Mobile Telemedicine Sensor Networks with Low-Energy Data Query and Network Lifetime Considerations

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Abstract—In this paper, we use an integrated architecture that takes advantage of the low cost mobile sensor networks and 3G cellular networks to accommodate multimedia medical calls with differentiated Quality-of-Service (QoS) requirements. We propose a low-energy, distributed, and concentric-zone-based data query mechanism that takes advantages of hierarchical ad hoc routing algorithms to enable a medical specialist to collect physiological data from mobile and/or remote patients. The medical specialist uses cellular network to report patients' data to the medical center. Moreover, we propose a transmission scheme among different zones with balance-based energy efficiency, which can extend network lifetime. We evaluate the validity of our proposals through simulations and analyze their performance. Our results clearly indicate the energy efficiency of the proposed sensor network query algorithms and the efficiency of our multiclass medical call admission control scheme in terms of meeting the multimedia telemedicine QoS requirements.

Index Terms— Mobile telemedicine, ad hoc networks, sensor networks, 3G wireless cellular networks.

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1 INTRODUCTION

RECENTLY, advances in microelectro-mechanical systems (MEMS) technology, wireless communications, and digital electronics have enabled the development of low-cost, low-power, and multifunctional medical microsensor nodes. These sensors consist of sensing, data processing, and communication components, and can be used in mobile telemedicine applications based on the collaborative effort of a large number of sensors [1]. Mobile telemedicine has the potential of providing telehealthcare to elderly and other patients who can continue to live a normal active life instead of being stranded at the hospitals (or having to regularly visit hospitals) that are already facing worsening resource problems including time unavailability, space limitation, and high on-site costs [2]. While most of the existing mobile health systems in Europe use IP over GPRS, UMTS or other mobile technologies [3], we argue that a *multimedia* telemedicine platform with *the integration of 3G-cellular and Wireless Sensor Networks (WSN)* can also be promising. In this paper, we consider a 3G-based *multimedia telemedicine* application scenario as follows: The area of a community or part of a large city is covered by a cell of the 3G cellular network. The patients carry medical communication equipment, such as a *medical phone*. When a patient moves from one *cell* to another, handoff occurs. Medical microsensors are implanted or externally installed on patients' bodies for monitoring important health parameters, such as blood pressure, ECG, or even cancer chemical material level [4]. The served population includes *ambulance patients*, *serious*, and other *general patients*. The sensor network in each cell of a 3G network is expected to be large-scale (e.g., > 500 sensors in each cell with radius of 1 Km). Periodically, the remote medical center needs to query the current health parameters of different patients using mobile medical specialist(s). For this, a medical specialist issues a query to the sensor network. In response to the query, the sensors return the patients' medical data back to the medical specialist through multihop, energy-efficient routes. The medical specialist then establishes a cellular connection (call) with the medical center to transmit the query resolution data.

In this mobile telemedicine scenario, many challenging issues need to be addressed. In this paper, we will focus on the following two issues: 1) *Energy-efficient*[1] *data query* in large-scale mobile sensor network. The fact that the patients carrying these sensors have certain mobility (typically from 1m/s to 30m/s) makes it difficult for the data query resolution protocols to generate accurate results. 2) *Adoption of an efficient Multimedia Call Admission Control (CAC) scheme* to support different types of medical calls. We should consider *new-call blocking probability (NBP)* and *handoff-call dropping probability (HDP)*. Particularly, we need to give *Ambulance calls* Zero HDP.

1.1 Related Works

Energy-efficient data query in Wireless Sensor Networks (WSN) is a relatively new field. Large scale and wireless mobile nature of WSN make data query protocol design very challenging. The related work on data query in WSN mainly pertains to static, small-scale, flooding-based query

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Manuscript received 26 Mar. 2004; revised 7 Aug. 2004; accepted 15 Dec. 2004; published online 15 Feb. 2006.
For information on obtaining reprints of this article, please send e-mail to: tmc@computer.org, and reference IEEECS Log Number TMC-0122-0304.

[1] That is, the query protocol should have very low energy consumption in order to maintain a long network lifetime.

schemes instead of mobility-based, large-scale, and energy-efficient approaches [11], [12]. Perhaps the simplest form of query forwarding is global flooding. Obviously, this scheme does not scale well and consumes much energy. Directed diffusion [11] provides a data dissemination paradigm for continuous queries in sensor networks. The ACQUIRE algorithm [12] was proposed for complex query resolution in sensor networks, where the query message is active, querying up to d hops in each step. It however does not consider mobility. In [5], a mobility-assisted scheme uses the concept of "contact" to reduce the query overhead due to sensor mobility. The above WSN data query schemes have the following shortcomings when applied in our telemedicine scenario: 1) They do NOT provide a detail ***intracluster*** and ***intercluster*** routing architecture and, thus, it is not clear how they organize sensors into "clusters" and how they forward a query command inside each cluster and between neighboring clusters in an energy-efficient way. Our scheme (see Section 3) provides a MST-based ***intracluster*** routing scheme to achieve full interconnection with very low maintenance overhead. In terms of ***intercluster*** communication, we further organize clusters into different *concentric* domains with the *Medical Phone* as the center of each domain. Thus, the Medical Phones can perform **local** data aggregation and reduce long distance sensed data transmission. 2) They do NOT **quantitatively** provide the probability of becoming a Cluster Head (CH) for each sensor. We will use Voronoi Tessellation theory [41] to calculate CH election probability (see Section 3). 3) Moreover, we will **quantitatively** calculate the routing architecture *updating period* when the patients moves around, which has been ignored in the current literature.

To address the problem of ***multimedia CAC***, Oliveira et al. proposed a multiclass CAC scheme based on adaptive bandwidth reservation in [7]. Ramanathan et al. proposed potential resource estimation scheme (*PRES*) in [8]. A drawback of *PRES* is that it attempts to accept all of the handoff calls and thus results in very high NBP. The one step prediction scheme (*OSPS*) was suggested by Epstein and Schwarz in [10]. *OSPS*[10] can however overestimate the required bandwidth in the neighboring cells and unnecessarily deny many *new calls*, which could make the *NBP* unacceptably high when applied to practical 3G multimedia networks. **The current CAC schemes have the following *shortcoming*** when applied in our mobile telemedicine application: They can NOT provide a multiclass, priority-based CAC algorithm that can guarantee the QoS of *ambulance calls* (we call them Handoff-guaranteed calls since no handoff dropping is expected) with **zero** HDP *based on an accurate next-cell prediction* as we do (see Section 4) and other types of medical calls (we call them Handoff-prioritized calls since we allow different dropping probabilities for different calls) with an *HDP below a certain threshold with controllable dynamic guard channel schemes* (see Section 5). Moreover, the multiclass CAC scheme should also use resources more efficiently instead of blindly allocating bandwidth in ALL neighboring cells.

In addition, some works have been done on the integration of mobile ad hoc networks (MANET) and cellular networks [36], [37], [38]. However, their schemes are not suitable to our WSN-3G case since WSN has many different features compared to MANET [1]. For instance, WSN has much larger scale, more serious energy constraint, and less memory for protocols/data.

Our contributions in this paper mainly include the following three aspects:

1. We propose a low-energy query resolution mechanism in large-scale medical sensor networks. In order to forward medical query in an energy-efficient way, we introduce a tree-zone concept to take advantage of the "short delay" of proactive routing protocol and "low-energy" of reactive routing protocol.
2. We propose a communication protocol to balance the energy consumption of sensors to avoid the overusing of some sensors for data relay. The death of some sensors can cause network disconnection. Thus, our algorithm can extend the lifetime of the entire sensor network.
3. In order to differentiate different types of multimedia calls with varying QoS requirements, we introduce the concept of "Reservation Ordering" that determines priority to be given to each handoff call depending on QoS parameters and patient mobility features.

The rest of this paper is organized as follows: The infrastructure of mobile sensor networks for telemedicine applications is described in Section 2. Section 3 discusses our low-energy query resolution scheme in large-scale medical sensor networks. In Section 4, we state the detailed procedure for forming handoff prediction pool based on the next-cell prediction in order to make the **ambulance** HDP close to zero. We will also consider the CAC support for different classes of **nonambulance handoff calls** based on the concept of "reservation ordering." The simulation results, discussions and conclusions are provided in Sections 5 and 6.

