Reconfigurable Fabric Vest for Fatal Heart Disease Prevention

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Abstract

In recent years, exciting technological advances have been made in development of flexible electronics. These technologies offer the opportunity to weave computation, communication and storage into the fabric of the every clothing that we wear, therefore, creating intelligent fabric. The implications of seamlessly integrating a large number of communicating computation and storage resources, mated with sensors and actuators, in close proximity to the human body are quite exciting. This paper present Reconfigurable Fabric-Vest (*RFab-Vest*) designed and implemented at UCLA for a medical application. Such a vest would have sensors for physiological readings, and software-controlled, electrically-actuated trans-dermal drug delivery elements. Furthermore, computational elements are embedded in the vest for collecting data from sensors, processing them and driving actuation elements. Since the RFab-Vest will be used for medical, life-critical applications, the single most critical requirement of such a vest is an extremely high level of robustness and fault tolerance. Meantime, the key technological constraint for these mobile systems is their power consumption. Our target application for the RFab-Vest is the detection of possibly fatal heart problems, specifically unstable angina pectoris or ischemia. We illustrates the design stages of RFab-Vest as well as the technical details of reconfiguration and ischemia detection algorithms. Moreover, we measure the robustness of our system with existence of various faults. Finally we present a summary on the power consumption of several configurations of the RFab-Vest as well as the computational capability of our processing units for the specific application that we implemented.

1 Introduction

1.1 Motivation

Computation, storage, and communication are now woven into the fabrics of our society with much of the progress being due to the relentless march of the silicon-based electronics technology as predicted by Moore's Law. The emerging technology of flexible electronics, where electronics components such as transistors and wires are built on a thin flexible material, offers a similar opportunity to weave computation, storage, and communication into the fabric of the very clothing that we wear. The implications of seamlessly integrating a large number of communicating computation and storage resources, mated with sensors and actuators, in close proximity to the human body are quite exciting. For example, one can imagine biomedical applications where biometric and ambient sensors are woven into the garment of a patient or a person in a hazardous environment to trigger or modulate the delivery of a drug. Realizing this vision is not just a matter of developing innovative materials for flexible electronics, along with accompanying sensors and actuators. The characteristics of the flexible electronics technology and the novel applications enabled by it require innovation at the system-level technology level. The natural applications of these systems have environmental dynamics, physical coupling, resource constraints, infrastructure support, and robustness requirements that are distinct from those faced by traditional systems. This combination requires one to go beyond thinking of these systems as traditional systems in a different flexible form factor. Instead, a rethinking of the architecture and the design methodology for all layers of these systems is required.

1.2 Driver Application

Although the goal of the RFab project is to investigate system architecture and design methodology concepts for electronic textiles, successful systems research of this nature requires that one not only develop these concepts, but also validate them in context of real technology constraints and application requirements. Therefore, we use pervasive patient monitoring and sensor-driven personalized trans-dermal drug delivery as our driver application. One possibility of leveraging electronic textile technology in the context of such an application is to create a flexible garment (i.e., vest) that the patient can wear, which has sensing, computation, communication, and actuation elements embedded in it. We are developing such a prototype vest called the RFab-Vest. Ideally, such a personalized drug delivery vest should have sensors on both the interior (to measure physiological readings) and on

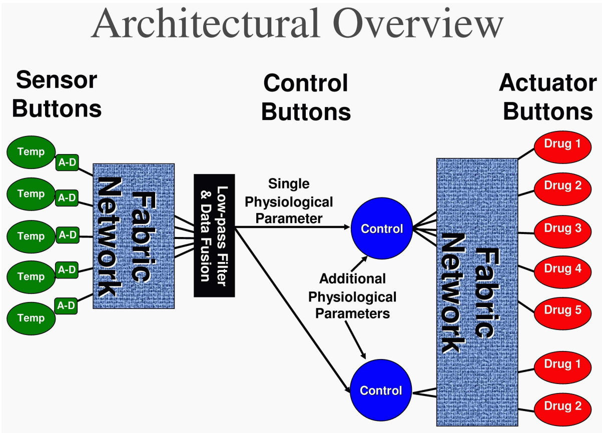

Figure 1: System Architecture of the RFab-Vest

the exterior (to measure environmental readings such as the presence of toxins in the surroundings), and a software-controlled, electrically-actuated trans-dermal drug delivery system. It should allow low-latency, fine-grained adaptation of the drug dosage based on continual physiological measurements in the case of patients, and based on both environmental and physiological measurements in the case of people operating in hazardous environments. More generally, our application driver is representative of biomedical applications where information technology is integrated into fabrics and textiles. Figure 1 shows the overall system architecture of the RFab-Vest. As is evident from the Figure 1, the vest consists of four main subsystems: control (or computation), communication, sensing, and actuation.

