

# The Mobile Patient: Wireless Distributed Sensor Networks for Patient Monitoring and Care\*

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## Abstract

In this paper, the concept of a 3 layer distributed sensor network for patient monitoring and care is introduced. The envisioned network has a leaf node layer (consisting of patient sensors), a intermediate node layer (consisting of the supervisory processor residing with each patient) and the root node processor (residing at a central monitoring facility). The introduced paradigm has the capability of dealing with the bandwidth bottleneck at the wireless patient - root node link and the processing bottleneck at the central processor or root node of the network.

**Keywords:** Mobile patient, wireless network, distributed sensor network, variable bit-rate control.

## 1 Introduction

Recent advances in digital cellular telephony technology, distributed sensor networks (DSNs) and sensor fusion open new avenues for the implementation of wireless networks for telemedicine. The idea of this wireless networks has been investigated by a large number of authors (see e.g. [1]-[5]). However, in many cases, the bandwidth bottleneck of currently available 2<sup>nd</sup> generation wireless links highly restrict these type of applications and the current focus is on 3<sup>rd</sup> and 4<sup>th</sup> generation wireless technology [6].

This paper develops a new concept for the use of current and future wireless network technology

to monitor patient's vital functions and provide instantaneous medical feedback. Recent advances in DSNs and data fusion are brought to bear in order to develop the proposed system. The envisioned concept provides the individual patient with greatly improved mobility and allows him/her to roam freely outside of treatment centers, thus facilitating a higher quality of life.

This capability (independence of wired monitoring/diagnosis equipment) is achieved by the patient carrying a sensor network that communicates with a central/supervisory processor which would typically be located at a treatment center.

The arising DSN is a tree structured three level network with the leaf node represented by the individual patient sensors. The intermediate level nodes are represented by supervisory, intelligent processors. Such a processor is carried by each patient and has the task of communicating through a wireless channel with the top node (central supervisory processor) of the network. Other tasks of the intermediate level nodes are to distribute the bandwidth between individual sensors of a patient according to their instantaneous importance and their nominal bandwidth requirement, to vary its data rate according to a measure of criticality that is handed down and determined by the root node, to handle the communication up and down the network tree as well as evaluating and fusing sensor signals to determine an initial estimate of the patient's criticality. The most challenging technology issues that will be addressed in the development of such a wireless DSN for patient

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monitoring are as follows:

1. Overcoming the limitation in battery power in the intermediate level (patient) nodes.
2. Overcoming the bandwidth bottleneck of the wireless link from the patient to the top-layer processor in the case of high criticality.
3. Overcoming the processing bottleneck at the top-layer processor.

Some of these issues will persist regardless of the available type of mobile network, i.e. even in the Third Generation Mobile Systems. This paper develops a concept that will effectively address the above problems and offers conceptual solutions.

## 2 Preliminaries

Distributed sensor networks utilize a variety of sensors that may be distributed logically, spatially and geographically [7]. The process of gathering data from such a DSN and combining or fusing it to obtain inferences that may not be possible from a single sensor alone is referred to as *multi-sensor data fusion* [8, 9]. In a highly dynamic environment, the enormous amount of data generated by a DSN need to be processed in near real-time if effective detection, tracking and identification of critical situations are to be accomplished. A DSN operating under such fast changing conditions and/or containing bursty sensors, require a sensor management scheme that possess the capability to select or cue sensors by assigning time-variant importance measures or weights to each sensor node at arbitrary instances of time. This is essential if the available link bandwidth and the processing bandwidth of the root node is to be effectively utilized with a minimal data loss.

## 3 The Variable Bit Rate DSN Concept

Consider the mobile patient DSN configuration shown in Figure 1, which contains three hierarchical levels: a leaf node layer, one intermediate node layer and a root node layer.