2 INTEGRATION OF SENSOR NETWORKS WITH 3G CELLULAR NETWORKS

The architecture of our mobile telemedicine system is shown in Fig. 1. The medical microsensors on patients' bodies are assumed to transmit the text-type data to the "medical wrist-worn watch."[2] This watch collects all the sensing data from the body *micro* sensors and may also perform further processing such as compression. For the convenience of discussion, we shall call the "medical watch" as *sensor* in this paper. Because the *micro* sensors communicate only within the body area and their relative positions are fixed, we ignore the issue of body-area-network consisting of microsensors and focus mainly on the large-scale ad hoc networks that consist of sensors (i.e., watches). Because the patients can move around, the resulting network is a mobile ad hoc network with a dynamic route topology.

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[2] (Refer to: http://www.telemedicine.lu/eng/chap13/c1301g.htm) London Dmatek Ltd. invented "Personal Watcher" that is an external, small body-worn device, equipped with microdata-collection units, built-in-computing, and RF communication capabilities. It can continuously collect data from body microsensors.

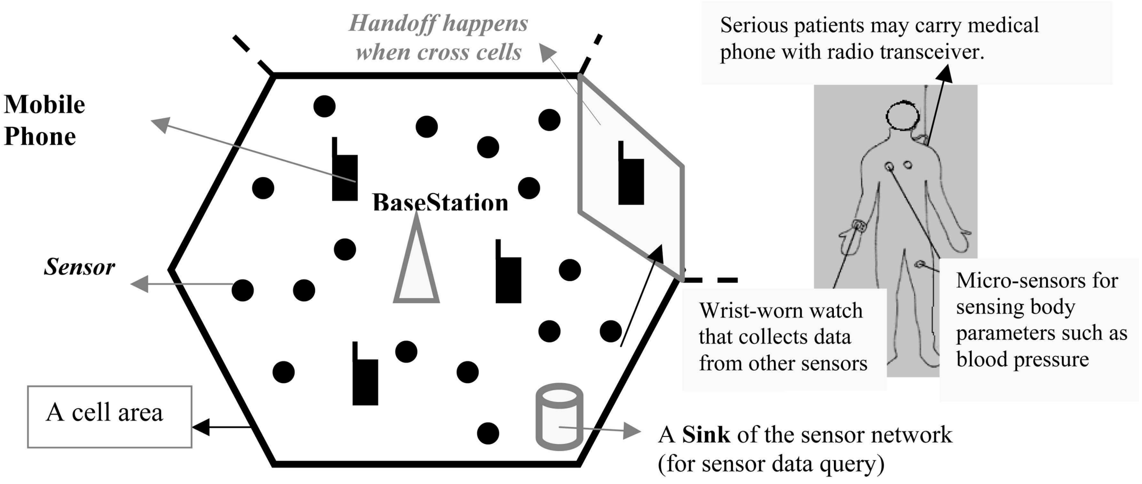


Fig. 1. Mobile telemedicine system architecture.

We divide the population obtaining telemedicine services into the following four types:

1. ***Ambulance patients*** *(with highest-priority calls).* In a typical ambulance system [14], cameras (remotely controlled by doctors in *Emergency Room* or *ER* of a medical center) take the patient's video clips. An ambulance workstation continuously collects data from the cameras and other sensors on patient's body, multiplexes it, and sends it to *ER*. We provide *zero HDP* to ambulance calls.
2. ***Serious patients or elderly people***. Their calls (i.e., data) are given the *second-highest priority*. They usually carry a special piece of equipment called "*medical phone*." The medical phone is similar to a regular cell phone with a standard infrared (IrDA) port that collects data from body microsensors [15].
3. ***General patients***. They may use *medical watches* instead of medical phones to transmit sensing data. Medical watches are typically more cost effective and smaller than medical phones [16]. However, they have much lower battery power than the medical phones and can only relay their data through multihop route to other nodes (such as a nearby watch or medical phone). If these patients carry a medical phone to directly transmit their data to the medical center, the system will assign a *lower priority* to their calls than those of the serious patients.
4. ***Medical Specialists***. They periodically send queries to the patients' sensor network through an energy-efficient routing and topology maintenance algorithm (see next section) and collect medical data based on the patients' sensor responses. The medical specialists are connected with the medical center to receive commands at any time. Please note that the medical specialists work in two kinds of networks: sensor networks (for handling medical query) and cellular networks (when communicating with the medical center). We assume that they have internal frequency transfer circuit and protocol interface to support the dual-operation mode. The call between a medical specialist and medical center is assigned a *lower priority* than normal patients' calls.

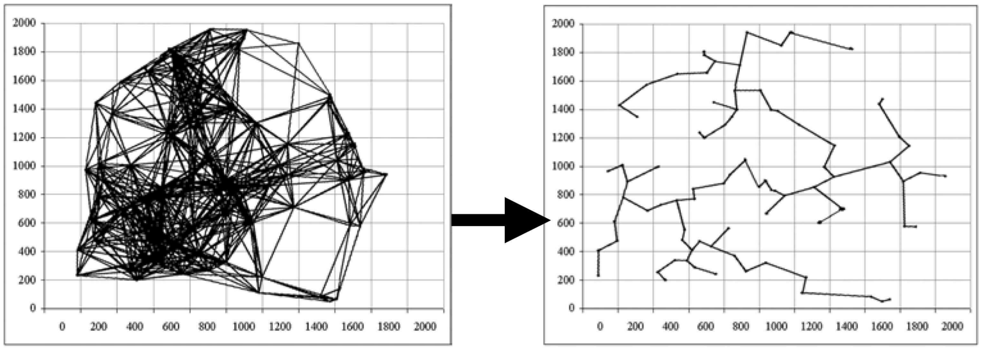
Because ambulance handoff calls have the highest priority, we treat them as "**Handoff Guaranteed (HG)** calls." Other three types of medical handoff calls are treated as "**Handoff Prioritized (HP)** calls." For the convenience of discussion, we shall call ambulance handoff calls as HG or "class 0" calls. Similarly, the "HP" handoff calls from serious patient, general patient, and medical specialist will be called as "Class 1~3" calls, in that order. Our *CAC* scheme uses resource reservation algorithms (see Section 4) to keep the *HDP* of HG calls close to zero, and to limit the *HDP* of HP calls below a certain threshold. The *new calls* from medical users are given lower priority than their *handoff calls*. Finally, the normal user' calls (new calls as well as handoff calls) are served using the remaining system bandwidth in a cell.

3 LOW-ENERGY MEDICAL QUERY IN MOBILE SENSOR NETWORKS

3.1 MST-Zone-Based Topology Management for Energy-Efficient Query Forwarding

Data query in a large-scale sensor network is a challenging issue when the sensors are moving around to cause frequent rerouting. Data query is implemented by routing protocols. Flat topology cannot be used to route packets due to its large communication overhead [17].

In this paper, we propose a tree-zone-based topology management and routing scheme. To limit wireless communication to a short distance, we require the sensors to self-organize themselves into different **zones**. In each *zone*, the sensors cooperate to form a Minimum Spanning Tree (MST) that is verified to have the optimized link maintenance overhead and the minimum number of hops to guarantee zone-connectivity. To address the scalability problem and improve energy efficiency inside each tree-zone, we use *intrazone* multihop communication to find the shortest path (with minimum number of hops) from node to node or node to the root. We use a *interzone border-cast* routing algorithm [18] to transmit data to neighboring *zones*.



(a) (b)

Fig. 2. Topology control scheme: (a) MPT-based scheme, (b) our MST-based scheme. (Note: X-axis and Y-axis: mean physical distance in meters).

