a cost of X and a W = (4 + 5) = 9. The increase on Case 1 is waiting and one hop = 3. There is a decrease from the merge to a ring connection (Y - X - W). Then the cost should be 98.

In Case 3, there is one extra hop for the reply since Node 0 (Back) cannot reach the Front Grid. That is an extra cost of 3 and now the cost is that of a merge plus "Wrong Route", thus a total increase of 8. The request in this case too is forced on a "Wrong Route" at Node 3 to Node 7 adding a cost of 3 (waiting and one hop) and the cost of 5 for the "Wrong Route" processing at Node 4 (Back); thus the total cost should be 108. The simulated values are: Case 1: 92, Case 2: 81, Case 3: 94. This test presented the increase in the communication cost by the introduction of Transverse connections.

6.5.4 Sleeping Nodes on a 16-Node Acoustic Beamformer

Inactive nodes in a network can move to a dormant state to lower the power consumption of the whole network. These sleeping nodes can affect the communication cost since their effect is the same as two link failures as shown in Figure 6.8. There is no difference between a sleeping node and a failed node to the routing scheme. The application protocol can be chosen in a way not to be affected by the sleeping nodes in the system, thus utilizing the ability to lower the power in the network without the communication costs.

The application protocol provided in this case is the following, where every ring in the 16-Node system represents an Acoustic Array Beamformer. The "master" on each ring will ask for data from the other nodes and compute a location for the vehicle. The location data can be verified by checking the data from another ring; in this case the scheme uses a ring at a perpendicular to the original ring. The communication can thus be constricted to a row and a column in the system. For specific cases it is assumed that the data is redundant and only the specific two rings need to be awake in the system. If Node 1 is the node in common between the two specific rings, the network will be as shown in Figure 6.30.

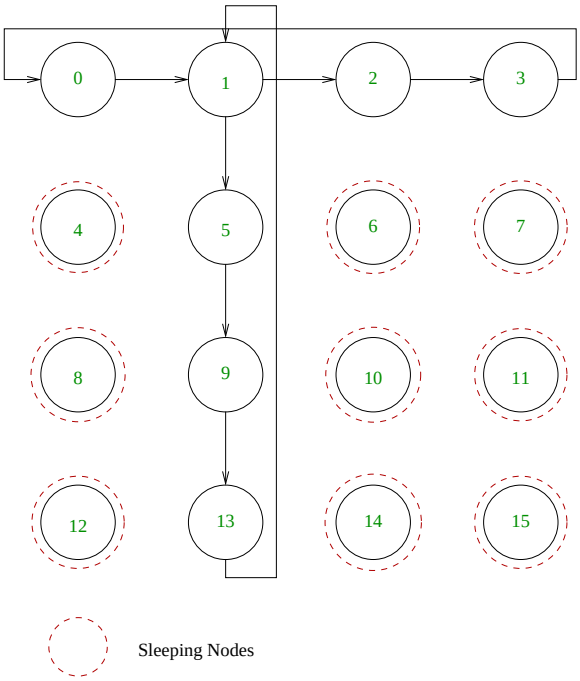


Figure 6.30: The 16-Node Beamformer with the insignificant nodes in a dormant state.

Node 0 is considered the master of Row 0 and Node 13 the master of Column 1. Both Node 0 and Node 13 send requests for the three other nodes in their ring. When Node 13 receives all needed replies, it sends its value to Node 0. When the response from Node 13 is received by Node 0 a cycle of the operation is finished. Analytically, Node 13 sends 3 requests on its ring and waits for 3 replies amounting to 6(X). The sending to Node 0 requires a merge (only one node is available to do the merge) (Y1). The total cost is 6(X) + (Y1) = 24 + 12 = 36. The simulated cost is 34. The gain in using the sleeping nodes in this case is attributed to power consumption. Every active node running the beamformer is either mic sampling or mic sampling and beamforming (the cost of communication is negligible in terms of power) [54]. If the sample size for the beamformer is 512 samples for example, the algorithm will read 512 samples from the mic; at the same time the beamforming will run once. According to the values in [54] the sampling requires 438 μs, thus 512 samples require 224.256 ms. The beamforming code requires 162.8 ms. The average current drawn during this period is 67.14 mA; if the voltage used is 3 V, then the average power consumed

is 201.42 mW. The power consumption of node in a sleeping mode is negligible and thus the savings to the system is 201.42 mW x (number of nodes asleep). In this specific example, 9 nodes were asleep and the power consumption is decreased by 1812.78 mW.