One of target applications of RFab-Vest is the detection of possibly fatal heart problems, specifically unstable angina pectoris. Angina Pectoris is a fatal medical condition with more than 7 million sufferers in the U.S. alone. In the unstable angina pectoris form of the condition, fatal attacks happen in an unpredictable manner, even when the patient is at rest. Using the architecture that has been discussed in the previous sections, we can achieve constant monitoring and life-saving drug delivery in the emergency situation even when the patient is away from any conventional emergency medical help. With the RFab-Vest the patient can have a personalized tuning for the system by his/her physician and can continue with the normal life activities with the vest. Drug delivery algorithms running on the vest, finely tuned by the patients physician, can be used prevent any fatal results.

Angina pectoris is characterized as an acute chest pain or discomfort due to coronary heart disease and is considered as a symptom of myocardial ischemia. Electrocardiogram analysis is the standard used for the diagnosis of ischemia. However, ECG waves are highly patient dependent and the analysis is generally performed by the clinician manually (through observation of the ECG waves).

2 Related Work

Several "wearable" technologies exist to continually monitor patient's vital signs, utilizing low cost, well-established disposable sensors such as blood oxygen finger clips and electrocardiogram electrodes.

The Smart Shirt from Sensatex [1] is a wearable health monitoring device that integrates a number of sensory devices onto the Wearable Motherboard from Georgia Tech [2]. The Wearable Motherboard is woven into an undershirt in the Smart Shirt design. Their interconnect is a flexible data bus that can support a wide array of sensory devices. These sensors can then communicate via the data bus to a monitoring device located at the base of the shirt. The monitoring device is integrated into a single processing unit that also contains a transceiver. The SmartShirt design features plastic optical fiber that can be used to detect punctures - however, they do not have any means of dealing with these punctures other than reporting them via the transceiver. In contrast, our design features a reconfigurable interconnect - rather than a large data bus - which can dynamically adjust to punctures or tears. Moreover, we provide further fault tolerance through distributed control buttons. In the event that their single processing unit (and transceiver) is damaged or the control lines leading to the device are torn, the Smart Shirt is virtually inoperable. In our design, we distribute control to multiple processing elements and can accommodate multiple communication buttons. This ensures that a tear or puncture to our vest will not result in total system failure. This fault tolerance is essential in the demanding and/or hazardous environments targeted by this research. Firefighters, policemen, soldiers, astronauts, athletes, and others working in hazardous environments need robust material that can sustain damage and yet still reliably provide service. Finally, our design supports actuation, such as a drug delivery system that could provide immediate medical attention to individuals in environments that would be difficult to bring medical personnel - either due to their remoteness (i.e. in the case of an astronaut or mountain climber) or the danger involved (i.e. in the case of a potential biohazard or fire). By automating the treatment, as well as the detection, our envisioned RFab capability will provide more fault tolerant means of safeguarding the life of the wearer of garments such as the RFab-Vest described earlier. Several other technologies have been introduced by MIT called MIThril [3], e-Textile from Carnegie Mellon University [4] and Wearable e-Textile from Virginia Tech [5]. None supports the concept of reconfiguration due to faults or tears as RFab-Vest does.