In order to utilize the *specific features* of our mobile telemedicine scenario and also to *save energy*, we do not want the tree-roots to *directly* send packets to the *medical specialist* of their cell. Instead, we require the nearby medical phone to organize a *concentric circle topology* around itself and to collect data from the roots of zones in a relay way. It may be recalled that the medical phones [15] have much more battery power, longer transmission range, larger memory, and stronger local processing ability than sensors, which have limited transmission range. This paper assumes that medical phones are uniformly distributed in the cell.

In sensor networks, topology management is often integrated with routing protocols in order to implement application-specific systems [17]. Some cluster-based self-organization topology management mechanisms have been discussed in [19], [20], [35]. However, these schemes have the following shortcomings when used in our mobile telemedicine applications. *First*, they do not consider the optimized deployment of clusters to minimize global transmission energy. In our scheme, we deduce the optimized zone number based on our mobile telemedicine scenario (see Section 3.4). *Second*, most of those schemes simply assume that the cluster-heads directly communicate to their member nodes and other cluster heads. In fact, even inside a cluster, multihop communication can save much more energy than single-hop. *Third*, most of them do not consider an energy-efficient *intercluster* communication mode. In fact, different intercluster routing schemes can have quite different communication energy consumption level.

We propose a self-organization scheme based on the "tree-zone" topology as follows:

1. We use a *Voronoi-Tessellation*-based algorithm [21] (see Section 3.4) to determine the number of *zones* and probability of each sensor becoming a *tree-root*. Here, the number of *zones* equals the *root-selection probability* multiplied by the total number of sensors.
2. Each *root* broadcasts a *root-hello* message to its neighboring sensors. The nonroot sensors compare the received signal strengths from all neighboring roots. The stronger signal strength means closer distance to the root [1]. Each nonroot sensor chooses the closest root and claims itself to be its member. A root and its members form a zone and each node in the zone maintains an ID array: (*root-ID*, *sensor-ID*, *sequence #*, *parent-ID*). Here, *root-ID* identifies the root, *sensor-ID* represents the sensor itself, *sequence #* is a 16-bit round-wrap number that increases by one for each topology update event, and *parent-ID* is its MST parent *sensor-ID*.
3. All the members (i.e., sensors) that belong to the same zone exchange messages to form an MST. The reasons of choosing MST for intrazone topology control instead of simple tree organization (as in most of other WSN topology control schemes) are as follows:

   a. *Spanning Tree* can provide a loop-free and multihop relay-based communication mode that saves much energy compared to single-hop direct root-sensor transmission such as in LEACH [32]. Each cluster head in LEACH [32] directly talk to its members and other neighboring cluster heads, regardless of their distance.
   b. Specially, we use a simple *intrazone* local MST algorithm and choose the transmission power between any two nodes as the weight of an edge to quickly converge to a stable MST. An important feature of our MST algorithm is to determine the minimum transmission power of each sensor to maintain connectivity [18]. This is in contrast to traditional topology control algorithms in which each node transmits using its maximum transmission power (MTP) [22]. Fig. 2 illustrates the traditional MTP-based topology control algorithm and our MST algorithm. The proposed scheme uses the **minimum** hops among sensors to achieve global connectivity.

In order to reduce the routing memory requirements in each sensor, we should limit the number of hops between any two sensors in the zone. We can formulate our zone-MST problem like this: *Given an undirected, edge-weighted graph G with n nodes and a positive integer k, find a spanning tree with the smallest weight among all spanning trees of G, which contain no path with more than k edges*. This problem is known to be NP-complete,

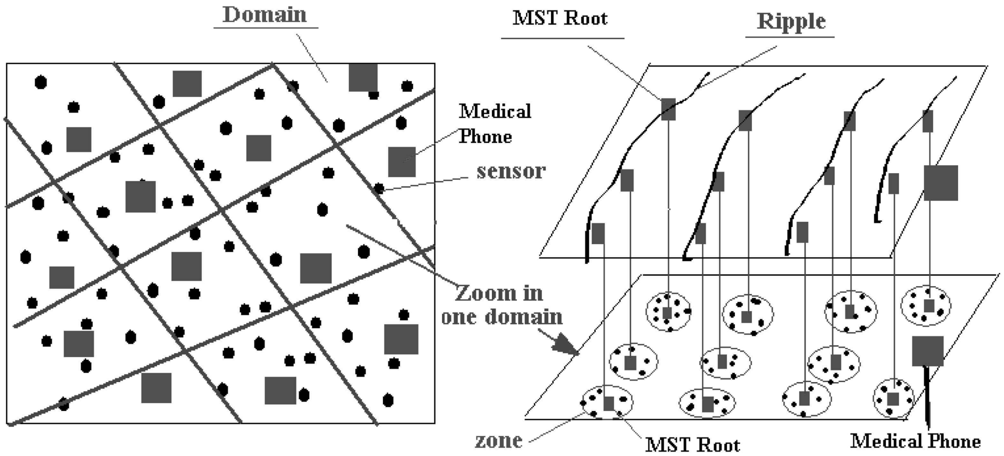


Fig. 3. Concentric GROUP structure around each medical phone (MP).

for all values of k, $4 \leq k \leq (n-2)$. Therefore, one has to depend on heuristics and live with approximate solutions. In our work, we use a modified greedy version of the Prim algorithm in [18] to solve the above problem and select edges to be added to the tree at each stage of the tree construction. Our algorithm is fast and simple [18].

3.2 Concentric-Circle-Based Global Query Response Structure

The above discussion provides the **intrazone** topology control mechanism. Now, we will investigate an energy-efficient **interzone** routing algorithm for query forwarding/response. To the best of our knowledge, none of the existing cluster-based routing algorithms considers the avoidance of redundant cluster scanning. For example, LEACH [32] simply asks each cluster head to report the data to the BS. This scheme has the following problems: 1) Sensors that typically have very limited wireless transmission range can quickly run out of energy. 2) If we need to collect the query results from all the sensors, we can only aimlessly forward the query from clusters to cluster and, thus, cause lots of cluster revisits. ZRP [26] cannot efficiently choose a **nonrevisit** zone since it just asks the border nodes in each zone to broadcast query to neighboring zones. CARD [5] is based on ZRP and chooses a small number of out-of-zone "contacts" as the query forwarding agents. But, in our mobile telemedicine application, the medical specialist needs to check **all** the patients in its community. Thus, CARD is not suitable as it may ignore many patients' data.

Our interzone routing architecture can be shown as in Fig. 3. When a *medical specialist* needs to send out a query to the patients in its coverage area, the query is first broadcasted to all the corresponding *medical phones (**MPs**)* that have much higher power than the sensors (i.e., watches). Each *MP* acts the center of a *Domain* that is formed as follows: The *MP* broadcasts a GROUP message to its *zones* with a certain transmission power. Thus, the GROUP message only covers a limited area of a cell and all MPs' GROUP messages together will cover the entire cell. The signal power level in different *zones* around a *MP* should follow the concentric distribution [27]. Thus, each zone's *root* can easily estimate its distances from different MPs, and join the GROUP whose received signal is the strongest. Based on the received power strength from a MP, each *root* knows its approximate circle-level (i.e., the circle corresponding to a certain power-db range) and can then determine its forward (for query forwarding) and backward (for query results return) *zone-IDs*.

MPs have much high power storage than sensors. Their signals can easily cover all the zones in their GROUP. Our scheme does not require each root to pass through a series of other *roots* to reach the medical specialist. Instead, we take advantage of the high-power MP to forward and collect data from its GROUP *zones*. The MP informs each *root* about its forward *zone-ID* and backward *zone-ID*. Thus, the *zone* knows its next transmission *zone*. An optimal data path is thus available for query results forwarding.

3.3 Balance-Based Energy Efficiency During the Transmission of Packets Among Roots

The radio models of wireless sensor networks fall into two categories: direct transmission and multihop transmission. With the former model, in our zone-based topology (Fig. 3), a root transmits data directly to the MP; while the latter approach follows multihop relaying between the roots and the MP. However, the direct transmission drains significant power of the roots far away from the MP because the wireless signals attenuate with the distance in an order of 2 to 4. The multihop transmission, on the other hand, consumes less power at each hop with the cost of increased total traffic in the sensor network. As a result, the roots close to the MP have to carry more traffic and accordingly may drain off their battery power quickly.

