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의료용 센서 네트워크에서 QoS 지원의 매체접속제어

On the QoS Support in Medium Access Control for Medical Sensor Networks

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요 약

환자모니터링과같은 특수목적의 무선센서망에 요구되는 프로토콜과 연관하여 매체접속제어(MAC) 기법을 설계하기위한 구조를 연구하였다. 의료시스템의 데이터는 엄격한 신뢰성이 요구되며 또한 본질적으로 비균질성의 트래픽 특성을 가지고 있다. 이러한 환경은 특별한 고려사항이 요구되어 미묘한 서비스 품질(QoS) 문제를 야기하게 된다. 의료용 혹은 감시시스템 등의 응용분야에서는 트래픽의 정규성 및 예측성이 어느 정도 보장이되어, 관리노드는 이웃 노드들의 자원을 관리할 수 있는 역할을 할 수 있다. 즉, 관리노드는 주어진 QoS 사양에 따라 충돌없이 타임 슬롯을 할당할 수 있다. 본 연구는 이러한 조건하에서 MAC의 핵심구조를 파악하고, 수퍼프레임 길이와 노드의 수에 따른 에너지 소비량 및 수율을 분석하였다.

Abstract

In line with the requirement of appropriate protocol support for such mission-critical wireless sensor network (WSN) applications as patient monitoring, we investigate the framework for designing medium access control (MAC) schemes. The data traffic in medical systems comes with inherent traffic heterogeneity as well as strict requirement of reliability according to the varied extents of devise-wise criticality in separate cases. This implies that the quality-of-Service (QoS) issues are very distinctly delicate requiring specialized consideration. Besides, there are features in such systems that can be exploited during the design of a MAC scheme. In a monitoring or routine surveillance application, there are degrees of regularity or predictability in traffic as coordinated from a node of central control. The coordinator thus takes on the role of marshaling the resources in a neighborhood of nodes deployed mostly for upstream traffic; in a collision-free scheme, it schedules the time slots for each superframe based on the QoS specifications. In this preliminary study, we identify the key artifacts of such a MAC scheme. We also present basic performance issues like the impact of superframe length on delay incurred, energy efficiency achieved in the network operation as obtained in a typical simulation setup based on this framework.

Key words : Wireless sensor networks, WBAN, ubiquitous healthcare, MAC protocol, QoS provisioning.

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Ⅰ. Introduction

INTERFERENCE-PRONE document is and broadcast nature of wireless medium requires that the MAC be highly optimized. This becomes particularly crucial for WSNs, consisting of supposedly large number of miniaturized battery-powered sensors networked wirelessly. This is of no surprise then that MAC protocol design and evaluation has had its fair share when it comes to the rise of WSNs as hot topic in networking research in the last decade or so.

Depending on application scenario, WSN pose a number of challenges that range from supporting mobility to provisioning for the QoS requirement in such mission critical applications as medical sensor networks. Accordingly, a MAC protocol has to embody appropriate provisions.

Consider a monitoring or surveillance network where a centralized coordinator node is employed amongst a number of sensor nodes. It regulates these sensor nodes to send data on regular intervals. The intervals are expected to change at the application end, and the sensor nodes might have variety in terms of burstiness, priority and frequency of traffic associated with their sensing task.

The natural design choice in such setup for controlling access to the wireless medium is centrally controlled dynamic Time Division Multiple Access (TDMA). Grouped into contiguous time slots to form a superframe, the fair share of the wireless channel can be attained by getting the coordinator to dynamically schedule the TDMA upstream slots for different sensor nodes meeting the real-time demand at the application end. This also enables maximizing sleeping time for the unscheduled sensor nodes as well as providing the best possible QoS for different nodes.

Specific example of the type of sensor networks we consider are those meant for collecting information about personal physical, physiological, and behavioral states and patterns in real time with the wirelessly networked sensors being either carried on by the user or in close vicinity in living space (BSN or WBAN are in the narrower sense from this genre). Such scenario arises in routine patient monitoring in hospitals (getting rid of the uncomfortable jumble of wires, and facilitating mobility), in assistive applications in monitoring age-related chronic diseases so as to enable the caregivers for early detection and intervention, in large-scale infield medical and behavioral studies that require continually collecting physiological and behavioral data from the subjects. The advantages are readily conceivable, both in qualitative as well as in quantitative terms. For instance, compared to short stays in the hospital, the data gathered during a long time interval in patient's natural environment has proven to offer a clearer view to the doctors[1].

The rest of this paper is organized as follows: the next section gives a brief outline of the related works, followed by Section 3 which contains problem statement and system model; Section 4 outlines the pertinent features and the provisions in the MAC studied while Section 5 illustrates the findings in a rudimentary simulation. Finally, Section 6 concludes the paper.