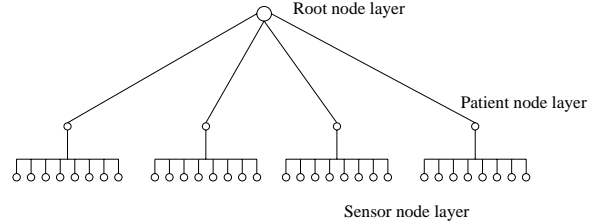


Figure 1: Tree structured three level DSN

In this three level network, the link from the patient layer up to the root node is band-limited due to the limited wireless link capacity from the patient to the cable network. Furthermore, how much of this link capacity is actually utilized depends on the criticality of the patient, as it is determined by the root node. The root node passes down to the patient nodes a weight  $w_i(n)$ , which signifies the relative criticality of a particular patient. This allows to distribute the root node processing bandwidth between the patients in an “importance” based manner. In this way, excessive processing speed requirements of the root node can be avoided. The root node also hands down weights to each individual sensor via the patient nodes. This again allows to optimally distribute the patient node processing bandwidth according to the criticality of each sensor. (In a patient sensor node LAN, this can simply be done by dynamic scheduling.) Such a scheme therefore allows to optimally distribute resources according to sensor/patient criticality.

A further improvement in the efficiency of bandwidth and processing power utilization of such a scheme can be achieved by weight quantization to zero, in which case the patient node disconnects itself from the root node. Of course this requires the patient node to possess some intelligence, so that through data-fusion and reference signal storage, it can determine an increase in the patient’s criticality, in which case it would reconnect to the network.

In Figure 1, each node receives signal information from the nodes in the layer below and control information (queue length, weights, etc.) from the layer above. This information must be buffered for processing. Each node has a processing bandwidth reflecting its data processing speed. Current root

node buffer length and weight information, i.e. control information, is available to patient nodes via a communication link which introduces delays. Typical communication networks have two different types of delays: constant and variable delays. The processing and transmission delays are fairly constant while the access and buffering delays are highly time-variant due to variable occupancy levels of buffers. A method similar to the ABR protocol of the ATM Forum Traffic Management Specification may be used to carry such control information via resource management cells that are periodically inserted within the data cell stream [10]. Each patient node is equipped with a local controller, that adjusts the bit-rate according to the status of the root node buffer and the weight distribution determined by and passed down from the root node. Local controller parameters are chosen to guarantee the node rate to conform to the allocated weight within a specified settling time. Connections between sensor nodes and patient nodes as well as between patient nodes and the root-node may connect or disconnect depending on the criticality. For the sake of simplicity, we assume the controllers to be of FIR type. The only assumption we make about the communication links is that the specified bit rate is actually made available, assuming it does not exceed the maximum link capacity.

## 4 The System Model

In this section, we provide models for root node buffer and the patient rate controllers. In order to keep the notation to a minimum, we will define the relation only between root node and patient nodes. The presented model is valid for the root node being connected to maximally  $M$  patient nodes  $i$ .

### Notation:

$\Delta_s$ : controller time step;

$n$ : discrete time;

$\tau_{i \rightarrow}(n)$ : delay from patient node  $i$  to the root node;

$\tau_{i \leftarrow}(n)$ : delay from the root node to the patient node  $i$ ;

$q_0(n)$ : queue (buffer) occupancy level of the root node;

$R_i(n)$ : rate at which patient node  $i$  sends data;

$B_0(n)$ : processing bandwidth at the root node.

$e_i(n)$ : binary signal, which equals 1 if patient node  $i$  is connected to the root node, and 0 otherwise;

$sat_q(x)$ : saturation nonlinearity for buffer over- and underflow.