In this paper, we propose efficient path balancing and traffic splitting algorithms for balancing the energy consumption among roots. A *Balance-based Energy-Efficient (BEE) communication protocol* is developed based on our proposed algorithms. The BEE protocol employs the above two approaches (i.e., direct transmission and multihop transmission) proportionally during data transmission in order to optimize the lifetime of the entire sensor network as an integral entity. For simplicity, we start with a linear network model, which consists of $\underline{n}$ roots and a MP distributed along a straight line, as shown in Fig. 4.

Without loss of generality, the roots are labeled as 1 to n rightward. The distance between any two neighboring roots is d, while the distance between the MP and the closest root is L. The per-bit signal transmission power is $x^{\alpha}\varepsilon$, where ε is

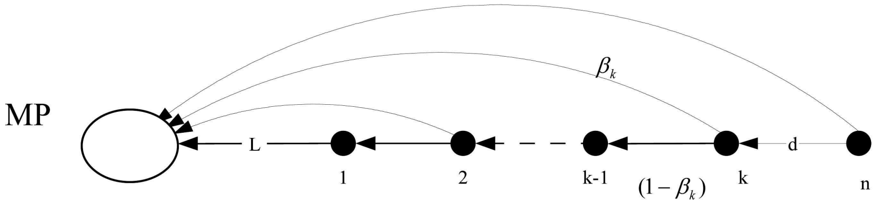


Fig. 4. Path balance algorithm for linear networks.

a constant, α is the order of signal attenuation (usually between 2 to 4), and x is the distance between the sender and the receiver. Radio electronic dissipation is E per bit. Each root k has an initial energy of E_k^{init} and an average data rate of R_k. $T_k(t)$ denotes total traffic sent out by root k during an interval t.

The roots collect data from sensors in its zone and transmit them to the MP either directly or through multihop routing. We introduce a variable β_k, which denotes the fraction of the total traffic directly sent from root k to the MP. $(1-\beta_k)$ is the fraction of traffic sent from root k to its neighbor toward the MP (i.e., root $k-1$) as shown in Fig. 4. The objective is to determine β_k $(1 \leq k \leq n)$ in order to maximize the *network lifetime.*[3]

As a result, the energy consumption of root k (denoted as M_k) includes the energy used in its direct transmission to the MP (M_k^{direct}), the energy used for one-hop transmission to root $k-1$ ($M_k^{one-hop-send}$), and the energy consumed to receive traffic from root $k+1$ ($M_k^{one-hop-receive}$). Therefore, we have, $\forall 1 \leq k \leq n$,

$$\begin{aligned} M_k &= M_k^{direct} + M_k^{one-hop-send} + M_k^{one-hop-receive} \\ &= \beta_k \times T_k(t) \times \left[\left(\sum_{i=1}^{k} d_i + L \right)^{\alpha} \varepsilon + E \right] \\ &+ (1-\beta_k) \times T_k(t) \times (d_k^{\alpha}\varepsilon + E) + (1-\beta_{k+1}) \times T_{k+1}(t) \times E. \end{aligned} \tag{1}$$

Since the last root (i.e., root n) does not consume energy for receiving additional traffic (i.e., $M_n^{one-hop-receive} = 0$) and the first root has no hop-by-hop transmission (i.e., $M_1^{one-hop-send} = 0$ and $\beta_1 = 1$), we have

$$\begin{aligned} M_n =& \beta_n \times T_n(t) \times \left[\left(\sum_{i=1}^{n} d_i + L \right)^{\alpha} \varepsilon + E \right] \\ &+ (1-\beta_n) \times T_n(t) \times (d_n^{\alpha}\varepsilon + E) \end{aligned} \tag{2}$$

and

$$M_1 = 1 \times T_1(t) \times (L^{\alpha}\varepsilon + E) + (1-\beta_2) \times T_2(t) \times E. \tag{3}$$

In order to maximize the network lifetime, all roots shall drain off battery power simultaneously. Therefore, we have the following equations:

$$E_1^{init} - M_1 = E_2^{init} - M_2 ... = E_n^{init} - M_n = 0. \tag{4}$$

From (1)-(4), we can obtain n independent equations that involve n variables $(t, \beta_2, \beta_3, \ldots, \beta_n)$, which may be solved by standard methods. The result of t shows the maximum lifetime of the sensor network, while $\beta_2, \beta_3, \ldots, \beta_n$ are the optimized proportions between direct transmission and hop-by-hop routing at each root.

We now extend the above approach to a two-dimensional $n \times m$ grid model, as shown in Fig. 5, which is closer to our practical scenario (see Fig. 3). Clearly, each column forms a path to the MP. Similar to our earlier discussion, the goal is to balance the residual power at all roots in order to maximize the lifetime of the sensor network.

The lifetime of the roots on each column can be first balanced by applying the path balance algorithm discussed in above 1D case. We denote $t_{(i,j)}$ to be the lifetime of $node_{(i,j)}$ (i.e., the root on line i and column j) after applying the path balance algorithm on each column separately. By using this approach, however, the nodes on different columns may have different lifetimes because traffic on a different column is different. To address this problem, we propose a *Traffic Splitting Algorithm*. After traffic splitting, all roots on the same line i should have the same (or very close) lifetime, denoted as t_i'. Therefore, the traffic change is

$$\Delta_{i,j} = R_{(i,j)} \times (t_i' - t_{(i,j)}). \tag{5}$$

If $t_i' > t_{(i,j)}$, $node_{(i,j)}$ should offload $\Delta_{i,j}$ traffic to other roots on line i; if $t_i' < t_{(i,j)}$, it should accept $\Delta_{i,j}$ traffic from other roots to maintain the traffic balance. If all the traffic on line i can be balanced, the following equation should hold:

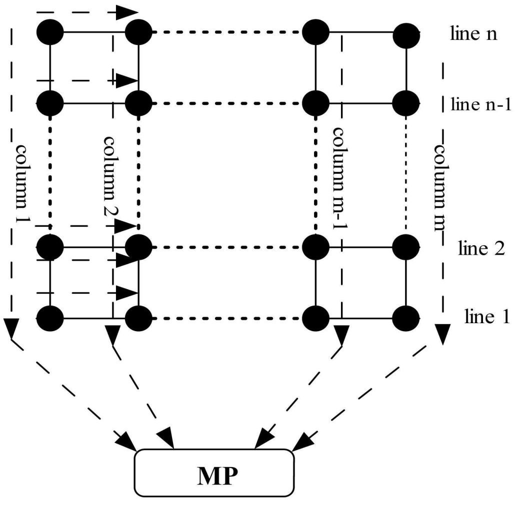


Fig. 5. Two-dimentional grid networks.

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[3] When the residential energy in all roots is similar, they will die at approximately the same time. However, if energy consumption (among different links) is not balanced, some roots will die earlier than others and the entire sensor network can have communication disconnection due to no relay roots in some places. Lifetime is defined as the time until the first root dies.

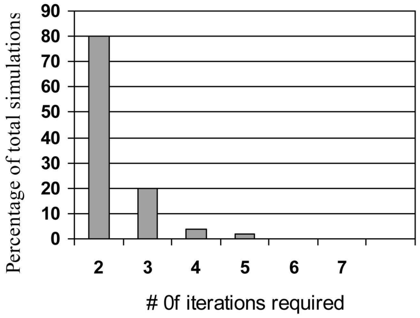

Fig. 6. Number of iterations of path balance algorithm and traffic splitting algorithm (node's initial energy is randomly chosen between 0.6 and 0.8 J/node).

$$\sum_{j=1}^{m} R_{(i,j)} \times (t'_i - t_{(i,j)}) = 0, \tag{6}$$

where $Min(t_{(i,j)} \leq t'_i \leq Max(t_{(i,j)})$.