Another application scheme is provided in Figure 6.31, Node 0 is the master of Column 0, Node 13 is master of Row 3, and Node 3 of Column 3. The application proceeds as mentioned earlier with Node 13 and Node 3 sending their information to Node 0. This application is processed under two routing circumstances, the first considers the sleeping nodes when communicating between Node 3 and Node 0 and thus routes around the sleeping nodes (Node 1 & 2) using "Wrong Routes" and a merge. The second wakes up Node 1 and Node 2 with a token and sends its value directly to Node 0. This application will show the effects of using the fault tolerance routing on time and power consumption.

In the first case, Node 13 sends its result to Node 0 with a merge at Node 12. Node 3, sends its result to Node 7, Node 11 and then to Node 15 using "Wrong Routes" after that a merge at Node 12 relays the message to Node 0. Sending from Node 3 requires more time and thus it dictates the time required for the application scheme. In the second case, Node 3 wakes Row 0 and sends its data directly to Node 0. In this case the communication from Node 13 takes more time and dictates the time for the application scheme. The simulation values collected were 63 for the first case and 58 for the second case. There is a decrease in time consumed when the sleeping nodes are woken up but at an increase in the power consumption. Node 1 is awoken at counter increment 28 and Node 2 at 29, this increases the power consumption by 2 * 201.42mW. Following from the results of this example, there is a trade-off between power and time consumption that has to be considered for each specific application.

6.5.2 Conclusion

The implemented networking scheme was discussed in the previous section. This networking scheme provides connections while dealing with faults and sleeping nodes while degrading

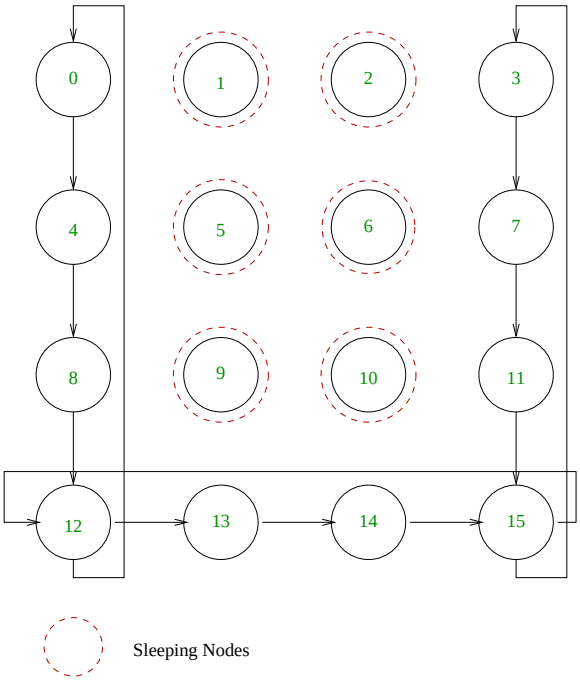


Figure 6.31: The 16-Node Beamformer with the insignificant nodes in a dormant state.

gracefully in performance. The simulation results displayed the effects of different situations on the networking scheme. An analytical method was provided to estimate the communication cost for specific application protocols. The comparison between the simulated and the analytical results provide insight into the expected behavior of the networking scheme. This analytical method introduces more errors as it analyzes a longer time as can be seen in Figure 6.32 representing the simulation times versus the analytical times predicted. As a general statement, faults in the network increase the communication cost by changing a route to a more expensive one, a ring connection to a merge or "Wrong Route" (X $\rightarrow$ Y or W), or a merge connection to a "Wrong Route" (Y $\rightarrow$ W), for example.

Case	Simulation Result	Analytical Result	Difference	Description
1	34	36	2	16-Node Beamformer
2	81	98	17	Shirt Case 2
3	92	100	8	Shirt Case 1
4	94	108	14	Shirt Case 3
5	211	254	43	GCP No errors
6	222	275	53	GCP 1 error
7	233	275	42	GCP 1 error
8	234	275	41	GCP 1 error
9	312	350	38	GCP 1 error
10	336	350	14	GCP 1 error
11	372	381	9	GCP 2 errors
12	489	566	77	GCP Tears
GCP: General Communication Protocol				