3 Design of RFab-Vest

3.1 Interconnection Topology

The interconnection medium for our proposed system is a mesh of wire segments. The mesh interconnection topology is a wire-frame that has a regular structure, each vertex being connected to exactly four other vertices.
Mesh networks have several significant advantages. Each node has a dedicated communication link with every other node on the network and also has access to the full bandwidth available for that link. Nodes on buses must share the bandwidth available on the bus medium. Besides, in a mesh, multiple paths exist between devices. This brings a great robustness against faults. If a direct path between two nodes goes down, messages can be rerouted through other paths. Moreover, it has considerable scalability and can be easily manufactured. The manufacturing issues become more significant because in our system wires are integrated into the fabric and with current fabric manufacturing technology, this can be easily achieved. Furthermore, the mesh interconnection is highly regular which assist us in routing and placement of sensors and computational units. A picture of our fabric with mesh interconnection is shown in Figure 2.

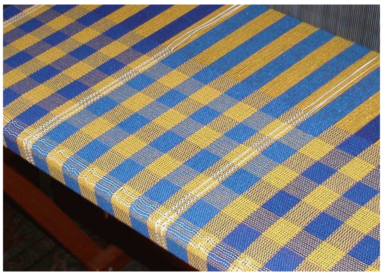

Figure 2: Fabric with Mesh of Wires

3.2 Computational Units/Controllers

The dot motes developed at the University of California, Berkeley offer a tiny, low cost computation platform for embedded applications. It comprises a programmable ATmega128 microcontroller from Atmel. The ATmega128 [6] is a low-power CMOS 8-bit RISC microcontroller. The ATmega128 achieves a throughput of up to 1 MIPS per MHz. The ATmega128 also provides 128K bytes of In-System Programmable Flash, 4K bytes of EEPROM, 4K bytes of SRAM, and several peripherals including a real time counter, four timers, two UARTs (*Universal Asynchronous Receiver and Transmitter*), an ADC, and a byte oriented two-wire serial interface – also called the Inter Integrated Circuit (I^2C) interface.

3.3 Switches

The dot motes are connected to UART lines through programmable switches to create the distributed computation fabric drawn in Figure 3. The switches used for this purpose are SN74LV4052A ICs from Texas Instruments. These dual 4-channel CMOS analog multiplexers/demultiplexers are designed for 2-V to 5.5-V VCC operation and are bidirectional in functionality.

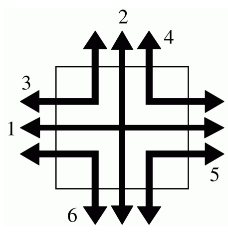

Figure 3: Switch Model

All three terminals on each side is connected to a horizontal or a vertical wire segment. Six type of connection may be established with this switch. Two connections are straight connections whereas the other are bent connections.

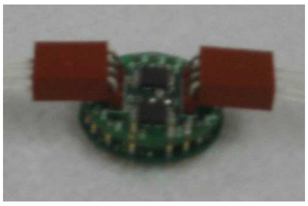

Figure 4: A Dot-Mote along with a Switch

3.4 Sensing Components

Myocardial Ischemia is basically caused by lack of oxygen and nutrients to the contractile cells. Frequently it may lead to myocardial infraction. This causes severe consequence of heart failures or arrhythmia that may yield death. An electrocardiogram (ECG / EKG) is an electrical recording device of the heart signals and is used in the investigation of heart diseases including Ischemia. The ECG monitoring system, that we use, utilizes ten electrodes. The electrodes (or leads) are attached to the patients arms, legs, and chest. The electrodes detect the electrical impulses generated by the heart, and transmit them to the ECG machine. From the ECG tracing, the heart rate, the heart rhythm, whether there has been a prior heart attack, whether there may be coronary artery disease and whether the heart muscle has become abnormally thickened can be determined. Digitized samples are sent to the dot-motes for Ischemia detection process through UART protocol. The ECG that we utilize is manufactured by Midmark Diagnostics Group [7].

3.5 Actuators

Nitroglycerin is used to prevent Ischemia (Angina). It works by relaxing the blood vessels to the heart, so the blood flow and oxygen supply to the heart is increased. Various routes of adminestartion is proposed such as sublingual tablets, extended-release capsule, skin patches (transdermal), spray and ointment. A rich area of research over the past 10 to 15 years has been focused on developing transdermal technologies that utilize mechanical energy to increase the drug flux across the skin by either altering the skin barrier (primarily the stratum corneum) or increasing the energy of the drug molecules. These so-called active transdermal technologies include iontophoresis (which uses low voltage electrical current to drive charged drugs through the skin). Ionotophosis is defined as the introduction, by means of a direct electrical current, of ions of soluble salts into the tissues of the body for therapeutic purposes [8]. It is a technique used to enhance the absorption of drugs across biological tissues, such as the skin. Transdermal iontophoresis becomes an excellent candidate for our application since it is controlled by electrical signals. Such a drug delivery unit is shown in Figure 5.