If the traffic to be split to left and right neighbors of $node_{(i,j)}$ is denoted as $\delta_{left(i,j)}$ and $\Delta_{right(i,j)}$, respectively, we have

$$\Delta_{left(i,j)} = \sum_{k=1}^{j-1} \Delta_{i,k} \text{ and } \Delta_{right(i,j)} = \sum_{k=j+1}^{n} \Delta_{i,k}. \tag{7}$$

Therefore, the fractions of the total traffic to be split to left and right neighbors are

$$F_{left} = \frac{\Delta_{left(i,j)}}{\Delta_{i,j}} \text{ and } F_{right} = \frac{\Delta_{rightt(i,j)}}{\Delta_{i,j}}. \tag{8}$$

Equations (5)-(8) can be applied on each line to achieve a uniform lifetime of roots on that line. After the traffic splitting algorithm is applied, the lifetime of roots along lines becomes balanced, while the balance along columns breaks. Even so, we observe that the lifetime deviation of the whole network is reduced. In order to obtain a balanced outcome, the path balance algorithm and the traffic splitting algorithm can be performed for multiple iterations until the difference in lifetime of the roots is smaller than a predefined threshold, or the difference between two rounds of iteration is below a threshold, or the maximum number of iterations has been reached. Our simulation (see Fig. 6) shows that only two or three iterations are needed to obtain the optimal results for a grid network with 5×5 to 50×50 roots in an area of $100m^2$. For the wireless network with an arbitrary topology, one can first map it onto a grid [40] and then apply the above proposed balance-based energy efficient algorithm.

3.4 Determining the Optimized Number of Zone-Masters

The number of zone-roots, Θ, should be chosen carefully to minimize the system query energy. We utilize the *Voronoi Tessellation* theory [21] to build our sensor distribution model [18]. We extend the sensor transmission energy model in [28] to our concentric query architecture in order to deduce the optimized value of Θ. Let us assume that a sensor becomes a tree root with probability $\boldsymbol{p}$ and the sensors are distributed in each *zone* with radius $\boldsymbol{r}$ according to a homogeneous spatial Poisson process. Thus, the number of sensors in each zone is a *Poisson* random variable, $\boldsymbol{n}$, with mean $\lambda \bullet \pi r^2$, where λ is sensor density. Assuming all the sensors have the same radio range $\boldsymbol{d}$, i.e., $E[N] = \lambda \bullet \pi r^2$. Also, assuming that the mobile phones are distributed in each cell with radius $\boldsymbol{R}$ according to a homogeneous *spatial Poisson process*, and the number of medical phones in each cell is a *Poisson* random variable with mean $\lambda_1 \bullet \pi R^2$, where λ_1 is medical phone density. We can find out that the optimized value of root selection probability p should satisfy the following equation (The corresponding proof of this equation is provided in the Appendix, which can be found on the Computer Society Digital Library at http://computer.org/tmc/archives.htm):

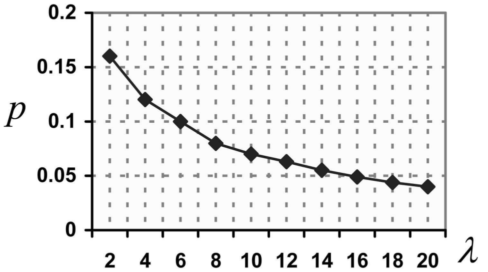

Fig. 7. Tree-root choosing probability as a function of sensor density λ.

$$\begin{aligned} &2k_2 p^{3/2} + k_1 p - k_1 = 0, \\ &k1 = \frac{\pi r^2 \sqrt{\lambda}}{2d}, k2 = \frac{0.5\pi^2 r^2 R^2 \lambda \lambda_1}{d}. \end{aligned} \tag{9}$$

Once we determine the optimized value of p, the number of *zones* is $\boldsymbol{np}$. If we assume $d = 1$, $\lambda_1 = 0.1$, $r = 10$, and $R = 100$, we can obtain the numerical solutions $p \sim \lambda^{-1}$ as shown in Fig. 7. When the network density λ is higher, the probability $\boldsymbol{p}$ is smaller. However, we found out that $\boldsymbol{np}$ is larger in a denser network [18], which means we have more zones.

3.5 A New Timing Control Scheme for Data Aggregation

To save sensor energy, it is very important to reduce communication overhead through Data Aggregation (DA) in each zone-master. Timing control is a challenging issue in DA process. Because later masters which are located in a concentric-circle closer to a medical phone have to wait for data from their previous masters (that are further away from a medical phone) to arrive, there will necessarily be some increase in the time it takes them to respond to queries. As illustrated in a simple aggregation case (Fig. 8), a master at Level 2 would need to wait longer than a master at Level 1 in order to send aggregated data to its parent master. There is a design trade-off in the maximum amount of time to wait. If an aggregating master waits too long, the results of the query may not be time-relevant. This is especially true in situations in which the data sink may want initial results immediately. On the other hand, if its waiting period is too short, the results may not be accurate since some low-level masters may not send their data yet. We propose an aggregation-accuracy-adaptive scheme to control the waiting period between different levels as follows:

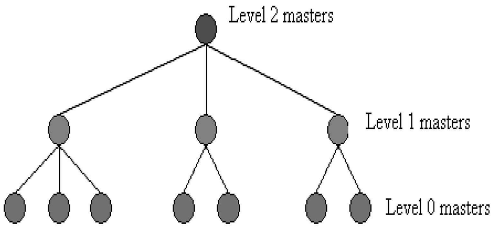

Fig. 8. Use Aggregation to reduce Data Query Redundancy.

Initially, the waiting period in each level can be set up as follows: $T_0(i) = L^+ - (D - i) \cdot \Delta$, where $T_0(i)$ is the maximum waiting period for a node at level i, D is the depth of the aggregation tree (i.e., the number of levels between a medical phone and the furthest masters). Δ is the difference between maximum waiting periods at two neighboring levels, and L^+ is the maximum tolerable delay for the query result transmission from the furthest nodes to the root. We further denote $N_{opt}(i)$ as the *optimal number* of responses expected to be received in Level i. To focus on our timing control scheme, we assume that its value can be specified based on the data accuracy requirements in specific WSN applications. Assume $\mathrm{N_{act}(i)}$ is the *actual number* of responses received. If $\mathrm{N_{act}(i) > N_{opt}(i)}$, we should *decrease* the value of $i\text{th-level}$ waiting period, $T_N(i)$ (representing the value in Updating Round N) when next updating round comes (we denote the new round value as $T_{N+1}(i)$. To quickly adapt to the aggregation accuracy requirements, we adopt *exponential* increase/decrease versus *linear* change if the difference between $\mathrm{N_{opt}(i)}$ and $\mathrm{N_{act}(i)}$ is larger than a predetermined threshold.

The Finite State Machine (FSM) of our data aggregation time control scheme is shown as Fig. 9, where C is the predetermined exponential factor (1<C<2) and θ is a linear change factor (θ > 1 time unit).

4 CALL ADMISSION CONTROL FOR MEDICAL CALLS

4.1 CAC for Handoff Guaranteed (HG) Calls (i.e., Ambulance Calls)

Most existing reservation-based CAC schemes assume that the Mobile Host (MH) may handoff to **any** neighboring cell with equal probability when predicting required bandwidth, which is a waste of wireless resource [7], [8]. In our scheme, we predict the *next cell* that the ambulance will move to. It is not a very difficult task with the progress in GPS and other location prediction systems [27], [30]. In [30], an extended self-learning *Kalman filter* was adopted to deal with unclassifiable random movements such as sudden turn or abrupt deacceleration, by tracking intracell trajectory. Using the *Received Signal Strength Indication* (RSSI) measurements and *Kalman filter* linearization in the well-equipped ambulance, we can easily estimate its dynamic state on a cell-by-cell basis. The next cell is determined to be the neighboring cell with maximum cell-crossing probability, which is computed on the basis of state equations and cell geometry [30]. We use the concept of *Core Area* (CA) as shown in Fig. 10. In CA, there may be a high probability for the MH to make a dramatic change in its direction and speed. The similar idea is also proposed in [30]. If MH moves beyond CA towards cell boundary, the chances of sudden change of direction are reduced. Thus we can improve the accuracy of next-cell prediction by using *Kalman filter* [30].