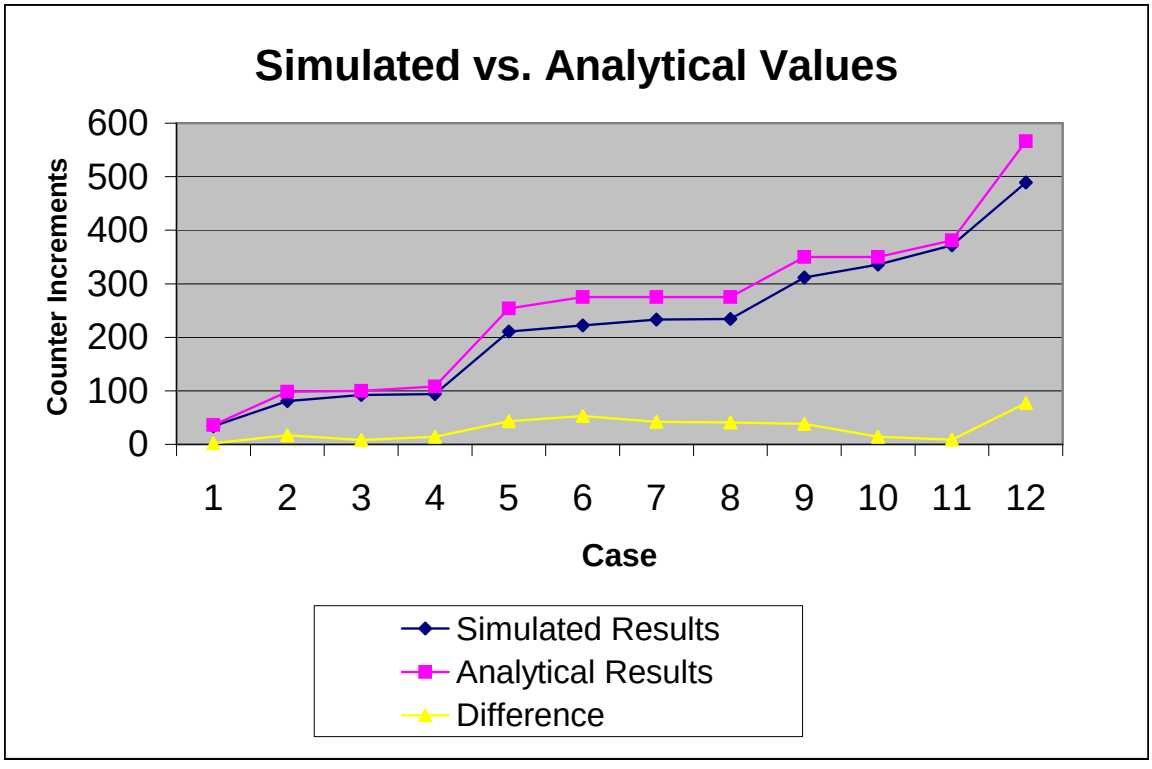


Figure 6.32: There is a general trend of increase in difference between the simulation and the calculated analytical results as the value of the counter increases.

Chapter 7

Conclusion

The major goal of this research was to create an electronic textile architecture that embodies the experience gained from constructing hardware prototypes, provides the framework for a simulation environment for e-textile systems, and maps future directions for the e-textile architecture. This goal was reached by developing a set of precepts to govern future endeavors and to guide the process of creating e-textile applications.

Three main areas of precepts, embedding of conductive channels, manufacturing, and software, were presented in Chapter 4. The listed precepts provide the basis of an evolving electronic textiles architecture. The precept discussions provided details on previous attempts and failures along with foreseen future directions. As an example, the developed precepts recommend the use of *digital* communication through *insulated* wires governed by a *fault-tolerant low-power* communication scheme. More experience and experimentation will develop these precepts from open-ended guidelines to a more established set of precise rules.

The process of formulating the precepts based upon acquired experience helped in the creation of the software environment that acts as a simulation and evaluation toolkit for hardware prototypes. This environment can be used at the outset of a project to test the feasibility and make design decisions. The simulation process will later help in fine-tuning

the created hardware by varying system parameters, which is easier in the virtual world. The research done in [54] augmented this simulator with a power consumption and fabric fault simulator, while the work in [53] dealt with creating an acoustic data and beamformer algorithm simulator; the simulator was discussed in Chapter 5. This simulation also aids in exploring the design space of e-textiles. This design space is too large to be explored with only hardware prototypes. The simulation environment provides the ability to simulate both the sensed environment and the response of the e-textile system.