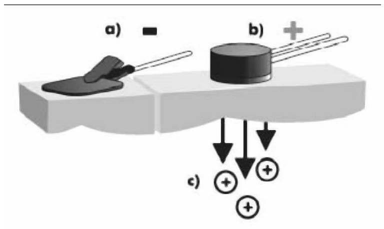

Figure 5: Electrode for Transdermal Iontophoresis System

Nitroglycerin may lose its effectiveness over time, so physicians generally schedule nitrate-free breaks to prevent tolerance. A valid concern exists that nitrate-free periods might increase the risk for angina and adverse heart events. With on-line monitoring RFab-Vest, we avoid excessive amount of drug administration and eliminate its risks.

4 Ischemia Detection and Drug Delivery Method (IDDD)

4.1 ECG Interpretation

As the heart undergoes depolarization and repolarization, the electrical currents that are generated spread not only within the heart, but also throughout the body. This electrical activity generated by the heart can be measured by an array of ECG electrodes placed on the body surface. A typical ECG signal is shown in Figure 6.

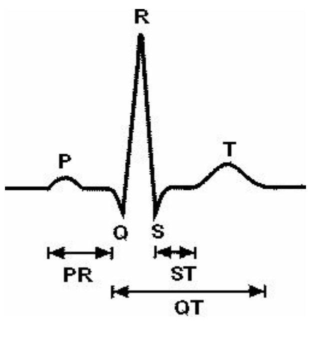

Figure 6: A typical ECG Signal

The **P wave** represents the wave of depolarization that spreads from the sinoatrial (SA) node throughout the atria, and is usually 0.08 to 0.1 seconds (80-100 ms) in duration. The brief isoelectric (zero voltage) period after the P wave represents the time

in which the impulse is traveling within the AV node where the conduction velocity is greatly retarded.
The period of time from the onset of the P wave to the beginning of the QRS complex is termed the **P-R interval**, which normally ranges from 0.12 to 0.20 seconds in duration. This interval represents the time between the onset of atrial depolarization and the onset of ventricular depolarization. If the P-R interval is > 0.2 sec, a conduction defect (usually within the AV node) is present (first-degree heart block).
The **QRS complex** represents ventricular depolarization. The duration of the QRS complex is normally 0.06 to 0.1 seconds. This relatively short duration indicates that ventricular depolarization normally occurs very rapidly. If the QRS complex is prolonged (> 0.1sec), conduction is impaired within the ventricles. This can occur with bundle branch blocks or whenever a ventricular foci (abnormal pacemaker site) becomes the pacemaker driving the ventricle. Such an ectopic foci nearly always results in impulses being conducted over slower pathways within the heart, thereby increasing the time for depolarization and the duration of the QRS complex.
The isoelectric period (**ST segment**) following the QRS is the time at which the entire ventricle is depolarized and roughly corresponds to the plateau phase of the ventricular action potential. The ST segment is important in the diagnosis of ventricular ischemia or hypoxia because under those conditions, the ST segment can become either depressed or elevated.
The **T wave** represents ventricular repolarization and is longer in duration than depolarization (i.e., conduction of the repolarization wave is slower than the wave of depolarization).
The **Q-T interval** represents the time for both ventricular depolarization and repolarization to occur, and therefore roughly estimates the duration of an average ventricular action potential. This interval can range from 0.2 to 0.4 seconds depending upon heart rate. At high heart rates, ventricular action potentials shorten in duration, which decreases the Q-T interval. Because prolonged Q-T intervals can be diagnostic for susceptibility to certain types of tachyarrhythmias, it is important to determine if a given Q-T interval is excessively long. In practice, the Q-T interval is expressed as a "corrected Q-T (**Q-Tc**)" by taking the Q-T interval and dividing it by the square root of the R-R interval (interval between ventricular depolarizations). This allows an assessment of the Q-T interval that is independent of heart rate. Normal corrected Q-Tc intervals are less than 0.44 seconds.