Ⅱ. Related Works

Substantial part of the literature addresses issues with WSN in the specific domain of healthcare as it is noted in a number of recent surveys[2-5]. This domain comprises of a number of closely knit areas known as medical sensor networks, body sensor network (BSN) or wireless body area network (WBAN). There are a plethora of work in the area of MAC protocol design and evaluation for WSN [6]. They mostly come in two varieties: contentionbased and schedule-based, and some are adaptive or hybrid.

Contention-based protocols are particularly suited for infrastructure-less distributed network with variable load though they perform poorly at consistently higher load and not much QoS respecting in general, whereas schedule-based are good at maintaining good throughput and energy efficiency at higher load, but require time synchronization and do not perform well in infrastructureless network.

There are not very many MAC protocols specifically designed for healthcare applications in WSN. In [7] there is an attempt to map the delay constraint based traffic classification in 802.11e to the medical criticality. Study on IEEE 802.15.4 in [8] show that it provides limited answer overall for medical sensor networking in terms of power consumption in non-beacon mode, and in terms of data-rate in beacon enabled mode [9]. BSN-MAC [10] comes close to our scheme in that it is akin to 802.15.4 and works with feedback-based dynamic adjustment of contention-free and contention-based periods to achieve energy efficiency and lower latency. In related studies, [11] and [12] conclude that 802.15.4 go some way in facilitating QoS, but it is not scalable enough in terms of power consumption, and does not stand out as it is to be adopted as the de facto choice for all types of medical sensor networks.

Ⅲ. Problem Statement and the System Model

In a candid yet persuasively robust critique in [13], Raman et al. strongly make the point that bulk of the works on protocol design for WSN are guilty of the following blames: part of the assumptions are either practically invalid or needlessly exaggerated, that they are ambiguous or imprecise in articulating their targeted applications, and the preference to go for complicated design choices even when simpler options are available (and meant to be more fitting); And the implication is that the deployments often do not live up to the expectations.

The above critique is no less relevant when it comes to medical sensor network applications. In clinical applications, some of the sensors may be deemed to be more critical than others (possibly configurable by the physician or caregiver), the regular schedules for the sensors to send upstream data are configured from application layer with the exception for the emergency/alarming cases when a node might want to initiate a transmission, there are no redundant nodes in the network (unlike standard assumption of densely deployed redundant array of sensors in WSN). In more sophisticated scenario, there can even be actuators to take action (eg. drug delivery) at predetermined moments or in response to an external event (eg. injecting insulin when glucose level drops).

To illustrate the uniqueness of the traffic characteristics, recall that a pulse oximetry application, which measures the levels of oxygen in a person's blood, must deliver at least one measurement every 30s [2]. In a different note, Table I shows the inherent heterogeneity in node-wise traffic regarding associated data-rates.

Thus, the requirements are contrasting in that the bandwidth-greedy node should get the available channel access time as long as it is available, while a mission-critical low data-rate node should get

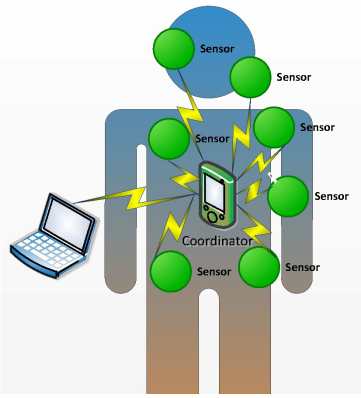
〈Table 1〉 Traffic heterogeneity in medical, sensors([14,15])

Device	Number of Sensors	Resolution (bits/sample)	Data Rate
ECG	5-9	12	15 kbps
Heart Rate	2	24	0.6 kbps
EMG	2+	12	600 kbps
EEG	20	12	4.2 kbps
Respiratory Rate	1	16	0.8 bps
Glucose Monitoring	1+	12	1.6 kbps
Temperature	1+	16	80 bps

prioritized access to channel regardless of the demand of the other nodes. In the proposed scheme, we attempt to support both fairness and priority making use of the distinct characteristics of the presumed system model.

In a monitoring or surveillance network of this sort, a centralized coordinator node is employed amongst the sensor nodes forming a piconet responsible for transmitting mostly periodic data (Fig. 1). The coordinator regulates these sensor nodes to send data on specified intervals. The intervals could change at the application end, and the sensor nodes might have variety in terms of burst-size, frequency of transmission and priority associated with their sensing task. Thus the wireless channel is shared among the nodes in a way that could be exploited so as to get the coordinator to schedule the occasions for different sensor nodes to transmit data in accord with the real-time demand at the application end.