In particular the last two symbols are defined as follows:

$$e_i(n) = \begin{cases} 1 & \text{if patient node } i \text{ is connected} \\ & \text{to the root node during} \\ & [n\Delta_s, (n+1)\Delta_s] \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

$$sat_q[x] = \begin{cases} 0 & \text{if } x < 0 \\ x & \text{if } 0 \leq x \leq q_{max} \\ q_{max} & \text{if } x > q_{max} \end{cases} \quad (2)$$

### Root node buffer model:

The buffer dynamics of the root node which is connected to a maximum of  $M$  lower level patient nodes is given by:

$$q_0(n+1) = sat_q \left[ q_0(n) - B_0\Delta_s + \sum_{i=1}^M e_i(n - \tau_{i \rightarrow}) R_i(n - \tau_{i \rightarrow}) \Delta_s \right] \quad (3)$$

For the purpose of this paper, the following simplifying assumption are desirable:

- (a) There is no delay for data from the patient node  $i$  to the root node:  $\tau_{i \rightarrow} = 0$ .
- (b) The processing bandwidth is constant:  $B_0(n) = B_0$ .
- (c) The buffer occupancy level and the rates  $R_i(n)$  stay in the linear range.

These assumptions result in the following simplified buffer model:

$$q_0(n+1) = q_0(n) + \sum_{i=1}^M e_i(n)R_i(n)\Delta_s - B_0\Delta_s \quad (4)$$

**FIR-Controller equations at patient node  $i$ :**

$$\begin{aligned} v_i(n) &= a_0 q_0(n - \tau_{i\leftarrow}(n)) + \\ &+ a_1 q_0(n - 1 - \tau_{i\leftarrow}(n - 1)) + \\ &+ \dots + a_N q_0(n - N - \tau_{i\leftarrow}(n - N)) \end{aligned} \quad (5)$$

with  $i = 1, \dots, M$

where  $v_i(n)$  is the rate controller output at the patient node  $i$  and  $a_\nu, \nu = 1, \dots, N$  are the FIR controller coefficients. The delays  $\tau_{i\leftarrow}$  are the delays control data undergoes when being sent from the root node down to the patient nodes  $i$ . This delay is mainly due to the queue/processing delay at nodes  $i$ . All rate controllers are assumed to be identical for the sake of simplicity.

**Patient node rate management scheme:**

The patient node rate is nominally given by the patient criticality weight times processing bandwidth of the root node. An additional control term is introduced so that depending on the queue status in the root node, the rates are modified to achieve the desired buffer set point level:

$$\begin{aligned} R_i(n) &= \text{sat}_R[w_i(n - \tau_{i\leftarrow}(n))B_0(n) \\ &+ \beta\Delta_s^{-1}(v_i(n) - L)] \end{aligned} \quad (6)$$

where  $L$  is the set point parameter for  $q_0$  as it translates to the controller output,  $\beta$  is a parameter to weight the control term and  $w_i(n)$  is the weight assigned by the root node to patient node  $i$ . The saturation  $\text{sat}_R$  on the bit rate is similarly defined at  $\text{sat}_q$  in (2).

With the simplifications  $B_0(n) = B_0$  we obtain for operation in the linear region:

$$R_i(n) = w_i(n - \tau_{i\leftarrow}(n))B_0 + \beta\Delta_s^{-1}(v_i(n) - L) \quad (7)$$

**Weight Distribution:**

$$\sum_{i=1}^M w_i = 1 \quad (8)$$

i.e., the net input rate into the root node buffer and the net output rate are identical in steady state conditions. (In this case, the control term in equation (7) is zero.)

An analytical analysis of the behavior of such a DSN with weight based bandwidth assignment was performed in [11, 12]. The network can be designed to almost instantaneously react to weight changes without causing the root node (and patient nodes) buffer to underflow or overflow.

## 5 Conclusion

In this paper we introduced the concept of wireless three level DSN for patient monitoring and care. Resource allocation in such a network is criticality based, i.e. bandwidth is distributed among nodes according to patient criticality in the communication between the top two layers and according to sensor importance in the communication between sensors and the patient supervisory node. Such a scheme minimizes the processing bandwidth requirements at the root node, it optimally distributes bandwidth between sensors and it allows for increased energy efficiency due to an importance based connect/disconnect mechanism between the patient and the root node.

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