4.2 Ischemia Detection and Drug Delivery

Our ischemia detection algorithm incorporates a collection of initial tuning sessions to extract the normal heart pattern of the patient. These initial ECGs are selected to include a range that span different activity levels and various days of the initial tuning period (rest, exercise, stress...etc). For diagnosis, common ECG patterns of the heart signal are used such as: heart rate, PR interval, QRS duration, QT interval duration, ST intervaletc. In addition, a collection of abnormal ECG patterns associated with the ischemic conditions are stored. Normal ECG patterns of the patient along with the standard indications and abnormal patterns of ischemia are incorporated as a basis for the rest of the automated analysis that is performed by the reconfigurable vest as shown in Figure 7. At the end of the initial tuning period, the drug delivery decision is based upon tuning information provided by the patient's cardiologist. Tuning of the algorithm will determine the criticality of the wave according to the deviation from the normal values of the patient and the matching with abnormal ischemic patterns according to the guideline provided by the clinician through tuning.
Nitroglycerin delivery through a patch is used as an initial response to heart attack. One of the main reasons that nitroglycerin is used in this system is the fact that it does not generate any risk to the patient if the condition is not actually a heart attack. as: lack or inversion of T region in the ECG signal, deviation in the elevation and slope of the ST interval.
In the ischemic ECG, the ST region of the curve has values abnormally lower or non-existing compared to patients average heart signal shown in Figure 7. Similarly an abnormal heart signal detected with unusual QRS complex with extremely low 1mV R voltage on the specific probe of the ECG as shown in Figure 7.
At this stage of implementation our ischemia detection algorithm is capable of detecting ischemic heart attacks that show ST region indications such as: non-existing ST region, elevation, slope abnormalities according to the preset normal and abnormal ranges. Furthermore, the algorithm is capable of detecting other heart signal abnormalities such as QRS complex width, abnormal interval ranges and voltages for P,R,S,T,Q waves, etc. As a crucial part of its nature the algorithm is fast and runs on real-time data.