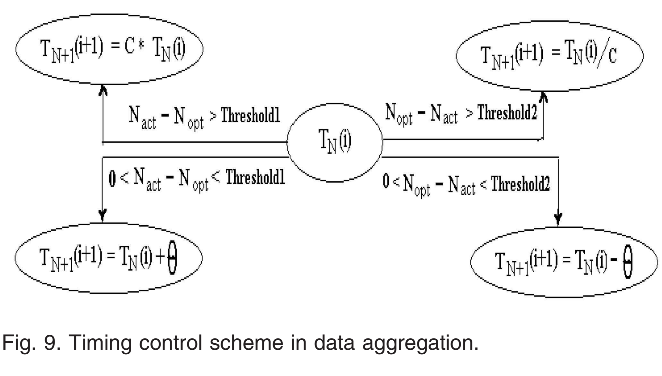

Fig. 9. Timing control scheme in data aggregation.

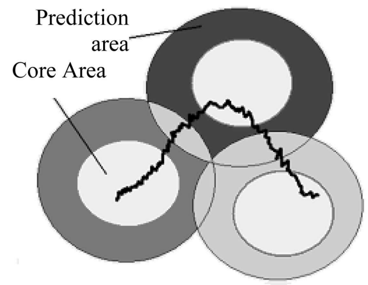

Fig. 10. Next-cell prediction.

The next-cell prediction accuracy directly determines our ambulance call's handoff success probability. Once the system knows the destination cell of ambulance, it reserves appropriate "free" channels. Different ambulance handoff calls (consisting of video, voice and/or data) may have different bandwidth requirements. We will investigate the influence of *prediction accuracy* on ambulance HDP in Section 6.

4.2 CAC for Handoff-Prioritized (HP) Calls

To handle three types of HP calls, we propose our complete CAC scheme as shown in Fig. 11. It includes the handling approach for HG calls (class 0), HP calls (class 1~3), and new calls.

In order to provide the highest priority to handoff calls from ambulance (i.e., close to zero HDP), our CAC scheme allows ambulance calls to borrow channels from *GC* pool, if required. If no free *GC* channels are available, they can preempt ongoing normal user calls (i.e., other nonpatient mobile users). Handoff calls from serious patients are also allowed to preempt ongoing normal user calls, if channels in GC pool are fully occupied. Other patients' handoff calls access GC pool that is dynamically adjusted based on the target HDPs of different classes of handoff calls. New medical calls from ambulance and serious patients are also given higher priority than normal user new calls. Because we use two resource reservation approaches for serving medical handoff calls, i.e., "1:1 matching prediction" (for ambulance patients) and "adaptive GC pool" (for other

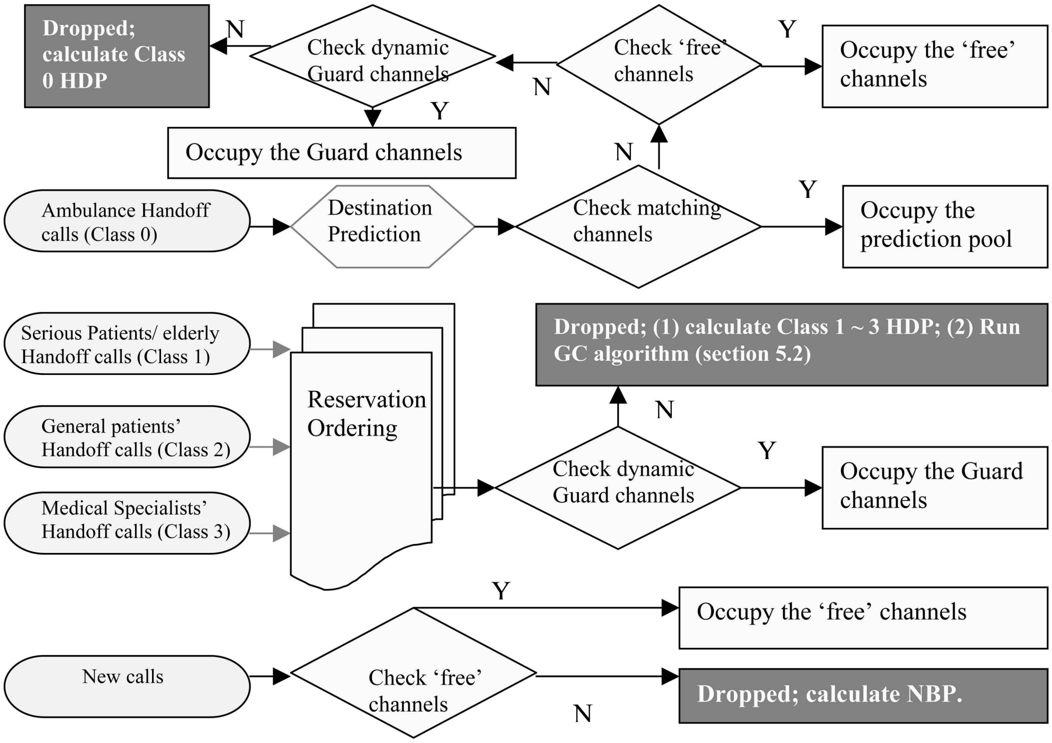

Fig. 11. Proposed Multimedia CAC scheme.

patients), the interruption in the service of ongoing normal users is minimized.

We have proposed the concept of Reservation Ordering (RO) to differentiate between different priorities of calls [39]. We assign different RO indices to handoff calls depending on their *QoS* profile, as shown below.

$$RO = [W_1 \times (\Delta RSS/\Delta t) + W_2 \times (RSS) + W_3 \times (\mathbf{Pr}iority\ Factor)] \quad where\ \ (W_1 + W_2 + W_3 = 1). \tag{10}$$

Here, *Priority Factor* (PF) depends on *QoS* parameters such as delay tolerance and *HDP*. We have used the PF values of 1, 0.8, 0.5, and 0.1 for ambulance, serious patient, general patient, and medical specialist calls, in that order. However, PF cannot be used as the only factor for determining the value of RO. For example, when a patient is moving close to the new BS (Base Station) such that the signal from the old BS is too week to maintain the normal signal-to-noise ratio, we should serve its handoff request immediately even though its PF is low, otherwise the call will be dropped. In other words, the RSS (Received Signal Strength) should also be considered in determining the RO priority. In addition, the user speed is also important, as a faster patient will generally require an earlier handoff than a slower one. $\Delta RSS/\Delta t$ reflects the mobile speed. We assign weights W_1, W_2, and W_3 based on the influence that above-mentioned three factors may have on RO. A reasonable weight assignment for W_1, W_2, and W_3 is 0.1, 0.4, and 0.5, in that order. Here, PF is assigned highest weight ($W_3 = 0.5$) because it plays an important role in multimedia network. Weight ($W_2 = 0.4$) given to position information is higher than that given to speed. We normalize the value of $\Delta RSS/\Delta t$ and RSS between *0* and *1*.

4.3 The Advantages of the Proposed CAC Scheme Compared to Other Existing Ones

In this section, we shall point out the advantages of our CAC scheme compared to other multiclass CAC works when applied to our proposed WSN-based Telemedicine environments.

1. *One hundred percent Handoff Success Rate guarantee for Ambulance Calls*. Because Ambulance handoff calls have the highest priority due to their multimedia nature (we need to transmit a patient's video, voice, and medical data), we utilize GPS or other positioning technologies (which are possible since ambulances typically have good equipments compared to *medical phones*) to first predict the next-cell that an ambulance will go to. We can thus allocate corresponding channels in the destination cell to guarantee ***zero*** HDP for ambulance calls. This is different from existing CAC schemes, which do not accurately predict the next-cell and just allocate channels in all neighboring cells, which can waste wireless bandwidth.
2. *The consideration of patient speed when determining the priority of a nonambulance handoff call*. Most of existing multiclass CAC schemes just simply assume different *bandwidth* requirements for each type of handoff calls and then calculate the desired channels. We introduced the concept of RO (Reservation Ordering), which consists of three factors: absolute positions (based on RSS measurement), moving

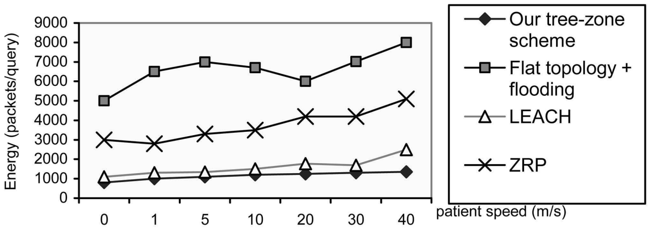

Fig. 12. Sensor network data query energy consumption.

speed, and QoS indices. To reflect the importance of QoS factor, we assign the highest weight to it. Our RO concept can *truly* reflect the different urgency levels of an approaching handoff call.