Providing low-power fault-tolerant communication between separate nodes on an e-textile is a must. The creation and testing of such a networking scheme was made possible using the simulation environment. Testing and developing this networking scheme was only possible in the simulation environment due to the limited number of hardware prototype nodes. Chapter 6 presented the theory, operation, analysis, and simulation results of this networking scheme. The presented networking scheme provides connectivity in the presence of faults. Faults are expected on an e-textile during manufacturing and deployment. Low-power operation requires the use of sleeping modes in the processing nodes on an e-textile to save on power. The networking scheme provides support to these sleeping nodes by offering alternate routes to keep these nodes in the sleeping mode. The performance of this network can be accurately predicted using the analytical method discussed in Chapter 6.

Finally, a 30-foot Acoustic Beamforming Array was created to test the theories and the precepts. This e-textile detects the presence and the line of bearing of a large vehicle using acoustic beamforming. The triangulation of the computed line of bearing from four autonomous clusters provides location data for the sensed vehicle. This is the first e-textile to include computing and networking on the fabric. This work helped in moving forward the evolution of the electronic textiles architecture.

The contributions of this dissertation work are summarized in the following list:

- Definition of an *electronic textile architecture* by creating architectural precepts based on experience and on-going research (Chapter 4)

- Creation of a *simulation environment* to test new concepts and improve extant prototypes using the Ptolemy environment (Chapter 5)

- Development of a *networking scheme* that routes around faults and sleeping nodes with predictable performance (Chapter 6)

- Implementation of the *acoustic beamforming array* as the first e-textile hardware prototype that combines sensing and processing on the fabric (Section 3.4)

The future directions foreseen for this architecture can be divided into immediate issues and general paths. The immediate issues include creating fabric/electronics connections to provide for easier and more stable connections of components, integration of fiber and thin-film form components in the prototypes, and experimentation with different weave patterns and conductive channels.

The general paths encompass the creation of a more thorough electronic textiles architecture. The general open-ended precepts reported in Chapter 4 should be developed after thorough research into a set of specific rules to manage all the details of creating electronic textile systems. Design paths should focus on creating more general nodes and fabric swatches to take advantage of mass producing the electronic components and the fabric backplanes to lower the cost of these systems and minimize re-invention. To fully exploit the low cost manufacturing of textiles, the design of e-textile systems should correspond to the extant fabric manufacturing techniques. The generality in design should cover all aspects of e-textile research and conform to the created precepts. Future research endeavors should focus towards the deeper establishment of the general electronic textile architecture.

The presentation of the software architecture should be in a more user-oriented fashion. The software should provide services based on the precepts and algorithms given in this dissertation. The use of these services will inherently force the implementation of the developed rules, facilitating the design process and minimizing re-invention.

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Appendix A

Pseudo Code

Row Token Arrival:

- **if(Self_Column_Error == TRUE):** Retrieve information about errors in columns and update the value in the token to reflect this error

- **else:** Retrieve information about other column errors.

- **if(Data Packet ready for sending):**

  - **If(Destination on same Grid):**

    - **If(both destination row and column have an error):** Discard

```
If(Destination on same row):
     if(No error on row): Send data directly on Row ring.
     else: Data will be pushed on the column "Wrong Route" using
           the Column Token.
else:
     If(Destination on different Column):
          if(Row Error == TRUE):
               if(Error on destination row): Data will be pushed
                    on the column "Wrong Route" using the
                    Column Token.
               else: Column Token will take care of it, no action.
          else:
               if(Column Error == TRUE):
                    if(Destination column has an error): Push Data
```

```
                                        down the row "Wrong Route".
                                   else: Ask for a merger with this Row and
                                        Destination Column.
                              else:
                                   if(Destination column has an error):
                                        if((Error on this Column)||
                                              (Error on Destination Row)):
                                              Push Data down the row "Wrong Route".
                                        else: Return to Data Queue for
                                             later processing.
                                   else: (all good): Ask for a merger with this
                                        Row and Destination Column.
                         else:
                              if(Column Error == TRUE): Push Data down the row
                                                        "Wrong Route".
                              else: Column Token will take care of it.
```

- **else:** Transverse Token will take care of it, no action.