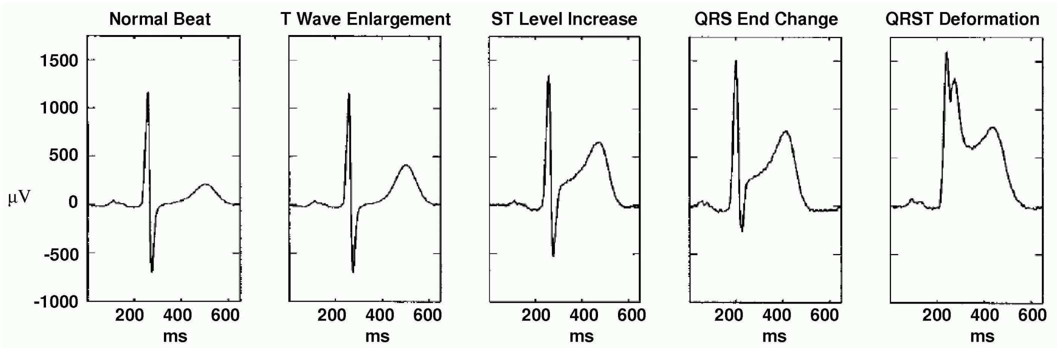

Figure 7: Normal and Abnormal ECG Signals

4.3 Implementation of Algorithm on Processing Units

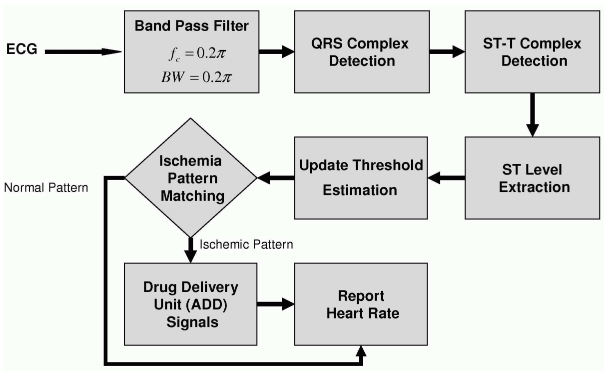

Figure 8: Ischemia Detection Operations

As shown in Figure 8, at the first step of the algorithm, signals from ECG are passed through a bandpass filter to reduce the noise and remove the bias voltage. The filter is a $5th$ order Butterworth band pass filter with cutoff frequency adjusted to 0.2π and bandwidth of 0.2π . Rest of the algorithm can be partitioned into two sections, ECG signal characterization and ischemia pattern matching.
ECG Signal Characterization:
After the signal is filtered, QRS complex is detected and consequently heart rate is observed. Each time a local peak is detected, it is classified as QRS complex, T-Wave or noise. So, at the end of each period new values of QRS complex, ST interval and T-Wave amplitude are updated. Basic rules to find a QRS and ST segments are as follows:

- Peaks that precede or follow larger peaks by less than 200 ms (50 samples) are ignored.
- If a peak has occurred after 360 ms (90 samples) of the previous peak and the maximum derivative of the signal is at least half of the previous peak (i.e. QRS complex), identify the peak as T-Wave.
- If the peak is larger than the threshold, call it QRS complex.
- Update the threshold as the mean of the last 8 QRS peaks detected multiplied by constant factor TH ($TH = 0.9$). A good estimate on QT duration can be achieved from the following equations [9]:

$$QT = \begin{cases} 0.384RR + 99 & \text{RR} < 600\text{ms} \\ 0.156RR + 236 & 600\text{ms} \leq \text{RR} \leq 1000\text{ms} \\ 0.166RR + 277 & \text{RR} > 1000\text{ms} \end{cases}$$

RR is the heart beat period. At the beginning, the threshold is estimated to be the mean of the two maximum peaks in a 2 second interval.
Ischemia Pattern matching:
Ischemia may change ECG signals in different ways and mostly affect ST-T complex. In our algorithm, four major patterns in ECG are considered as ischemic patterns [10]:

- T-Wave Enlargement. If the T-Wave Amplitude is increased by more than 1mV.
- ST Level increase. If ST segment deviation is greater than 1mV.
- QRS end change. An upper shift in the QRS end (S-wave) may be a sign of ischemia.
- QRST deformation. Myocardial ischemia may cause a deformation in ECG signals which results in increase of the integral of the waveform from S-wave to T-wave. At each period this integral is evaluated and compared to a threshold.

Once an ischemic behavior is detected in one period of ECG signals, we keep track of ischemic patterns for at least 30 seconds [11]. If we detect a continuous 30 second ischemic behavior, this would be considered as occurrence of ischemia and drug administration will start.

5 Reconfiguration in RFab-Vest

5.1 Network Topology in RFab-Vest

As discussed earlier, the interconnection medium of RFab-Vest is a mesh of wire segments. We employ four dot-motes as computational units placed at the corners of a square in our interconnection network as shown in Figure 9. Every dot-mote is accompanied with a switch which is described in Section 3.3. In this prototype, we use a mesh of size 3x3. The center square of wire segments are associated with inter-mote communication and will be referred as inner square in this paper. The outer square of wire segments (mesh of size 3x3) is responsible for carrying ECG and drug delivery signals. The switches, controlled by dot-motes, connect either ECG, drug delivery or inter-mote communication lines to the motes. There exists two pairs of wires in inner square to improve the reliability of inter-mote communication. In case if a pair of wires fails, switches can swap to the other pair and reconfigure the circuit.