5 PERFORMANCE EVALUATION

5.1 Performance Evaluation for Medical Query in Sensor Networks

To evaluate our tree-zone-based medical query resolution scheme, we built an OPNET-based sensor network model that included 500 randomly distributed nodes in an area with radius of 1Km. For mobility, we use the *random-way point* model [5], in which a node chooses a random destination and picks a random velocity in the range (0, 13m/s). For performance comparison, we assume a simple query: *searching a specific patient in a cell area*. We then use the number of transmitted packets per query to represent the energy consumption. We compare our tree-zone scheme to LEACH cluster-based scheme [32], flat-topology-based flooding scheme [33], and ZRP scheme [25], and show the results in Fig. 12. That the flooding scheme has the highest power consumption is not a surprise since it simply uses a flat topology to flood the query to the global network. Although ZRP scheme defines intrazone /interzone routing algorithm, it does not optimize the routing scheme in each zone. In addition, ZRP requires each node to maintain the routing table for the neighboring nodes that are m-hops away from it. Our scheme requires only the tree root to maintain the topology information in each zone and thus saves energy as compared to ZRP scheme. The performance of LEACH scheme is close to our scheme. But, it will have higher energy consumption when we consider the high energy level required to send cluster information to the global network, as each cluster head in LEACH need to broadcast its cluster member information to other cluster heads and the BS. Here, we assign 10 times of one-hop transmission energy to each LEACH broadcasting packet.

In order to study the delay performance of different query schemes, we define the number of hops passed for each query as the *delay* cost. As shown in Fig. 13, the performance of our scheme is close to ZRP and LEACH. The flooding scheme uses almost-full connection algorithm to scan through the whole network and, thus, needs the longest delay to solve a query. LEACH has the best delay performance because it requests each cluster head to directly communicate to other heads and does not pass through the hops inside each cluster. Although LEACH has better delay performance than our scheme, it needs relatively long-distance transmission (between cluster heads) and consumes more energy than our multihop transmission.[4]

5.2 On the Balance-Based Energy Efficiency When Transmitting Data from Roots to a MP

We evaluate the performance of the BEE protocol and compare it with the direct transmission and the MTE (minimum transmission energy [1]) protocols by simulations in three network models: the linear network, the grid network, and the general network. We define a sensor network to be healthy if at least 80 percent sensors function properly. We assume by default $E = 50nJ/bit$, $\varepsilon = 100pJ/bit/m^2$, and $R_1 = R_2 = \ldots = R_n = 5bit/time\ unit$. The results are shown in Fig. 14. As we can see, BEE significantly improves the lifetime of sensor networks. In the linear network where $d = 10m$, $L = 100m$, and $E_{init} = 0.5J$, all nodes drain off their battery power almost simultaneously when BEE is employed, prolonging the healthy lifetime by 146 and 587 percent compared with direct transmission and MTE, respectively.

We also study a two-dimensional grid network with 10×10 nodes, where the column distance and the line distance are both $10m$. Node's initial energy is randomly chosen between 0.6 to 0.8 J/node. The average data rate is between 1 to 8 bits/time unit. As we can see in Fig. 14b, the number of active nodes decreases almost linearly with network running time, when direct transmission or MTE is employed. With our proposed BEE protocol, roughly 90 percent nodes drain off battery power simultaneously. Therefore, BEE achieves about 131 and 104 percent longer healthy lifetimes compared with direct transmission and MTE, respectively.

The simulation result of general shaped network is presented in Fig. 14c, where 100 nodes are randomly distributed in an area of $10 \times 10m^2$. The initial energy of sensors is randomly chosen between 0.6 to 0.8 J/node. The average data rate is between 1 to 5 bits/time unit. As demonstrated, BEE outperforms the direct transmission and MTE protocols. The healthy lifetimes are improved by about 61 and 71 percent compared with direct transmission and MTE, respectively.

5.3 Simulation Results for Multimedia CAC

5.3.1 *Simulation Model*

We used the mathematical analysis in [34] to build the network model for simulation experiments in our mobile telemedicine scenario. To evaluate the performance of the proposed Multimedia CAC scheme, a network model of a single cell with channel capacity C was constructed in C-based discrete-event driven simulator. A number of call generators generated *Poisson* arrivals of new call and handoff call requests from different service classes.

We set the prediction accuracy for ambulance handoff call arrivals as 0.95. We set up other typical system parameters as follows (some of them will be changed later): The capacity of each cell is $C = 128$ channels. We regard the HDP value of below 0.0001 as a good approximation of zero HDP. The target HDP P_i^H of the HP services were set to 0.01

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[4] As discussed in Section 3, we ask a zone root to forward the query along its tree branches to the tree leaves that further forward the query to the tree leaves in another zone.

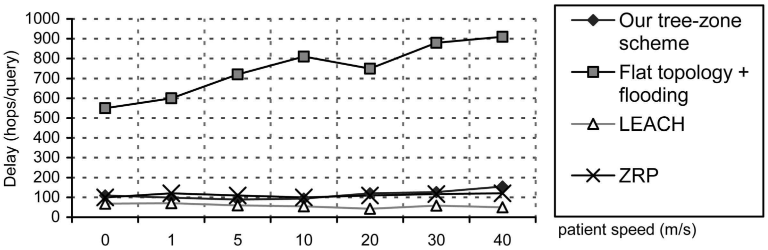
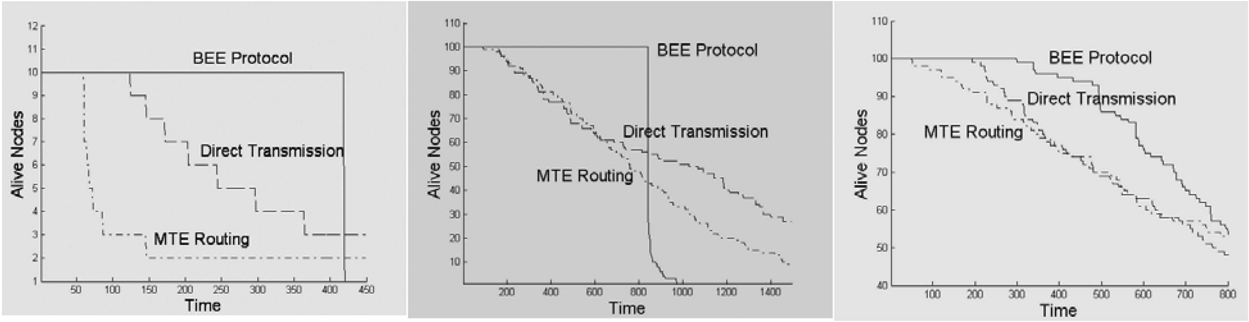


Fig. 13. Data query delay.



(a)

(b)

(c)

Fig. 14. Lifetime comparison. (a) Linear network. (b) Grid network. (c) General network.