One of the key advantages in this measure is getting the sensor nodes to sleep for the longest durations possible which are particularly attractive when it comes to the energy-efficiency of such energy constrained sensors as implant medical devices. On the other hand, the provision for supporting varied QoS specifications of the devices is a central Figure 1. Piconet comprised of sensors and



〈Fig 1〉 Piconet comprised of sensors and coordinator

coordinator issue in the networks deployed for mission critical applications.

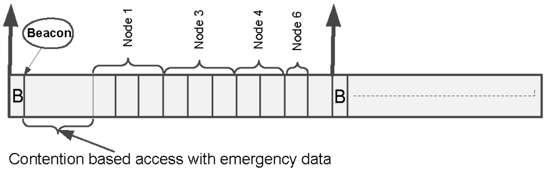
With this backdrop and the key artifacts of such a framework, we studied the required attributes of a MAC scheme appropriate in this regard and the effects of some of the system parameters on delay and energy consumption. We illustrate that both maximizing the sleeping time for the unscheduled sensor nodes as well as guaranteeing the best available QoS for the sensor nodes based on their characteristic classes are possible while the coordinator can still listen to emergency pledge from the sensor nodes in reservation request slots. To the best of our knowledge, this particular framework is not considered in other works.

Ⅳ. MAC Features and Provisions

For patient monitoring or regular surveillance applications and services, there are a number of capacities expected from the underlying MAC. In each single hop piconet, the coordinator leverages the feature of top-down control of the data service in the network by dynamically making explicit schedules for the nodes.

1. Dynamic TDMA for Centralized Scheduling

Unlike typical network models where the occasion of transmitting data is always devised to be senders' concern, such network as patient monitoring involve medical sensor devices planted by a physicians to send physiological data at prescribed (and supposedly varied) intervals. We exploit this feature by centrally scheduling the TDMA slots in superframe-wise (Figure 2) dynamic fashion at the piconet coordinator. This collision free scheme results in lower power consumption.



〈Fig 2〉 Node-wise slot allocations in superframe

2. The case for QoS-aware MAC

We consider the schedules as set of transmission requests sent down to the coordinator from application end. The variability involved in sensor-wise monitoring routine is served with random generation in simulation. Yet, the coordinator translates them as deterministic for a period for the sensor nodes in that each node gets to listen to the beacon at the beginning of the superframe. The beacon contains information for sensor nodes in regard to their schedule or slot-assignment in the following superframe (Fig 2). This leaves rest of the sensor nodes with the opportunity to sleep, except for the possibility of emergency data on their own. Sensor nodes are distinguished into two QoS classes for the moment: heavy and light, depending on traffic burstiness or communication granularity specific to each sensor node as well as their corresponding priorities (high or low).

3.Scheduling Scheme

Transmission requests sent down to the coordinator from application end are translated into schedules of superframe slots broadcasted by the coordinator in beacon. The variability involved in sensor-wise monitoring routine is served with random generation in simulation at the coordinator. The coordinator takes them as randomly periodic inputs that the sensor nodes get to listen in beacons at the beginning of the superframe to decidedly learn about their slot allotments, if any, in the immediate superframe. This leaves rest of the sensor nodes with the opportunity to sleep, except for the possibility of emergency data on their own. Sensor nodes are distinguished into two classes for the moment: heavy and light, depending on burst-size in traffic or communication granularity, and priority specific to each sensor node. The allocation procedure is delineated in algorithm *MAC-Slot-Reservation*

Algorithm 1 MAC-Slot-Reservation (*superframe* (t))

Require: $n \in N(t)$: set of backlogged nodes in current superframe t; π_n: node-wise priority spec, Δ_n: burstsize spec (node-wise); $b_n(t)$: node-wise backlogged packet count in current superframe t; current superframe size $\Psi(t)$.
Ensure: node-wise slot allocation α_n $(n \in N(t))$ respecting QoS specs.