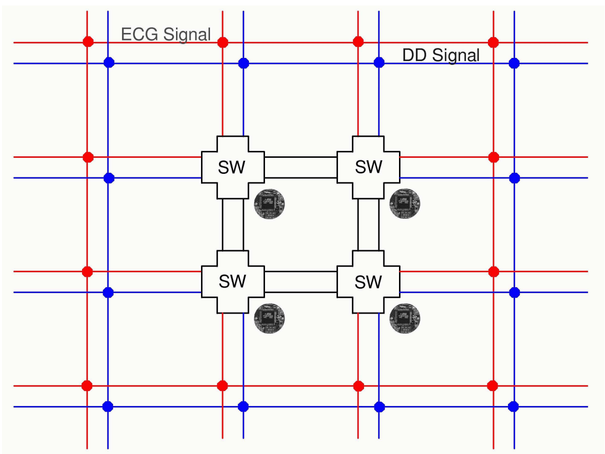

Figure 9: Network Topoplogy

5.2 Processing, Synchronization and Reconfiguration in RFab-Vest

The ischemia detection algorithm is previously elaborated in Section 4.3. The dot-motes perform the processing, however, since we have eight channels of ECG, the computational capability of one dot-mote does not suffice to process the data from all ECG channels. Therefore, the algorithm is distributed over four dote-motes. Each mote accomplishes interpretation of ECG signals of two channels. The synchronization ensures that every ECG channel is being processed by at least a dot-mote. Therefore, synchronization among dot-motes is inevitable. Furthermore, in case of fault occurrence, the network is repaired in reconfiguration stage. Once ischemia is detected, appropriate signals are sent to the drug delivery units. As for drug delivery units, due to some limitations, we do not utilize actual drug delivery units. Instead we exploit a Pocket PC for monitoring purposes. We emphasis that the pocket PC does not carry out any computations for ischemia detection algorithm.

The only communication protocol that is available on dot-motes is UART (I^2C still is not fully functional on mica2dots), hence all processing, synchronization and reconfiguration tasks are carried out through the UART protocol. Therefore, are tasks are executed sequentially as shown in Figure 10 According to [11],

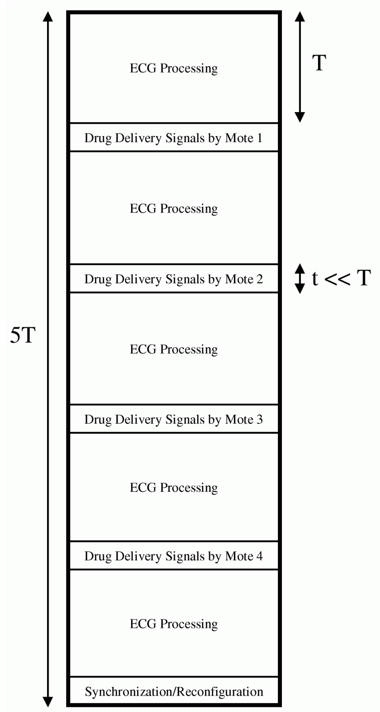

Figure 10: Task Multiplexing in RFab-Vest Network

when ischemia happens, the ECG signals stay deformed for at least 30 seconds. Physicians recommend that the appropriate drug is administered in about one minute once ischemia occurs. In the worst case, if a fault occurs in the RFab-Vest at the same time when ischemia occurs, the network may require reconfiguration in order to accompolish successful drug administration. If ischemia is detected suddenly after synchronization/reconfiguration phase, the circuit will be reconfigured in the next synchronization/reconfiguration phase which takes $5T$ and drug is administered in the the first upcoming drug delivery phase which is away $5T + 4T$ from the time ischemia is detected. The time limit for drug administration is 60 seconds, therefore:

$$30 + 9T \leq 60 \tag{1}$$

We chose $T = 2.5sec$. Decreasing the time T would decrease the response time to the faults, however, it will increase the overhead of reconfiguration/synchronization and may affect the accuracy of processing and ischemia detection algorithm since the data sent by the ECG device during drug delivery or synchronization/reconfiguration process is lost. No data flow control mechanism is designed by the manufacturer of the ECG device. The ECG device transmits its data at 115200 bps.