- **else:** No Action

- **If(Waiting_For_Row_Token == 1):**

  - //Column Token has been captured

  - Create a Row_Column Token

  - Merged_Status = 1;

  - Waiting_For_Row_Token = 0;

  - Send Token on Row ring.

- **If(Merged_Status == 0):**

  - **If this node was asked to go to a merged state:**

    - Grab the token

    - Waiting_For_Column_Token = 1;

- **else:** Release the Row Token on the Row ring.

Column Token Arrival:

```
if(Self\_Row\_Error == TRUE): Retrieve information about errors in rows and
      update the value in the token to reflect this error.
else: Retrieve information about other row errors.

if(Data Packet ready for sending):
     if(Destination on same Grid):
          if(both destination row and column have an error): Discard

          if(Destination on same column):
               if(No error on column): Send data directly on Column ring.
               else: Data will be pushed on the Row "Wrong Route" using the
                    Row Token
          else:
               if(Destination on different row):
                    if(Column Error == TRUE):
                         if(Error on Destination Column): Data will be pushed
                               on the row "Wrong Route" using the Row Token.
                         else: Row Token will take care of it, no action.
                    else:
                         if(Row Error == TRUE):
                              if(Destination Row has an error): Push data down
                                    the column "Wrong Route".
                              else: Ask for a merger with this column and
                                    Destination Row.
                         else:
                              if(Destination Row has an error):
                                   if(Error on Destination Column): Push data
                                        down the column "Wrong Route". (Should
                                        not get here)
                                   else: Return for Data Queue for later
                                        processing. (Other merge will take care
                                        of it)
                              else: (All Good): Ask for a merger with this Row
                                   and Destination Column.
               else:
                    if(Row Error == TRUE): Push Data down the column "Wrong Route".
                    else: Row Token will take care of it.
     else:
          if((Error on Transverse)&&(Transverse reached the Destination Grid)):
               Push Data down the column "Wrong Route".
```

```
else:
     if((Error on Row)&&(Transverse cannot reach the Destination Grid)):
          Push data down the column "Wrong Route".
     else: keep the data for later processing by other tokens.
```

- **If(Waiting_For_Column_Token == 1):**
  - //Row Token has been captured
  - Create a Row_Column Token
  - Merged_Status = 1;
  - Waiting_For_Column_Token = 0;
  - Send Token on Row ring.
- **If(Merged_Status == 0):**
  - **If this node was asked to go to a merged state:**
    - Grab the token
    - Waiting_For_Row_Token = 1;
- **else:** Release the Column Token on the Column ring.

Data Packet Arrival:

- **if(This is the source of the Data Packet):** DISCARD
- **if(Data Packet is meant for this node):** DONE
- **else:**
  - **if(Destination on same Grid):**
    - **switch(Channel data recieved on)**
      - **case(Row):**
        - **if((Destination_Row != Row_ID)&&(Destination_Column != Column_ID)):** can be a "Wrong Route" or Merged_Ring
        - **if(there is a column error on column before): re-process the packet.**
        - **else:**
        - **if(Merged_Status == 0):** Forward on Row ring.
        - **else:** Forward on Column ring.
      - **case(Column):**
        - **if((Destination_Row != Row_ID)&&(Destination_Column != Column_ID)):** can be a "Wrong Route" or Merged_Ring
        - **if(there is a row error on row before): re-process the packet.**
        - **else:**
        - **if(Merged_Status == 0):** Forward on Column ring.
        - **else:** Forward on Row ring.
      - **case(Transverse):**
        - Data just arrived from another grid, add it to the Data Queue to be processed later for forwarding.

- **else:**
    - **if Data received on Transverse ring:** Forward Data on Transverse
    - **else:** Let the Transverse Token deal with forwarding this packet.

Vita

Zahi Nakad was born in the winter of 1976 in a small town called Jdita in the Bekaa Valley, Lebanon. After graduating from his high school, he was accepted to the Computer and Communication Engineering program at the American University of Beirut. After graduating with distinction in 1998, Zahi joined the Computer Engineering program in the Bradley Department of Electrical and Computer Engineering at Virginia Tech as a graduate student. In the spring of 1999, Zahi joined the Configurable Computing Lab and received his Master's degree in 2000 under the guidance of Dr. Mark Jones. Zahi's work then focused on e-textiles and creating the VT e-Textiles Group in the Configurable Computing Lab under the guidance of Dr. Mark Jones and Dr. Thomas Martin. He received his Ph.D. degree in Computer Engineering in 2003.