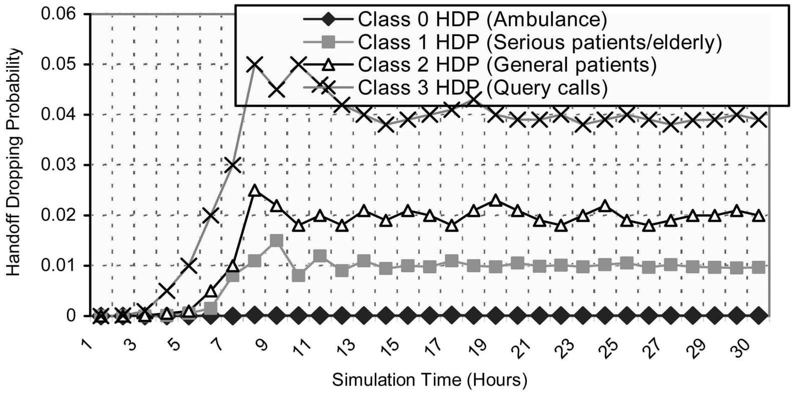


Fig. 15. HDP for HG and HP calls.

for Class 1 (serious patients /elderly), 0.02 for Class 2 (general patients), and 0.04 for Class 3 (query) calls. We assume that voice, data and video, each require two, one, and four channels, respectively. We further assume that ambulance calls are all multimedia services (i.e., include voice/data/video), Class 1 calls transmit data and voice, and Class 2 and Class 3 calls only transmit sensing data.

The results for *30-hour simulation* are shown in Fig. 15. We can see that HDP of different classes of calls is close to their target values. Here, we have used an Ambulance Call Reservation (ACR) timer (15s), which is used to free the channels reserved for an HG call if they are not used by the ambulance (primarily due to reservation error) before the timer expires.

5.3.2 Effect of Destination Prediction Accuracy and Mobility Mode

To investigate the influence of prediction accuracy on the performance of our CAC scheme, we vary the value of prediction accuracy from 0.3 to 0.9 and observe the HDP of HG ambulance calls. Fig. 16 clearly demonstrates that the HDP of HG calls rapidly increases with degradation of next-cell prediction accuracy. HDP also increases with an increase in handoff call density (HCD). Here, HCD is the ratio of handoff calls to all the calls.

In the above simulation, we assumed that users are moving in all directions randomly at the same speed. In order to investigate the influence of user mobility, we assume that Class 2 users move towards a desired cell with a higher probability than other neighboring cells, i.e., we set up a biased mobility mode. We compare HDP in the two cases (even and biased mobility modes) in Fig. 17. Because the biased mobility mode generates more handoff requests in the reference cell, we can see that the HDP performance is worse. However, the HDP in Fig. 17 decreases with an increase in user speed because a faster handoff call has higher *Reservation Ordering* and, thus, a lower dropping rate.

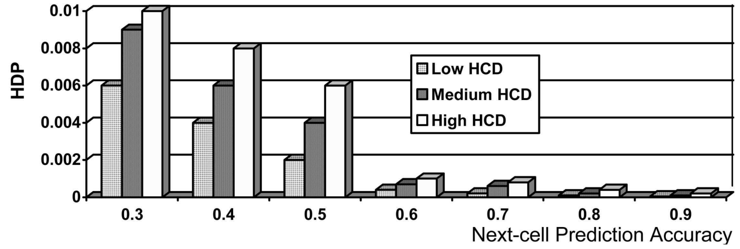


Fig. 16. The influence of next-cell prediction accuracy.

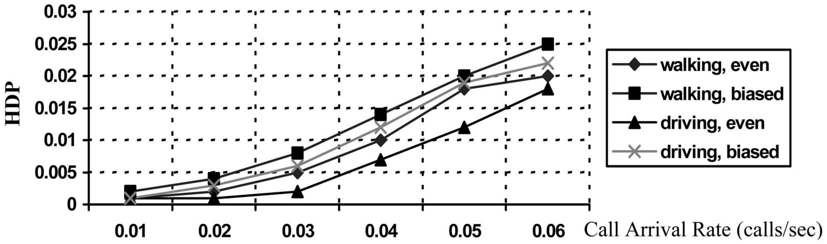
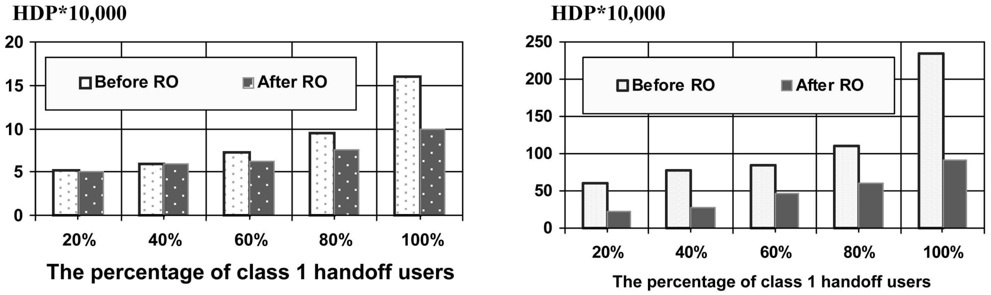


Fig. 17. HDP with patient moving speed.



(a) (b)

Fig. 18. Effect of handoff Reservation Ordering (RO). (a) HDP for Class 1 calls with handoff load 25 percent. (b) HDP for Class 1 calls with handoff load 75 percent.

5.3.3 *Effect of Handoff Reservation Ordering (RO)*

In order to highlight the effect of RO on HDP, we consider Class 1 (serious patients) calls, under light to heavy handoff load. Here, we assume that RO depends only on *PF*. Fig. 18 shows the simulation results. Here HDP has been multiplied by 10,000. It can be seen that HDP decreases when RO is used. The effect of RO is very dominant for heavy handoff load (Fig. 18b). Here, handoff load represents handoff calls of all the classes.

6 APPLICATION DISCUSSIONS AND CONCLUSIONS

In this paper, we described a mobile telemedicine application—a hybrid network architecture based on wireless sensor network and the 3G cellular networks to monitor mobile patients and serve four classes of multimedia medical calls—ambulance (class 0), serious patients (class 1), general patients (class 2), and medical specialists who send sensor query results to the doctor (class 3)—that have different QoS parameters (bandwidth requirements, handoff dropping probability, new call blocking probability). To guarantee the zero-HDP of ambulance calls, we used next-cell prediction to reserve the channels based on "1:1 matching." For handoff calls of the other three classes, we used an adaptive guard channel scheme to achieve the target HDP of each call. To address the issue of medical specialist's query resolution, we proposed a zone-tree topology management algorithm that could implement a minimum spanning tree in each zone and forward the query to the neighboring zones through the interzone routing algorithm. We have also proposed a transmission scheme among zone-header nodes with balance-based energy efficiency. Our simulation results show that our sensor query scheme has very low energy consumption, which is the main concern in the wireless sensor networks.

As a matter of fact, our network topology can also be regarded to consist of three types of wireless networks: 1) Large-scale Wireless microSensor Networks (WSN), 2) 3G cellular networks, and 3) Small-scale mobile ad hoc networks, i.e., MANET, (in our case, each node is a medical phone). Recently, some research [36], [37], [38] has been conducted to organize the phones to a MANET in a cellular network to enhance the uplink (phone-to-basestation) throughput performance. In this study, we further used the WSN to collect environmental data. To enhance the WSN query performance, we used the medical phones, which have much higher energy and processing capability than medical sensors, to manage the local routing topology and aggregate medical data. Those medical phones can directly send data to a WSN sink (i.e., medical specialist). Moreover, they participate in the 3G communications.

The proposed telemedicine architecture can also be applied in other similar mobile sensor network application scenarios. For example, in a battlefield covered by a satellite cellular network, high-power PDAs, which are attached to soldiers' bodies, tanks, or planes, can self-organize themselves into a MANET. Those PDAs can also use the satellite ground-station to contact with a remote command center. Moreover, each PDA can collect/aggregate the local sensed data (such as bomb locations, chemical materials) from battlefield sensors and send those data to a command center. The other example is Building Monitoring, where high-power Wireless LAN nodes can query sensors in the building and send the sensed data (such as fire events) to a remote control center through 3G networks.

ACKNOWLEDGMENTS

This work is supported by the 2004 Cisco URP grants (at RIT) and US National Science Foundation CAREER 2004 Award (at the University of Louisiana).

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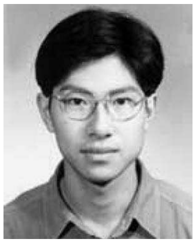

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