The motes communicate with each other using UART as a broadcast medium. The interconnection reconfiguration algorithm needs to maintain a broadcast medium in the face of link failures. The general idea of the algorithm is that the nodes collect connectivity information by sending ping messages to each other periodically at synchronization/reconfiguration phase. When a node notices that it has not received a response from one or more nodes within some timeout period, the node attempts to reconfigure its local switch to regain connectivity. Because a node has a map of the interconnect topology (based on the results of sending ping messages) it can determine how the network has been partitioned. In our prototype, there are only four nodes. Therefore, the only partitions possible are horizontal, vertical, or a corner partitions. In the case of a horizontal (vertical) partition there are two groups of two nodes. Because a node's horizontal and vertical connectivity are independent, a dot-mote is able to change its horizontal connectivity without affecting its vertical connectivity (and vice versa. When a node detects a horizontal (vertical) partition, it only changes its vertical (horizontal) connectivity bus. In the case of a corner partition, a single node is partitioned from the other three. The single node must change both its horizontal and vertical data bus. In the three node partition, only the two adjacent nodes can affect the connectivity. A broadcast algorithm is designed to check the connectivity of the network periodically. In case of a partition, a token is generated to circulate among the partitioned nodes. After some predefined time, when no response is received from one or more motes, the mote which has the token sends a halt message to all the motes on the UART bus and will attempt to fix the topology based on the algorithm described before. Upon receiving the halt message, all the other motes initiate to fix the topology as well. When fixing topology is finished, they all go into the halt mote. The master mote wakes all the motes up by broadcasting a wake up message once it observes that the network is fixed and connected again. In our implementation, each node is connected to two horizontal and two vertical buses. Therefore, in the worst case, three faults can be sustained while maintaining connectivity.

6 Experimental Analysis

Figure 11: RFab-Vest Prototype

This section presents various experimental analysis performed on RFab-Vest. Initially we present a picture of our prototype in Figure 11. As shown in the picture, a PC sends ECG signal (extracted from ECG database) to the RFab-Vest and a pocket PC which is employed as a drug delivery unit (for only monitoring purposes).

All the experiments are carried out with real ECG signals. We used ECG signals from European ST-T Database. The European ST-T Database is intended to be used for evaluation of algorithms for analysis of ST and T-wave changes. This database consists of 90 annotated excerpts of ambulatory ECG recordings from 79 subjects. The subjects were 70 men aged 30 to 84, and 8 women aged 55 to 71. Each record is two hours in duration and contains two signals, each sampled at 250 samples per second with 12-bit resolution over a nominal 20 mV input range [12]. The signals extracted from database are sent to the RFab-Vest by a PC through UART. The data format of PC is exactly the same as ECG device. Hence, RFab-Vest is fully functional when we replace the PC with an

ECG device.

In the first set of experiments, we measured the latency of fault detection and circuit reconfiguration for various types of faults as shown in Figure 1. V/H wire faults refer to vertical/horizontal partitions of the broadcast medium. Corner wire faults refer to corner partitions. ECG and drug delivery faults refer to the disconnection of wires responsible for carrying ECG and drug delivery signals. Finally, mote fault corresponds to the loss of dot-motes (due to either physical failures or power outage).

Fault Type	Fault Detection Time (msec)	Detection + Reconfiguration Time (msec)
V/H Wire Fault	58	63
Corner Wire Fault	59	67
ECG Wire Fault	8	9
Drug Delivery Wire Fault	4	5
Mote Fault	92	N/A

Table 1: Fault Detection/Reconfiguration Time

The next set of experiments are performed on power consumption versus reliability trade-offs of the RFab-Vest. If we decrease the number of dot-motes on the RFab-Vest, we reduce the power consumption while the reliability of the system degrades. A summary on the maximum number of faults which can be tolerated while the system is still functional is presented in Table 2. Finally, in Table 3 we present

Number of Dot-Motes	Power Consumption (mW)	Number of Failed Motes Tolerated	Worst Case Number of Failed Wires Tolerated
4	980	3	3
2	470	1	1
1	230	0	1

Table 2: Power Consupmtion/Reliability of RFab-Vest

a brief summary on the processing time required for ischemia detection on each channel of ECG device. As shown, the processing time increases largely with complex ECG signals.

Signal Complexity	Sample(/Channel) Processing Time (usec)	Sample Rate (Hz)	Maximum Number of Channels
Average	250	250	8
Highest	420	250	4

Table 3: Computational Capability of Dot-Motes

7 Conclusion and Future Works

The Reconfigurable Fabric project at UCLA promises to make advances in sensors, materials, and system architecture for intelligent garments. In the future we plan to expand our prototype, creating larger topologies, and updating our link reconfiguration algorithm for use in larger topologies. In addition, we plan to work on a RFab-Vest prototype where stand-by mode would be supported on the dot-motes. This can reduce the power consumption of the RFab-Vest drastically. Lastly, we plan to connected the ECG sensors directly to the motes to increase the reliability of the system.

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