$N \leftarrow N(t)$
$\Psi \leftarrow \Psi(t)$
for each $n \in N$ **do**
  $\Omega \leftarrow \sum_{n \in N} \pi_n^2 . \Delta_n$
  $\alpha_n \leftarrow \left\lfloor \frac{\pi_n^2 \Delta_n}{\Omega} . \Psi \right\rfloor$
  if $\alpha_n > b_n$ **then**
    $\alpha_n \leftarrow b_n$
  end if
  $\Psi \leftarrow \Psi - \alpha_n$
  $N \leftarrow N - \{n\}$
end for

The algorithm outlined functions dynamically on a per-superframe basis at the end of the coordinator. Priorities come from a combination of two elements: first, the device priority as decided by medical experts, and secondly, the severity/emergency of the sensed value to be transmitted as indicated by the closeness to the respective threshold. Together with successively updated backlogged packet count, the burstsize specification conveys the traffic heterogeneity information. The heuristic that governs the algorithm for slot assignment in each superframe puts emphasis on the normalized priority level in quadratic measures while burstsize level is taken linearly. The running time of the algorithm is of second order in number of nodes (N); this is due to the fact that within each run of the main iteration, there is requirement of measuring for normalization condition which also takes O(N) times each in the worst case.

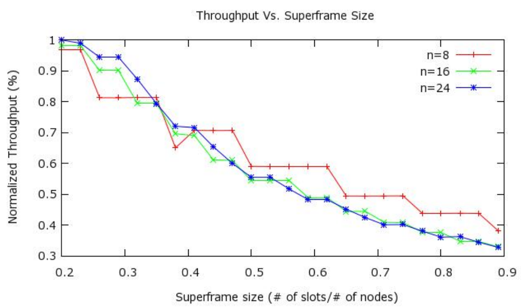
Therefore the above observations characterize the algorithm which can be formally expressed through the following theorem.

Theorem 1. In scheduling for N nodes, algorithm MAC-Slot-Reservation allocates slots in quadratic order of priorities and in linear proportion of burstsize while running in O() time.

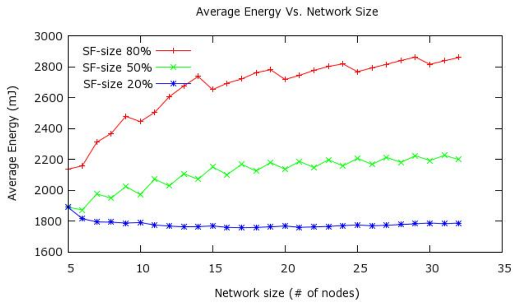
Ⅴ. Performance Considerations

With the advantage of centrally coordinating the transmission schedules, we model the upstream traffic which constitutes the bulk of the entire network traffic for the described application domains. Accordingly, Poisson arrival is assumed in topdown fashion in the form of transmission requests distinguished by such QoS metrics as priority and burstiness.

We show the effect of some crucial parameters exclusive to this framework of application, traffic characteristic and protocol upon such metrics as throughput and energy consumption. We varied portions of nodes (randomly assigned) to have bursty traffic with a stream of packets to send rather than single packets, and rest of them have light (single packet) load. Poisson traffic for both types is distributed across the available slots in each superframe with normalized slot-assignments based on priority and remaining packet loads for all nodes.



〈Fig 3〉 Normalized throughput with superframe size



〈Fig 4〉 Energy variation-with network (and superframe) size

Simulation shows that larger superframes (compared to number of nodes) result in lower delay; though, as a payoff, however, such long superframes lead to higher energy per transmitted packet being required across the network, and under lower load, achieves lower throughput.

For unsaturated condition with both classes of traffic and priority, Figure 3 shows how aggregate throughput goes down when superframe length grows compared to network size for a fixed arrival rate at the coordinator's end. This is because much of the channel access time is wasted in inactive/unused slots of the superframe, as the coordinator can only dictate the sensor nodes with reservations during a beacon period, which is further apart in larger superframes.

The average energy consumption is depicted as per packet-delivered statistics in Figure 4. When throughput reduces under low load, the overhead due to coordinator's energy consumption and sensor nodes' listening during the beacon period causes the ratio to grow further up. Since the superframe-length is taken with a constant factor of the network size, it grows with fixed interval along the line of networksize growth in the x-axis; thus the superframe-length becomes relatively long (compared to network size) right before next increment level comes (this is similar to the famous TCP sawtooth behavior), and shorter superframe size leads to higher throughput which yields lower energy consumption in a per-packet estimate.

Ⅵ. Conclusions and Future Work

There are medical and non-medical applications with requirements which do not fit well with standard assumptions in regard to network and traffic characteristics when it comes to designing MAC protocols. Such scenario brings forth novel hurdles to overcome just as it involves opportunities to exploit for network performance.

We briefly presented the framework of this scheme and studied the impact of some key parameters particularly crucial for this context. Some of the design parameters are exclusive to this scheme for tuning performance of the system because of the presence of trade-off. More rigorous study of this protocol is under way; specifically, we intend to add some of the finer features, conduct a more detailed simulation and integration of multi-objective QoS optimization features and analysis thereof (particularly, with multi-class bulk arrival queues).

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